ABSTRACT

BELT, ALEX JASON. Exploring Customization Option Assessment and Selection during the Early Stages of Redesign. (Under the direction of Dr. Scott Ferguson).

In the pursuit of mass customization, firms have adopted product platforms and customization options, or options that allow consumers to slightly modify their product, as ways to offer more product variety. Numerous methods exist for creating product variety through product platforms, but far fewer approaches exist for customization option assessment and selection. Furthermore, few methods for product variety incorporate marketing information with engineering information. To address these gaps, a five step, bottom-up approach is proposed to assess and select customization options during the early stages of redesign.

This thesis extends an existing engineering change tool and combines it with market analysis to create a tradeoff plot that allows engineers to explore and select customization options for further development. Specifically, the Change Prediction Method is modified to obtain total cost estimates for each customization option, and discrete choice conjoint analysis is used to obtain market shares of preference for each option. Two case study problems, a desk fan and gas grill, are explored to investigate the effectiveness of the proposed approach. Results from these case studies provide initial validation and indicate that the approach can be successfully used to assess and select customization options during the early stages of redesign.

Exploring Customization Option Assessment and Selection during the Early Stages of Redesign

by
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DEDICATION

To my mother and father,

whose love and support allowed me to preserve and complete this thesis

BIOGRAPHY

Alex Jason Belt received his Bachelor of Science degree in Aerospace Engineering, as well as a Minor in Graphics Communication, from North Carolina State University in May 2011. During his undergraduate career, he completed an undergraduate research project on an experimental setup for characterization testing of ferroelectric, polycrystalline and single crystal stacked actuators under the direction of Dr. Stefan Seelecke. Additionally, Alex conducted research on characterizing high speed dust particles in a small dust accelerator at the Colorado Center for Lunar Dust and Atmospheric Studies.

While attending graduate school, he completed several classes related to product development and joined Dr. Scott Ferguson's System Design Optimization Laboratory to conduct research in this area. Upon graduation, Alex plans to become a product designer for an aerospace engineering company, preferably in the Western United States.

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CHAPTER 1: INTRODUCTION & MOTIVATION

1.1: Introduction

Before delving into the motivation behind this thesis and the associated research questions, a product development strategy is proposed. The reasons for this strategy are twofold: (1) to help set up the realistic motivation behind this thesis and (2) to formalize and provide some anecdotal support for the underlying assumption that products evolve over time, and, as a result, mass customization does not begin with the generation of an entirely new product concept. The next section presents this strategy followed by the motivation behind this thesis and the associated research questions at the end of this chapter.

1.2: Mass Customization from a Product Development Strategy Perspective

For several industries, product development strategies have evolved from craft production to mass production and most recently towards mass customization. When a product based on new technology is first introduced, the strategy of craft production (CP) is adopted. During this epoch, engineers are still developing the new technology, and often only manufacture a few unique products. The products are bought by a small market of innovators and early adopters [1] whose needs, either homogeneous or heterogeneous, can be fulfilled by the manufacturing firm.

As a new technology matures, the next epoch of the product is produced using the tenets of mass production (MP). During this time, improvements to the product's design and manufacturing process allow engineers to create a large amount of the standardized product with reduced costs. This reduction in cost allows the product to be offered at a lower price, attracting customers who are becoming more familiar with the product and its new technology. In comparison to the CP era, the markets have grown from small to mass as early and late majority consumers [1] adopt the product. Though many people are purchasing the product and companies realize the heterogeneity of their preferences, these companies offer as few products as possible by targeting large pockets of consumers whose preferences are very similar and can be considered homogeneous. By following such a strategy, companies in MP can save costs, but consumers are not fully satisfied with the offered products.

As firms further fractionize these pockets in an attempt to more fully satisfy the heterogeneous preferences of consumers, the next epoch of mass customization (MC) is begun. At this point, engineers redesign the products from standardized goods to a product family aimed at satisfying the heterogeneous desires of the mass market. A popular approach for satisfying the heterogeneous desires of mass markets with product variety is product platforms [2]. As will be discussed later in this chapter, product platforms allow engineers to get closer to MC, but it is not pure MC. Pure MC is defined with Davis' definition: a product development strategy that enables firms to offer consumers "exactly what they want when they want it" [3]. In order to reach pure MC, a strategy other than solely product platform-based design must be developed to bridge the gap, as shown in the below figure:

FIGURE 1.1: PRODUCT DEVELOPMENT STRATEGIES

The purpose of this thesis is to explore this gap and propose an approach to help bridge it. In particular, this thesis conducts a product review to support this proposed product development strategy, suggests a conceptual-level idea to help bridge the gap, and finally proposes a quantitative approach to implement this conceptual-level idea using existing marketing and engineering tools. Further details and research questions concerning the purpose of this thesis are given at the end of this chapter.

The three product development strategies are now discussed in more detail. Specifically, the strategies are explicitly defined and their key characteristics, or principles, are discussed. Following the presentation of these strategies, the motivating problem and research questions for this thesis are given. Lastly, in Chapter 2, several product examples are presented to support this proposed product development strategy.

1.2.1: Craft Production

Before mass customization and mass production, the dominant business paradigm was craft production (CP) [4]. Traditionally, craft production is defined as a type of production in which raw materials are transformed into a finished product by skilled artisans with or without the assistance of simple hand-held tools. With this definition of CP, products that involve woodworking, metalworking, glass working, clay forming, etc. come to mind. Product examples range from functional cabinetry to decorative pottery.

Though there are many types of products that fall under the umbrella of CP, they all exhibit four common characteristics. Craft-produced goods (1) are typically high-quality, (2) are unique, (3) lack economies of scale, and (4) exhibit low production volumes [5]. Artisans take pride in their skillful work [4], and subsequently create high-quality finished products. The products they create are unique in that no two products are identical because they are hand-crafted and use limited or no standardized parts. Additionally, craft-produced goods are unique because they can be made-to-order. Consequently, craft production can serve the needs and wants of both homogeneous and heterogeneous markets. However, this type of production can only serve small, and not mass, markets due to the lack of economies of scale and low production volumes. From the absence of economies of scale, the cost to produce many products is only slightly less than the cost to produce a few products. Concerning low production volumes, a small amount of products are produced annually due to the long production times associated with hand-crafted goods. All of these characteristics are related to the traditional definition of craft production.

For the purpose of this thesis, the traditional definition of CP was considered too narrow, and thus it was expanded. In this work, craft production is a type of production where raw materials are transformed into a finished product by skilled artisans with or without the assistance of simple hand-held tools and machinery. The difference between these definitions is that the product can be created by hand with the support of complex machinery. This definition is in agreement with Pine's view of craft production when machinery was introduced into the American production process: machinery enhances the craftsman's skill and allows the craftsman to create a larger variety of products [4]. Products that fit this definition of CP range from designer dresses to Tiffany lamps [4] to Aston Martin sports cars [5], [6].

Even with the revised definition of craft production, the product characteristics of the typical CP definition remain intact. Craftsmen that use complex machinery still create high-quality products because they take pride in their work, and the products are still unique because they are created by hand, use limited to no standardized parts, and can be tailored to meet the heterogeneous wants and needs of an individual customer. Finally, from being hand-made with only machine augmentation, these products still lack economies of scale and have low production volume.

Though machinery was used to augment artisans' skills, machines were also used to replace craftsmen to increase production volume and ensure consistently high-quality products [4]. With an additional focus on lowering production costs and prices, economies of scale were improved. Consequently, the wants and needs of mass markets could be met. The product development strategy that utilized machinery and focused on low costs and prices was mass production.

1.2.2: Mass Production

Mass production (MP) is a product development approach in which standardized products are made by specialized workers and machinery. This product development strategy was created in America during the twentieth century from the American System of

Manufactures. Though closely related to mass production, the American System of Manufactures was distinct in that it did not focus on lowering costs and prices, but instead focused on increasing production volume and ensuring consistently high-quality products [4]. Beginning in the late nineteenth century, this product development strategy struggled in enabling companies "to meet the demands of an increasingly geographically dispersed economy" [4]. Consequently, the strategy of mass production was introduced and adopted.

From the American System of Manufactures, MP borrowed four characteristics and added several others. For the interested reader, a more in depth discussion of the American System of Manufactures is presented in [4]. The principles of mass production, as identified by Pine [4], include:

1. Interchangeable parts
2. Specialized machines
3. Focus on the process of production
4. Division of labor
5. Flow
6. Focus on low costs and low prices
7. Economies of scale
8. Product standardization
9. Degree of specialization
10. Focus on operational efficiency
11. Hierarchical organization with professional managers
12. Vertical integration

These principles are numbered to facilitate discussion; in no way do they indicate the degree of importance. The first four principles were adopted from the American System of

Manufactures. In the American System of Manufactures, the first principle, interchangeable parts, was used to speed up the assembly process and repair products easily [4]. With the eighth principle, product standardization, the assembly process was even more streamlined and products could be more easily repaired. In both product development systems, specialized machines allowed products to be created with consistent, accurate tolerances. In the American System of Manufactures, the division of labor segmented workers to certain tasks in order to improve productivity and efficiency. In MP, this segmentation was taken even further; the tasks of workers and machines were narrowed down to one function or a number of related, small functions.

In addition to using these principles to improve productivity and efficiency, both product development strategies focused on the process of production. By expanding this focus to flow (principle five) and operational efficiency (principle ten), mass production increased productivity and efficiency. Concerning flow, factories were organized such that work flowed sequentially from worker to worker. The assembly line used by Henry Ford to manufacture Model T's is the most common example of this principle in practice. With regard to operational efficiency, factories were managed to ensure productivity and avoid increased production costs from a production slow down. To manage these factories that grew as a result of increased production volume, a hierarchical organization and vertical integration were implemented. The hierarchical organization consisted of managers who ensured factory productivity and efficiency, while vertical integration sought to further manage productivity by controlling all parts of the material flow from raw material gathering to production to distribution.

Finally, the motivation behind increasing productivity and efficiency was economies of scale and a focus on low costs and low prices. Regarding economies of scale, an increased production volume would lower costs. Furthermore, a focus on lowering costs would lead to lower prices, which would increase sales by targeting more people. Consequently, by focusing on economies of scale and low costs and prices, companies could obtain large profits.

In summary, mass production promised large profits for companies that could produce mass quantities of standardized products at low cost. The goal of this strategy was to continually decrease production costs by improving efficiencies at every level of production and using economies of scale. Through decreasing production costs, prices could be lowered, and the increased sale volumes would lead to greater profits. For much of the twentieth century, the paradigm of mass production enabled companies to flourish.

1.2.3: Mass Customization

However, approximately twenty-six years ago, a shift from mass production towards mass customization (MC) began. Firms began to fractionize their large markets into smaller ones to more fully satisfy the heterogeneous needs of consumers, who demanded products with more variety, features, and better quality than currently offered [7], [8]. Consequently, MP struggled to meet customer needs as it became possible to treat markets as heterogeneous, and the potential benefits of MC started being realized [4].

Though anticipated by Toffler in Future Shock, the term mass customization was first coined by Davis in his book Future Perfect, where he described it as a way to give consumers "exactly what they want when they want it" [3], [4]. Since the introduction of MC in 1987, this definition has been refined from Davis' idealistic view to a more practical one. The definition adopted in this thesis is a combination of the ones proposed by Hart [9] and Ferguson et al. [10]. Hart defined MC as "the use of flexible process and organizational structures to produce varied and often individually customized products and services at the low cost of standardized, mass-production systems" [9], while Ferguson et al. defined MC as "a product development approach which allows for the creation of goods which minimize the tradeoff between the ideal product and the available product by fulfilling the needs and preferences of individuals functionally, emotionally, and anthropologically" [10]. By combining these definitions, MC is a product development strategy that strives to offer (1) product variety, specifically customized products, through minimizing "the tradeoff between the ideal product and the available product by fulfilling the needs and preferences of individuals functionally, emotionally, and anthropologically" [10] and (2) such products "at the low cost of standardized, mass-production systems" [9].

In comparison to mass production, mass customization can be considered at the opposite end of a product development spectrum [6], [8]. Instead of focusing on low costs at the individual product level and economies of scale by improving plant productivity and operational efficiency, mass customization focuses on satisfying individual consumer needs and economies of scope by offering product variety and improving process efficiency [4], [7]. Put succinctly, the goal of this strategy is to offer more product variety than mass production, while maintaining near mass production costs [9]. By achieving this goal, companies can obtain more market share and larger profits in heterogeneous markets than could be achieved with mass production.

To be successful at mass customization, companies must be proficient in three fundamental areas: (1) solution space development, (2) robust process design, and (3) choice navigation [11]. Solution space development identifies the individual preferences of customers and then determines which product concepts to offer. Robust process design focuses on using the existing organizational structure to create a variety of products near mass production costs, and choice navigation assists customers in selecting a product. In the design community, a lot of research has been focused on the first two fundamental areas. For the purposes of this thesis, work in solution space development is relevant. In this area, research in product platforms has enabled companies to move along the aforementioned product development spectrum from MP to MC.

1.2.3.1: Platform-based Product Development and Match-to-Order Approach

Platform-based product development, or product family design (PFD), is a key MC technique that is currently being used by companies to help them meet the heterogeneous needs of their customers [2]. PFD is a product development strategy in which a set of related products are designed from one or more product platforms [12]. A product platform is therefore a set of elements that enable (and enforce) commonality between product family members. With a product platform, companies can offer a variety of products at costs similar to mass production. An overview of the numerous research conducted in PFD will be presented in Chapter 3.

Though PFD has helped several companies move closer to MC, PFD is not the same as mass customization; it is just a tool that helps companies get closer to MC. Platform-based product development limits the amount of customization available to consumers when compared to Davis' definition of MC in which consumers get "exactly what they want when they want it" [3]. When not compared to pure MC, PFD could still limit the amount of customization available to consumers when combined with a match-to-order approach. In this approach, customers have the freedom to select from a variety of products within the product family, but they have no freedom to alter the product's design; they simply select the product that best meets their preferences from a set of standardized products [13]. In order to move closer to Davis' definition of mass customization, PFD can be combined with an assemble-to-order approach, where consumers determine the final form of their product by selecting from a set of standardized parts.

1.3: Motivating Problem and Research Questions

As reported by Smith et al. and shown in Chapter 2, most companies pursuing mass customization are combining product family design with an assemble-to-order approach [14]. These companies offer customization options, which allow a consumer to alter his/her product's final design within constraints. With an assemble-to-order approach, consumers are able to select from a set of standardized parts to obtain a product that better satisfies their unique preferences.

As shown in Figure 1.2, this new epoch - toward mass customization with customization options - does not completely bridge the gap identified in Figure 1.1. Rather, it expands upon product platforms and helps firms move closer to Davis' definition of MC by allowing customers to have more freedom with their product's final design.

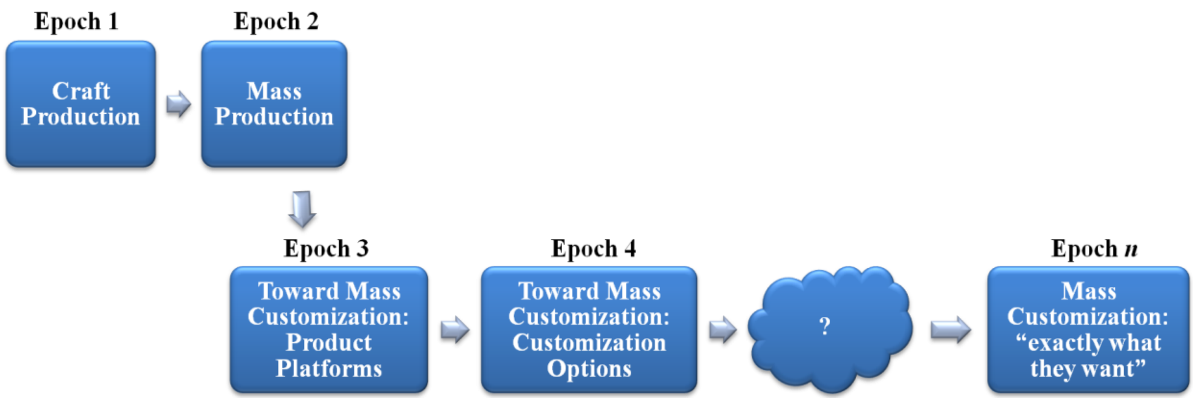


FIGURE 1.2: NEXT STEP FOR PRODUCT DEVELOPMENT STRATEGIES

Now, consider a firm that currently uses platform-based product development and a match-to-order approach to offer a variety of products. This firm wants to further pursue mass customization by allowing customers to make slight modifications to their offered products. The proposed plan is to offer customization options in an assemble-to-order approach with their platform-based products. Before embarking on this new strategy, the firm wants to determine the affect of customization options on the product architecture of their current products. In particular, the firm is interested in determining the amount of product change required to accommodate the customization options. From this scenario, the following research question (RQ) arises:

RQ 1: How can an existing engineering change tool be modified to analyze changes on an existing product induced by customization options?

Given an existing product and a list of customization options, Research Question 1 aims to quantify the affect of customization options on product architecture during the early stages of redesign. At this point in the redesign stage, the existing product has a detailed product architecture, but the customization options exist in conceptual form and have basic, but not detailed, product architectures. Though detailed product architectures do not exist, engineers qualitatively understand the affect of each customization option on the existing product's architecture in terms of the direct components affected and the general amount of change required to accommodate an option. The goal of RQ 1 is to identify and modify an existing engineering change tool to quantitatively analyze changes induced by customization options.

The answer to RQ 1 allows a firm to quantitatively evaluate the affect of customization options on the existing product's architecture during the early stages of redesign. However, before deciding which customization options to pursue, a firm must also consider the market ramifications of offering customizable products. In particular, the firm wants to consider the tradeoffs between the marketing and engineering domains prior to determining which customization options to pursue. This scenario leads to the next research question:

RQ 2: How can existing marketing and engineering tools be used to guide design decisions regarding customization option development during the early stages of redesign?

Given an existing product and list of customization options, Research Question 2 aims to explore the relationship between the marketing and engineering domains during product redesign for mass customization. During the redesign stage, the challenge is to select appropriate customization options that are favorable for both domains. By answering RQ 1, customization options can be quantitatively evaluated with respect to the engineering domain. Concerning the marketing domain, customization options affect how the existing product is viewed by consumers. The concern here is twofold: (1) a customization option could be undesirable to the customer, and (2) a customization option could cannibalize the sales of other products. Therefore, a marketing tool that can (1) determine a customization option's desirability from the customer's point-of-view and (2) represent the amount of cannibalization caused by a customization option should be used. The goal of RQ 2 is to develop a quantitative approach, using existing marketing tools and the answer to RQ 1, to assist decision makers in considering the tradeoffs between the marketing and engineering domains during customization option development.

1.4: Thesis Outline

The remainder of this thesis is as follows. Chapter 2 provides evidence to support the proposed product development strategy, and Chapter 3 provides background information on past research related to mass customization. Chapter 4 presents the approach developed for this research, and Chapter 5 presents two case studies following the methodology outlined in Chapter 4. Finally, Chapter 6 draws conclusions from the results and suggests ideas for future work.

CHAPTER 2: SUPPORTING THE PROPOSED PRODUCT DEVELOPMENT STRATEGY

2.1: Overview

Before presenting the relevant background information and addressing the two research questions, the product development strategy proposed in Chapter 1 is anecdotally supported by examining the history and current state of several consumer products of varying complexity and one industrial product. The products examined, with respect to the proposed product development strategy shown in Figure 1.1 and with an American perspective, include soft drinks, shoes, grills, portable drills, computers, automobiles, and airplanes. At the end of this section, conclusions from these analyses are given.

2.2: Soft Drinks

For centuries, effervescent mineral water was believed to possess health benefits, and thus soda fountains were developed in an attempt to recreate this type of water [15]. Benjamin Silliman, a believer in the health benefits of mineral water and a chemistry professor at Yale, recognized the business potential of man-made mineral, or soda, water and began selling his bottled mineral water in New Haven, CT in 1806. Silliman hand-crafted small quantities of his mineral water with the assistance of a Nooth apparatus (a device used to carbonate water). Consequently, the craft production of soda water began.

As the demand for mineral water grew, the craft production of this product continued. However, instead of hand-crafting soda water with a Nooth apparatus, soda fountains were used to create unflavored, and eventually flavored, mineral water [15]. In New Haven, demand increased for Silliman's mineral water, so he designed a larger apparatus for creating the soda water and opened up a local shop to sell it. The opening of this shop marked the beginning of the soda fountain era. Within a few years, Silliman and other businessmen from around the country introduced soda fountains to large cities, such as New York and Baltimore, and the soda industry began to boom. Soda fountains went from simple devices designed to create and deliver mineral water to elegant machines that were designed to be functional and catch the consumer's eye. Additionally, as early as 1819, syrups were used to enhance the flavor of effervescent water. Flavors ranged from strawberry and pineapple to sassafras and ginger. Unique flavors, now recognized as name brand sodas, such as Coca-Cola in 1886, were introduced as soda fountains became more and more prevalent. With inadequate bottle manufacturing techniques in America until the early twentieth century, Americans would visit drugstores, pump rooms, and coffee houses to purchase flavored, carbonated drinks. At these establishments, an employee, referred to as a soda jerk, would operate the soda fountain spigot handles to create each customer's drink. A customer would specify the flavor for their drink, and the soda jerk would create the drink by using the soda fountain to pour the syrup flavoring into the glass followed by soda water. From hand-crafting these drinks, the syrup-soda water ratio would never be the same between two drinks; hence the products were unique. It is also easy to imagine that some customers would ask for more or less syrup based on their taste preference. Consequently, even though machines were used to help create the drink, soda jerks were following the paradigm of craft production: they hand-crafted drinks, with the help of a soda fountain, to the customer's satisfaction such that no two drinks were exactly alike.

During the soda fountain era with soda jerks as the operators, many Americans all over the country purchased soft drinks. In fact, Funderburg reports that soda fountains were popular in the early twentieth century, and $500 million was spent in 1910 on soft drinks when they cost a nickel or a dime, which was more than twice the combined annual budget of the American Army and Navy [15]. This amount of money shows that the soda industry had reached many people, and it is argued that this era in the soda industry can be characterized by both craft and mass production. From soda jerks hand-crafting the product on site, each product was unique and could be designed to meet the needs of individual consumers. Additionally, the establishments with soda fountains could reach a limited number of people due to the physical limitations of the building and hours of operation. Yet, these establishments undoubtedly served large amounts of people as bottling techniques were just beginning to gain momentum during the early twentieth century. However, as bottled products with more consistent syrup-soda water ratios gradually outperformed soda fountains, larger markets could be reached, and the soda industry completely moved from craft production to mass production.

The improvement of American bottle manufacturing techniques and the invention of self-serve soda fountains ushered in the era of mass production for the soda industry. Eventually, the sales of bottled sodas outdid the sales of soft drinks at soda fountains with soda jerks [15]. In 1900, the annual consumption of soda was 12 bottles per capita, and by 1974 this number had risen to 485. Consequently, bottling allowed soda manufacturers to (1) reach more customers than could be reached with traditional soda fountains and (2) likely sell more consistent products by having the syrup and soda water mixed in a factory.

In addition to bottled soft drinks, self-serve machines, introduced in the 1950s, began removing the need for soda jerks [15]. These soda fountains were first introduced at Save-On Drugstores, and eventually used at Walgreens, who made them popular. They allowed customers to obtain their favorite fizzy drink with the click of a lever or button. Also, by automating the syrup-soda water mixing process, more consistent syrup-soda water ratios could be achieved than in the days of the soda jerk, thus making the product more standardized. As can be seen, by utilizing bottles and self-serve soda fountains, soda manufacturers adopted the paradigm of mass production for soda manufacturing.

With consumers looking for a larger variety of flavors, soda manufacturers began pursing mass customization to better meet individual consumer needs with product platforms. To illustrate this case, historical and current Coca-Cola products are used as supporting evidence. From 1886 to the 1950s, Coca-Cola only sold its name brand product in stores and bottles [16]. Then, in the 1950s and 1960s, Coca-Cola introduced Fanta, Sprite, and Fresca to target additional market segments. These product offerings can be classified under the Mass Customization: Product Platforms block in Figure 1.1 with the platform being soda water. Coca-Cola continued this match-to-order approach throughout the 1980s and early 2000s with Diet Coke (1982), New Coca-Cola (1985), Cherry Coca-Cola (1985), Vanilla Coca-Cola (2002), and Coke Zero (2005) among others [16]–[18]. However, with some of these products, such as Coke Zero which proclaims "real Coca-Cola taste and zero calories", the platform can be extended to part of the syrup chemistry. From these examples of Coca-

Cola products, soda manufacturers have used a match-to-order approach in the pursuit of mass customization.

Though Coca-Cola and other soda manufactures adopted a match-to-order approach to meet the heterogeneous needs of consumers, Coca-Cola continued to move towards Davis' definition of MC by adopting an assemble-to-order approach with the introduction of its Freestyle machine in 2010 [16]. This machine allows consumers to select from over 100 different flavors from a touch screen menu, and mixing flavors results in an endless number of drink combinations. In a way, the Freestyle machine is similar to the era of the soda jerk-operated soda fountains. With the machine or soda jerk, the customer can customize their soft drink to meet their taste preference. Though the Freestyle allows consumers who visit establishments with the machine to customize their drink, the Freestyle arguably cannot reach the number of customers that can be reached with a bottled product. Products, such as Sodastream, allow consumers to customize their own flavored, bottled soda [19]. Perhaps, in the future, technology will allow name brand, bottled soda to be customized in a similar fashion to that of the Freestyle.

The below graphic summarizes the evolution of soft drink manufacturing from craft production towards mass customization by using Coca-Cola as an example.

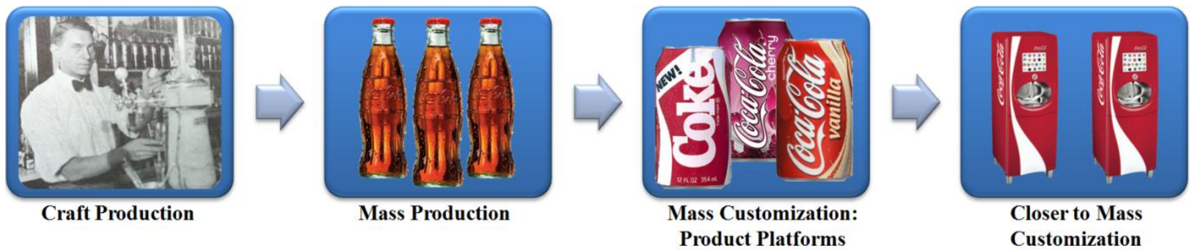


FIGURE 2.1: SOFT DRINK PRODUCT DEVELOPMENT SUMMARY

From Figure 2.1, soft drinks were first created using the paradigm of craft production with a soda jerk using a machine to mix the syrup-flavoring and soda water. Then, as bottle manufacturing techniques improved in America and self-serve machines became prevalent, soft drinks were mass-produced. Over time, people desired a larger variety of flavors, and the soda manufacturing companies responded by using a soda water platform with different syrups to create new flavors. With these platforms, soft drink companies began pursuing mass customization. Today, Coca-Cola is trying to get closer to Davis' definition of MC with their Freestyle machine, which gives customers more freedom in their soft drink selection by offering several customization options.

2.3: Shoes

The origin of the first shoe has been lost to history, but it is known that the Egyptians wore leather or papyrus-based sandals at least as early as approximately 4,000 B.C [19]. The Babylonians and Assyrians improved upon the sandal design, and their soldiers wore boots with leggings. Similarly, the Roman soldiers wore boots, while upper class citizens wore finer leather shoes with colors specifying social class. Moving East, the Indians and Persians wore pointed shoes, while the Chinese wore sandals in the warm climate areas and boots constructed of felt or fur-lined leather in the cold areas as early as the Tang dynasty. Upon Rome leaving the British Isles, communities were formed around a king, and shoes were constructed by skilled cordwainers, or shoemakers, "on traditional lines in the most serviceable fashion then known to them" [19]. Only a few upper class citizens had shoes fashioned for them in an extravagant manner, with more extravagant shoes gaining popularity in the fifteenth century. Near the end of the thirteenth century, guilds of cordwainers began forming and producing shoes for such communities. Regardless of the varying shoe styles between geographical regions and economic social classes, shoes were initially created with the traditional view of craft production: skilled artisans created shoes from raw materials using simple tools.

The practice of hand-crafting shoes continued all the way up until the mid 1800's, when machines were used to help produce shoes in larger quantities, which lowered their prices [19]. A machine, produced around the 1820's, allowed shoes and boots to be created in large quantities, but with inconsistent quality, such that individual shoes were still unique. The sewing machine, adopted by the shoe industry in the 1850's; however, allowed for more product consistency and faster production. Prior to the sewing machine, machines could create shoe parts, but human hands were still used to attach the upper part of the shoe to the sole, a process called lasting [20]. This process resulted in a small production volume with very skilled workers able to produce only 50 or less pairs of shoes in 10 hours [20]. The invention and modification of several shoe-specific sewing machines allowed these production volumes to dramatically increase; up to 700 pairs of shoes in the same amount of time [21]. Some notable sewing machines were created by Lyman R. Blake in 1858 [22], Charles Goodyear with his Goodyear Welt in 1871 [21], and Jan E. Matzeliger in 1883 whose machine became "the foundation of the modern consolidated lasting machine" [21]. With the invention of these manufacturing machines and the subsequent elimination of skilled cordwainers, the era of mass-produced shoes began.

Until recently, the paradigm of mass production was followed to produce shoes. Today, some shoe companies, such as Reebok, are shifting from mass production towards mass customization. These companies are pursuing mass customization by offering a variety of shoes based around a common platform. Consider the Reebok ZigLite running shoes product line, which consists of four shoes: ZigLite Electrify, ZigLite Run, ZigLite Distance, and ZigLite Rush [23]. From the figure below, it is clear that one major element of the platform for this product family is the zigzagged sole (or ZigTech).

FIGURE 2.2: REEBOK ZIGLITE PRODUCT FAMILY

Though the shoes in Figure 2.2 appear to be the same shoe with different color schemes, each shoe utilizes different technologies that distinguish it from the other shoes in the product family. The ZigLite Electrify use Smooth Fit technology to minimize irritation and improve comfort, while the ZigLite Run has a heel plate for stability support [23]. The ZigLite Distance incorporates a low-cut design for improved flexibility, while the ZigLite Rush uses 3DFuseFrame technology to lock the foot firmly into the shoe. With the ZigTech platform and the different technologies used in each shoe, Reebok has adopted a match-to-order approach in the pursuit of mass customization.

In addition to a match-to-order approach to MC, companies, such as Nike and Adidas, have pushed even closer to Davis' definition of mass customization by offering platform-based shoes with customization options via an assemble-to-order approach. Nike's NikeiD shoes, introduced in 1999 [24], and Adidas' miadidas shoes, introduced in 2002 [25], are examples of such customizable shoes. Nike allows customers to select their shoe color, material, cushioning, size, lace color, and embroidery either through an interactive website or in-store at one of their two NikeiD studios [24], [26]. Though Adidas follows a similar online customization strategy, it offers customers more customization options by dividing the shoe up into more customizable segments than Nike and by allowing customers to select different shoe sizes per foot [27]. With regard to price, both companies markup the customizable shoes from the base models, as Piller et al. reported [13].

To give a more concrete view of mass customization within these companies, consider the Nike LunarGlide+ 4 and the Adidas Supernova Glide 5 product families as examples. The Nike LunarGlide+ 4 consists of three shoes: the base model, the iD model, and the Shield iD model [26]. These three shoes are almost identical to each other with very minimal differences. The base model and iD model are identical except that the iD model allows the consumer to customize the shoe.

Specifically, a consumer can choose the shoe's color for 7 different regions on the shoe, its cushioning from a set of 2 options, its embroidery on the shoe's tongue, and, of course, its size. However, the iD model price is $145 while the base model price is $110; a markup of approximately 30%. The iD Shield model allows the same customization, is priced the same as the iD model, and adds a waterproofing feature to enable runners to train in wet weather [26], [28].

As for the Adidas Supernova Glide 5, there are two shoes in this product family: the base model and the mi model [27]. Similar to the Nike LunarGlide+ 4 base and iD models, the base model and mi model of the Supernova Glide 5 are identical except that the mi model can be customized. In contrast to the Nike shoe, consumers can choose the shoe's overall material, color for 11 different regions on the shoe, tread pattern and color, cushioning from a set of 3 options, and size for each foot. With respect to price, the base model can range from $115 to $120 depending on color, while the mi model price is $145; a markup of approximately 25%. From these two examples, it is clear that both Nike and Adidas offer platform-based shoes with some customization options that can be made at the point-of-purchase.

The figure presented below visually shows the development of shoes from the days of craft production to today, when mass customization is being pursued.

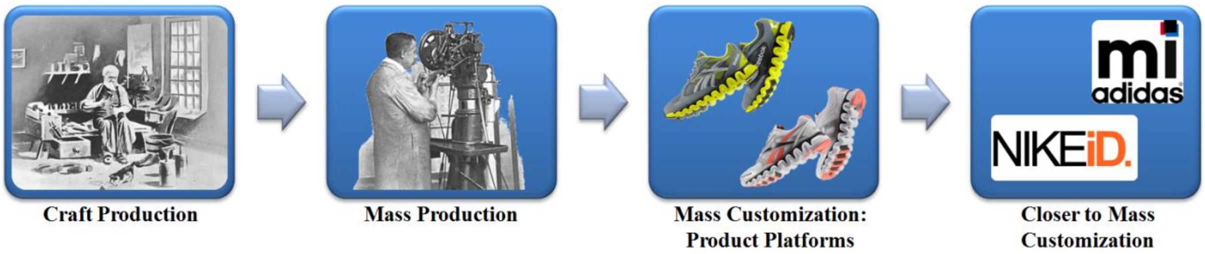


FIGURE 2.3: SHOE PRODUCT DEVELOPMENT SUMMARY

As shown in Figure 2.3, shoes were first manufactured by skilled shoemakers, or cordwainers, before being mass produced with machines. Then, as consumers desired more product variety, product platforms were used to meet those desires. Additionally, with companies like Nike and Adidas, consumers are now presented with customization options that enable them to modify their shoes to better meet their individual preferences. In the future, new customization options that move beyond the emotional realm (based on Ferguson et al.'s definition [10]) and into the functional or anthropological realm may be realized as technologies, such as the iStep, which scans the foot, become more prevalent [29].

2.4: Grills

In this work, a grill is defined as a device that allows people to cook food over an open flame. Prior to personal grills becoming available at local home improvement stores, people had to create fire from natural resources if they wanted to cook over an open flame. During this time, the paradigm of craft production was followed as fire was created by hand. Enough wood, or another fuel source, was gathered to cook the food for a given occasion, and something was built to raise the food above the open flame. A rack could be used to raise the food above a ground-level fire, while a trench could be used to create a below-ground fire [30]. Depending on the type and amount of food cooked, the size of the cooking fire would vary, thus each fire was unique. In terms of craft production, the cooking fire is the product, and each product is unique and manufactured in small volumes.

The act of hand-crafting cooking fires continued until people desired to cook food over an open flame without gathering wood and building racks or trenches. In America, the paradigm of craft production shifted to mass production as outdoor cooking equipment became available in the 1930s [30]. The first grills, called brazier grills, were small metal containers that held wood or charcoal with a cooking grate for raising the food above the open flames. A variety of these portable grills were mass produced by the 1940s, and some models had "accessories such as adjustable grill levels and spits for turning meat" [30]. These grills were sold in a variety of stores, such as hardware and heating supply stores, and they were even sold at car dealerships. In the 1940s, it was common to buy a portable grill and a bag of charcoal from a Ford dealership. Regardless of purchase location, these portable grills were a simple way to entertain people and deal with World War II prices and rationing.

Though the brazier grills were popular in the early twentieth century, these grills were poorly engineered, and users had trouble controlling the flames [30]. George Stephen was one frustrated cooker who, in 1952, decided to create a kettle grill from a buoy that enabled better flame control. With Stephen's invention, the Weber company was established, and they mass produced charcoal, and eventually gas, grills for the next several decades [31]. Though Weber eventually manufactured gas grills, they were not the first to sell them. Gas grills, which were introduced in the 1960s, were originally sold by local natural gas companies as a way to sell more natural gas [30]. Consumers would purchase these mass-produced grills, and the natural gas company would permanently install the grill in the customer's backyard. After some time, natural gas companies and other companies, such as Weber, began offering mass-produced, mobile gas grills. For decades, mass-produced charcoal and gas grills dominated the marketplace.

However, in recent years, companies have shifted away from mass production and towards mass customization by offering more product variety through product platforms. Weber products demonstrate this transition. After the introduction of the Original Kettle in 1952, Weber likely mass-produced several other unique charcoal grills over the next decades, such as the Westerner (1958), the Ranger (1965), and the Barrel Bar-B-Q (1972) [31]. Then, in 2000, Weber introduced the One-Touch product family of charcoal grills. Today, this product family consists of 4 kettles: Silver 18.5", Silver 22.5", Gold 22.5", and Gold 26.75".

The platform of these kettles is the classic buoy shape employed in the 1952 model and the tripod legs. The distinguishing features between grills in the One-Touch product family include cooking area and secondary features. The cooking area and the number of secondary features increase from the Silver 18.5" kettle to the Gold 26.75" kettle [32]. For example, the Silver 18.5" model does not have an enclosed ash catcher or a temperature gauge, while the Gold 26.75" model has these features as well as a lid holder and tool hook handles. From this brief analysis of the One-Touch product family, Weber has adopted a match-to-order approach in the pursuit of mass customization. Weber, among other grill manufacturers, has developed product families to meet the heterogeneous needs of their customers.

As shown in Figure 2.4 below, the production of grills has transitioned from craft production towards mass customization.

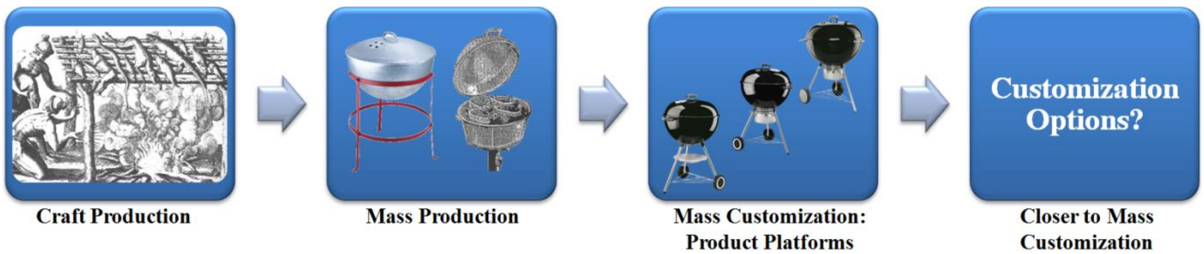


FIGURE 2.4: GRILL PRODUCT DEVELOPMENT SUMMARY

Prior to the metal grills of today, people had to build racks or dig trenches by hand to cook food over an open flame. As people desired to cook food outdoors without hand-crafting a fire, metal grills, such as the pictured 1952 Weber kettle and a permanent backyard gas grill, were mass-produced for the outdoor cooking chef. Then, grill manufacturers shifted to a match-to-order approach in the pursuit of mass customization. By designing grills with a common platform, such as the Weber One-Touch charcoal kettles, grill manufacturers could offer a variety of grills to meet heterogeneous customer needs. As these companies further pursue mass customization, customization options via an assemble-to-order approach may allow grills to be further modified to fit individual wants and needs.

2.5: Portable Drills

Prior to today's portable electric drills, people hand-crafted devices to create holes in wood and other materials by removing material. Historians have suggested that ancient civilizations hand-sharpened pieces of flint, a type of rock, into a point and then hand-turned the pointed flint to produce holes [33]. A similar technique involved placing sand between the material to be drilled and a pointed shaft (typically made of wood or metal), which was rotated back and forth with one's palms. This method of drilling holes was improved when a thong, or strap, was used to rotate the shaft instead of one's palms. During the Upper Paleolithic Period, the technique was further advanced by attaching the thong to a bow, which enabled easier drilling into stone. After the metal or wooden shaft and bow was created, the worker would steady the shaft while moving the bow back and forth to induce bidirectional, rotational motion on the shaft.

The Romans crafted a similar tool, called the pump drill, which rotated the shaft clockwise and counterclockwise with a pushing motion. A cross member was attached to the shaft with cords, and this member was pushed down to induce shaft rotation. When this member was raised up, the cords twisted around the shaft such that the next downward push rotated the shaft in the opposite direction. Both of these hand-crafted drills were appropriate for drilling small holes, yet they used bidirectional rotation to create such holes. Another device, called a brace, was introduced as early as 1425 and allowed small holes to be created from continuous, unidirectional rotation [33], [34]. This device consisted of a U-shaped frame, typically hand-crafted of wood and sometimes reinforced with metal, with a drill point, which in some models could be interchanged [34]. The drill point was a pointed piece of metal with two cutting edges that eventually resembled the shape of an arrowhead [33]. To operate a brace, a worker would rotate the U-shaped frame in a clockwise or counterclockwise direction with a hand on top of the frame to provide stability and pressure. Though braces were used, bow and pump drills were the dominant tools for creating small holes until 1805.

During this year, the brace was improved upon with the invention of the hand-operated, geared drill [33], and soon the era of craft-produced drills would be replaced with the era of mass-produced drills. This drill used a crank to produce continuous, unidirectional rotation of the drill point, and the gearing allowed the drill point to rotate faster than the crank, thus providing mechanical advantage. At first, the drill points were similar to those used in braces. Then, in 1822, drill points with spiral flutes were implemented to more efficiently remove chips from the cutting area. Originally, these drill points were craft-produced because the flutes had to be hand filed. In the 1860s, machines were invented to file the flutes. With these machines and the implementation of the American System of Manufactures, which advocated the use of interchangeable parts, the geared hand drill, and even the brace, became mass-produced. Catalogues of both geared hand drills and braces provide evidence of the transition from craft production to mass production [34]. Though these devices were mass-produced and popular drilling tools before World War II, the invention of the electric drill ended their popularity [33], [34].

In 1895, the world's first electric hand drill was invented by Emil Fein, and with this invention, the portable drill industry was forever changed [35]. Though Fein invented the first electric portable drill, the design did not withstand the test of time. Instead, Black &

Decker's patented electric hand drill with its pistol-grip design became the dominant design [36]. Consequently, for the remainder of this discussion, Black & Decker products are used as examples for the portable, electric drill industry.

Soon after patenting their craft-produced drill in 1916, Black & Decker mass-produced their tool for the public. Evidence of Black & Decker following this manufacturing paradigm includes the introduction of mass production during the early twentieth century [4], the opening of a large-scale manufacturing plant in 1917 [36], and the mass market advertising campaign in 1921. In 1946, the company introduced the first portable electric drill designed for the at-home, do-it-yourself consumer. By 1951, one million of these drills had been produced, thus providing strong evidence that, by this year, the company was mass-producing hand-held electric drills. For the next several decades, Black & Decker continued to mass produce several models of portable electric drills.

During the 1970s, a shift within the company occurred to transition them away from mass production and towards mass customization. As reported by Meyer and Lehnerd, Black & Decker had individually designed several motors across its power tool offerings (drills, circular saws, sanders, etc.), and in the 1970s, they were in the midst of motor redesign to satisfy new safety regulations [2]. Instead of redesigning the motor for each power tool offering, Black & Decker engineers used the ideas of modularization and standardization to create a product platform, the universal motor, to be used across product offerings. By creating this platform, Black & Decker was able to meet the new safety regulations and offer a variety of products at better costs than a mass production scheme. Meyer and Lehnerd reported that the company saved $1.28 million annually from the development of the universal motor.

With respect to portable hand drills, Black & Decker continues to employ a platform-based product design approach. Consider the MAX Lithium Cordless Drill/Driver product line, shown below [37]:

12V Model	16V Model	20V Model

FIGURE 2.5: BLACK & DECKER MAX CORDLESS DRILL PRODUCT FAMILY

From Figure 2.5, Black & Decker employs a common platform for this product family that results in similar-looking drills [37]. These drills are clearly differentiated based on voltage with the 12V, 16V, and 20V models shown above. Though Black & Decker uses product platforms in the pursuit of mass customization, the company has not stopped with a match-to-order approach to meet the heterogeneous needs and preferences of customers.

In 2009, Black & Decker began offering drills with SmartSelect technology, and recently they have introduced the Matrix Quick Connect System [36], [37]. SmartSelect technology allows the consumer to customize their drill's performance post-purchase and during product use [38]. By using the SmartSelect Clutch, users can determine their drill's task, such as drilling a hole or driving a screw. The drill will then automatically adjust its speed and power for optimal performance. With this technology, Black & Decker has embedded customization into the product's architecture. Similarly, the Matrix Quick Connect System embeds customization by using modularity [39]. The Matrix uses the familiar pistol-grip design as a platform and modular attachments, such as a drill head, an impact driver, and a sander. This product architecture allows customers to modify their tools design based on the task they need to perform. Overall, Black & Decker has allowed deeper customization than could be achieved with a match-to-order approach with its pseudo assemble-to-order approaches captured in SmartSelect technology and the Matrix Quick Connect System.

Portable hand drills have developed over time from being simple, craft-produced products to complex, mass-produced, and recently mass-customized, goods. The figure below highlights this evolution:

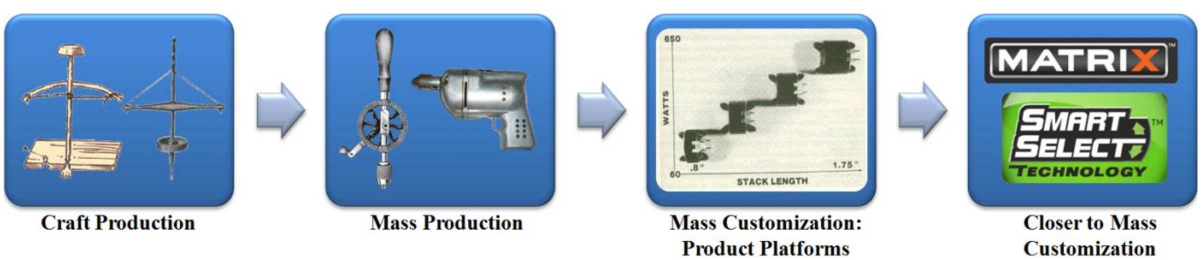


FIGURE 2.6: PORTABLE DRILL PRODUCT DEVELOPMENT SUMMARY

As shown in Figure 2.6, portable drills began as hand-crafted bow drills, pump drills, and braces made of wood and metal. Craft production continued with geared hand drills due to the hand filing of flutes, but soon transitioned to mass production with the advancement of production machinery and the implementation of interchangeable parts. The paradigm of mass production continued over the next several decades, and companies, like Black & Decker, benefited from it. However, mass customization through product platforms offered cost savings that mass production could not offer, and thus it was pursued. During this pursuit, Black & Decker has employed a match-to-order approach by offering product families of portable electric drills. In the continued pursuit of mass customization, Black & Decker has utilized a pseudo assemble-to-order approach with their SmartSelect technology and Matrix Quick Connect System.

2.6: Computers

Before the modern computer was capable of performing numerous tasks, computers were simple, mechanical devices that helped mankind perform mathematical calculations [40]. With this mindset about computers, the first computers were the abacus (3000 BC) and the slide rule (1620s); both of which were undoubtedly craft-produced. Following these devices, the Pascaline (1645) was hand-crafted by Blaise Pascal to perform addition and subtraction, and the Stepped Reckoner (1674) was invented, but never built in his lifetime, by Gottfried Wilhelm von Leibnitz to execute addition, subtraction, multiplication, and division. In the 1800s, Charles Babbage, known as the Father of Computers, invented and partially built two mechanical computers: the Difference and Analytical Engines. His Difference

Engine could solve a quadratic equation, and his Analytical Engine could perform numerous tasks and execute a program with punch cards [41]. These machines were the last notable purely mechanical computers, and in the late 19th century, computers transitioned from purely mechanical devices to electro-mechanical devices. In 1884, Herman Hollerith developed and constructed the Census Tabulating Machine to decrease the amount of time it took to analyze US census data [40]. Census data, in the form of punch cards, was fed into the machine, and the machine used electricity to analyze the data. Specifically, wires that passed through punch card holes created an electrical circuit, thus updating the appropriate counter(s). Hollerith's machine was such a success that he created his own company to sell it, and this company eventually became IBM.

IBM's first contribution to the computer world, with the assistance of Harvard University, was the Harvard Mark I, which was a room-sized, electro-mechanical computer hand-crafted for the US Navy. Just prior to the Harvard Mark I being completed in 1944, the world's first electronic computer, the Atanasoff-Berry Computer (ABC), was developed and hand-crafted by Dr. John Atanasoff and his graduate student, Clifford Berry. The development of the ABC marked the end of the electro-mechanical era of computers and the beginning of the electronic computer era. Following the ABC in 1946, John Eckert and John Mauchly developed the room-sized Electronic Numerical Integrator and Computer (ENIAC), which was programmed through rewiring. The computer was designed to conduct ballistic calculations for the US Army during World War II, but was completed after the war was over and was used to conduct calculations for the hydrogen bomb instead [42]. The ENIAC marked the beginning of the decline in craft-produced computers. All the computers before the ENIAC, and including it, were crafted by hand, produced in small quantities (typically one unit), and built for one client (usually the US government). After the ENIAC, the era of mass-produced computers began to be realized.

In 1951, Eckert and Mauchly built the first commercially-targeted computer, the Universal Automatic Computer (UNIVAC), which no longer used punch card programs, but instead stored programs [42], [43]. It was designed to replace accounting machines that used punch cards, and became a success in the business place. After the UNIVAC, many other computers were developed, and each new computer moved the industry closer and closer to mass production. Two years after the UNIVAC, IBM introduced the 701 EDPM and in the late 1950s, the ERMA/GE 100 became the first computer designed to process bank checks [43]. Development continued for the next two decades and by the mid 1970s, the computer industry had reached the general public.

In 1974, the Altair microcomputer was introduced to the market and allowed the consumer to build their own computer [42], [43]. This computer did not have any peripheral elements and programming was done in assembly language, but computer enthusiasts jumped at the opportunity to purchase one [42]. During this same time, computers, such as the IBM 5100 and Apple I and II and the Commodore PET, attracted more of the general public to the computer industry [43]. However, in the early 1980s, the computer industry gained substantial support from the masses with the IBM Personal Computer (PC) in 1981 and the 1984 Apple Macintosh, modeled after the Apple Lisa, which was the first computer with a graphical user interface (GUI). By this time, computer companies, such as IBM and Apple, were undoubtedly mass-producing computers for the general public. To provide further evidence, the IBM PC sold over 500,000 units within the first two years of being introduced [42]. Computers continued to be mass-produced until Michael Dell stepped onto the scene and began pursuing mass customization.

At first, Dell started out as a craft-producer of custom computers; he would upgrade existing IBM PCs and sell them for a profit during his years at the University of Texas at Austin [44]. Upon registering Dell Computer Corporation as PC's Limited in 1984, Dell began selling custom computers directly to users via phone orders. Customers would place a phone order for an upgraded PC, and then the PC would be upgraded-to-order. Around 1986, Dell began manufacturing custom PCs instead of just upgrading existing ones. By manufacturing their own PCs, Dell was able to better meet the preferences of their customers, who would place a phone order and then Dell would assemble the computer to order. This strategic business move by Dell allowed them to become the first computer manufacturer "to sell custom-built computer directly to end-users, bypassing the dominant system of using computer resellers to sell mass-produced computers" [44]. From their beginning in the early 1980s, Dell's pursuit of mass customization in the personal computer industry enabled them to grow from a dormitory room to a 30,000 square foot building in a few years.

By the early 1990s, Dell had outgrown its resources, including its phone line ordering system [44]. To help ease this strain and pursue another area of competitive advantage, Dell launched its website in June 1994. At first, their website just provided support information to knowledgeable customers, and then an online configuration tool was added that allowed customers to customize their PC and obtain the price of their configuration. However, the sale of the final computer configuration was still done over phone. This process changed in

June 1996 when Dell began selling customized notebooks and desktops on their website. By December of the same year, sales had risen to $1 million per day. To further support mass customization, Dell launched Premier Pages for its corporate customers. These customers could log-on to their webpage, configure computers, purchase these computers, track the assemble-to-order progress, and obtain support documentation. By 1998, the Premier Pages and the Dell website had enabled Dell to achieve $12 million per day in sales. Through consistently gathering consumer feedback, Dell was and is still able to design and manufacture computers that are desirable for their target customers [44].

Today, the company utilizes a unique assemble-to-order approach to sell customized computers directly to end-users via its website [45]. Dell uses platforms to design their product families, differentiates individual computers within a product family based on performance, and allows consumers to customize their product from a set of customization options [45]. These customization options are optional; the consumer can purchase a platform-based computer without any modifications via a match-to-order approach. However, the ability to slightly modify a computer's design separates Dell from other companies that solely pursue a match-to-order approach. Dell's assemble-to-order approach moves the company closer to Davis' definition of mass customization. Perhaps in the future, Dell will allow more customization options, such as the type of cooling system, to further accommodate customer preferences. Other companies, such as Puget Systems, already offer such customization options [46], and the future may offer even more opportunities for consumers to obtain their ideal computer.

Based on the above discussion, computers have evolved from simple machines being hand-crafted to complex devices that end-users can slightly customize to meet their individual needs and preferences. The below diagram highlights this evolution:

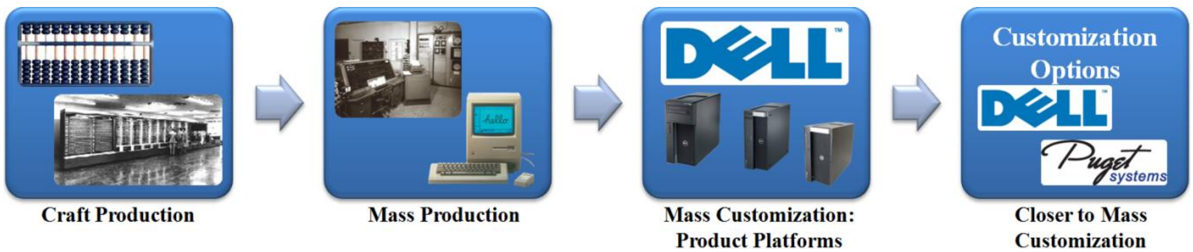


FIGURE 2.7: COMPUTER PRODUCT DEVELOPMENT SUMMARY

As shown in Figure 2.7, the computer started out as a simple hand-crafted device; the abacus is an example of such a computer. As technology increased, computers become complex, electro-mechanical machines that were craft-produced for a small number of consumers. The Harvard Mark I is an example. With further increases in technology and the shift to a more consumer-based product, computers, such as the IBM PC and Apple Macintosh, were mass-produced. During this time, computer parts were transformed from craft-produced pieces to standardized and modularized pieces. This standardization and modularization allowed companies, such as Dell, to begin pursuing mass customization. With Dell, match-to-order and assemble-to-order approaches were simultaneously offered. As the industry moves forward, more customization options will allow firms, such as Dell and Puget Systems, to move closer to Davis' definition of mass customization.

2.7: Automobiles

Even with their complexity, automobiles were produced first with the tenets of craft production [5]. In the 1890s, a French-based company, P&L, began manufacturing cars by hand for Paris' wealthy citizens. Parts of these vehicles were contracted to and produced by individual workshops, while assembly took place at a central location. Because the car parts were hand-crafted, the assembly process took a substantial amount of time to complete; each part had to be hand-filed to fit snugly with adjacent parts. Consequently, P&L manufactured a very small quantity of automobiles, and each automobile was unique. Nonetheless, P&L continued to hand-craft vehicles, and other companies across Western Europe followed in P&L's footsteps. By 1905, hundreds of automobile companies were hand-crafting vehicles in Western Europe and North America. However, after World War I, the automobile industry shifted from craft production to mass production. Though the majority of the industry transitioned, some companies continued following the paradigm of craft production, such as Aston Martin. To this day, skilled craftsmen at Aston Martin build automobiles by hand at a rate of one vehicle per day.

As mentioned in Chapter 1, the American System of Manufactures preceded mass production, and one characteristic of this product development strategy was interchangeable parts [4]. This characteristic was vital to both the American System of Manufactures and mass production, and Henry Ford realized the manufacturing advantages of implementing this characteristic. Instead of allowing parts to be produced with different gauge systems (or different standards), Ford implemented one gauge system for all parts on his Model T, thus eliminating "the skilled fitters who had always formed the bulk of every assembler's labor force" [5]. Standardized, interchangeable parts allowed larger production volumes to be reached than could have been achieved with craft production. In accordance with the other mass production characteristics outlined in Chapter 1, Ford hired unskilled workers to perform one task or operate specialized machinery. In 1915, there were workers that spoke over fifty different languages on the factory floor, but production remained streamlined due to this division of labor. Additionally, machines became so specialized that a worker would simply load the part into the device, and the machine would do the rest. Such a device for machining engine blocks was implemented in 1915. To further increase production volume and decrease production cost, Ford introduced the moving assembly line in 1913 so that the work moved to the workers, and he achieved complete vertical integration by 1915. With these manufacturing improvements, Ford was able to produce 2.1 million Model T automobiles in 1923. As a result of his success, other automobile manufacturers began adopting similar practices. One of these companies was GM, which developed the hierarchical management scheme under Alfred Sloan, and thus completed the picture of mass production known today. Mass production dominated the automobile industry in America and Europe for over fifty years since the introduction of the Model T, and it expanded into other industries (as has been shown in this chapter). By 1955, mass production was at its height in the American automobile industry. In this year, over 7 million vehicles were sold, and the "three giant enterprises - Ford, GM, and Chrysler - accounted for 95 percent of all sales, and six models accounted for 80 percent of all cars sold" [5]. However, this same year marked the beginning of the decline of American automobile manufacturers as customer preferences began to change and foreign manufacturers, like Toyota, began implementing lean production and eventually pursuing mass customization.

After World War II, the Toyota Motor Company began manufacturing cars for the Japanese population by adopting and modifying Henry Ford's mass production system [4], [5]. Henry Ford's version of mass production would not be appropriate for Toyota because the Japanese workers demanded better jobs than those needed for mass production, and the Japanese population required a wide variety of vehicles [5]. Therefore, the Toyota Motor Company created the system of lean production, which used a flexible production system and skilled workers to create a variety of products with the goal of minimizing production costs. By adapting this production system, Toyota, and soon other manufacturers, would be better equipped to pursue mass customization. As markets became increasingly global, Toyota's lean production techniques allowed the company to create cars that met the changing needs of Americans. During the 1960s and 1970s, American vehicle preferences were changing; they no longer wanted cars that utilized old technology and "isolated them from their driving environment" [5]. Innovations from foreign manufacturers, such as disc brakes and fuel injection, and foreign sports cars, instead of the typical American-made luxury car, interested American consumers. Additionally, as fuel prices rose in the early 1970s, Americans began desiring smaller cars [4]. Though vehicle preferences were changing, the American car manufacturers did not respond by redesigning their vehicle offerings. Instead, they tried to continue selling their mass-produced luxury cars. Consequently, American manufacturers began losing market share to foreign competitors, such as the Toyota Motor Company.

Toyota and other foreign manufacturers, such as Honda, were able to meet the changing, heterogeneous needs of Americans by not only implementing lean production, but also designing their vehicles around a product platform [2], [5]. The platform concept was not new to American manufacturers; Henry Ford made the Model T underbody (chassis, engine, transmission, wheels, gas tank, etc.) a platform [5], [47]. With this platform, Ford was able to meet different consumer needs in the form of nine different body styles, and specialized manufacturers were able to purchase this platform to offer even more customized solutions. After Ford, the increased complexity of vehicles has prevented the complete implementation of similar platforms, with GM's Skateboard concept coming close to Ford's underbody platform [47]. Nonetheless, domestic and foreign car manufacturers have continued the platform concept to offer more product variety. For example, Honda used platforms on its Accord and Civic lines to offer three to four product variants, and Ford created a platform for its Taurus product line in the 1980s [2]. From the use of product platforms, the number of distinct cars available in the American market increased from 151 in 1982 to 205 in 1990 [4]. Though both American and foreign companies have adopted this match-to-order approach to mass customization, the American manufacturers have not been as successful. Either the manufacturers used platforms to create products that were too similar, as GM did in the 1970s [4], or they used too many platforms, as Ford realized in the mid-1990s [2]. Furthermore, the American car companies did not allow customers to differentiate their vehicle's design through appropriate customization options.

To compliment product platforms, vehicle manufacturers have offered customization options via an assemble-to-order approach to further satisfy the heterogeneous needs of customers [4]. Pine mentions that, during the late 1980s and early 1990s, vehicles had "an ever-increasing number of options that allow[ed] drivers to tailor cars to their liking" [4]. He also mentions that American manufacturers allowed consumers to modify their vehicle's design through "peripheral" customization options, or options that do not add much personality. In contrast, Japanese manufacturers allowed customers to modify their vehicle's design on a more personal level by offering a variety of body styling options. Based on the past sales of American and Japanese vehicles, it is argued that customization options should be offered in areas that are most important to the customer.

With regard to the future, further developments in technology and the Internet may provide more opportunities for the mass customization of automobiles. Since the Internet became popular in the 1990s, companies in several industries, including the shoe and automobile industry, have used it to advance their pursuit of mass customization. As mentioned previously, Nike and Adidas have created websites to enable consumers to customize their shoes. Ford, Toyota, Mercedes, and other automobile manufacturers have followed a similar approach to allow customers to change their vehicle's body color, body style, interior styling, engine, transmission, wheels, etc. [48]–[50]. With time, customers may be able to use an online, computer-aided design (CAD) system to further customize their vehicle. In his book, Pine reported that Nissan and Toyota were aiming to allow customers to use a CAD system, likely at a dealership, for customization [4]. Such a CAD system may become available online, and it may allow customers of the future to customize their vehicle more than current customization options allow.

Automobiles have progressed from craft production in the 1890s to mass production in the twentieth century and recently towards mass customization. This progression is shown in the below diagram:

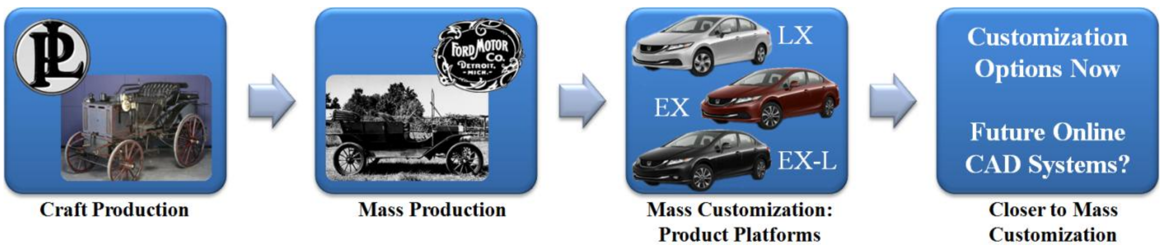


FIGURE 2.8: AUTOMOBILE PRODUCT DEVELOPMENT SUMMARY

From Figure 2.8, automobiles began being hand-crafted by skilled craftsmen in small shops. These cars, such as the Evelyn Ellis P&L car pictured above, were unique and took substantial amounts of time to file down and assemble each part. With Henry Ford, the need for skilled assemblers was eliminated as a standard gauge system across all parts was implemented. From this change along with other production improvements, such as the division of labor and specialized machinery, Ford ushered in the era of mass production and successfully demonstrated it with his Model T automobile. The new production system was such a success that it became a staple of the industry and even spread to other industries. However, after World War II, the market began to change as foreign competitors from Asia entered and American vehicle preferences changed. To accommodate the heterogeneous needs of American consumers, foreign and domestic automobile manufacturers adopted product platforms to offer product variety with the foreign manufacturers initially being more successful than their American counterparts. Three models of the Honda Civic 4-door sedan are created by using platforms: the LX, EX, and EX-L models, shown above. In their pursuit of mass customization, these companies not only followed a match-to-order approach, but also an assemble-to-order approach through offering customization options, such as interior packages, to further increase vehicle customization. In the future, new technologies and the Internet may allow consumers to use online, computer-aided design systems to personalize their vehicle at the point-of-purchase.

2.8: Airplanes

Before exploring the evolution of airplane manufacturing from the days of craft production to the modern day pursuit of mass customization, a note about mass markets for these complex products is discussed. Unlike the other six products evaluated above, airplanes are typically not designed for purchase by members of the general public. Instead, they are designed for airlines or militaries across the globe. Consequently, the production volume of airplanes is typically much smaller than that of the other six products designed for the general public. Nonetheless, an argument can be made that the airplane industry has evolved in a unique fashion from craft production towards mass customization with periods of mass production. The analysis presented below uses examples, mainly from Boeing and Douglas, to show that (1) small volumes of airplanes were craft-produced during the industry's infancy, (2) very high volumes of airplanes were mass-produced in factories during wartime, and (3) large volumes of airplanes (greater than the amount manufactured during the craft production era) were mass-customized as the industry grew and airplanes became a major method of transportation.

Similar to automobiles, airplanes were first manufactured with the paradigm of craft production. Prior to the development of powered, manned flight, the first manned airplanes were gliders made of raw materials, such as wood and cloth [51]. In 1853, George Cayley was the first man to design, build, and fly a manned glider, while Otto Lilienthal was the first to design, build, and fly a manned and controlled glider in 1891. With further advancements in aerodynamics and gasoline-powered engines, the Wright brothers were the first to manufacture and fly a manned, powered, heavier-than-air aircraft in 1903 at Kitty Hawk, NC. The Wright Flyer I, made of spruce and cloth, was first hand-crafted solely to advance the infant field of aerodynamics. With successful demonstrations of similar aircraft in the following years, the Wright brothers were able to sell a few aircraft to the American Navy, thus expanding the use of aircraft for practical purposes and ushering in the era of mass-produced warplanes.

Due to the small market for airplanes, these complex machines were not mass produced except during the two world wars: World War I and World War II. After the Wright brothers historic flight, airplane manufacturers all over the world began producing airplanes similar to the Wright Flyer I [52]. The aircraft produced during this time were propeller-driven, biplanes made of wood, fabric and glue. During World War I, these planes were used in dogfights, and large quantities were needed by both sides. The production volume of the SPAD XIII, a popular French warplane, is a good example of mass-produced planes at this time. By the end of 1918, 8,472 SPAD XII warplanes were mass-produced for the French pilots [53]. After World War I, advancements in technology and aerodynamics allowed propeller-driven, monoplanes to replace the biplane configuration and become the dominant design [52].

During World War II, this type of airplane was extensively used, and similar to World War I, these airplanes were mass-produced. For example, Douglas and Boeing, two major aircraft manufacturers in the United States, mass-produced warplanes for the US military. Douglas produced a total of 29,385 airplanes between 1942 and 1945 [54], and Boeing's airplane production increased from 60 per month in 1942 to 362 per month in 1944 [54]. From these production numbers in both world wars, the airplane manufacturers arguably used the tenets of mass production to build large quantities of warplanes.

Though manufacturers mass-produced airplanes during these wars, they typically built customized airplanes and are currently constructing airplanes with mass customization in mind. During peacetime, airplanes were still designed and manufactured for military purposes, but in much smaller quantities than during the world wars. For example, Boeing developed and manufactured 586 P-12/F4B pursuit fighter biplanes after World War I for the US Navy [54], and Douglas designed and produced over 420 F4D Skyray fighter jets in the 1950s for the US Navy and Marines [54]. In addition to military uses, airplanes were designed for more peaceful purposes, such as transporting mail and passengers. To transport mail, Boeing manufactured 77 Model 40 biplanes and variants between 1925 and 1932 [54].

After Charles Lindbergh's 1927 solo, nonstop flight across the Atlantic Ocean from New York to Paris, the public interest in flying dramatically increased and numerous airlines emerged [52], [54]. To meet the demand for air transportation, airlines developed airplane requirements and hired manufacturers to design and construct airplanes around these requirements [52]. This process of customizing airplanes for airlines started soon after Lindbergh's historic flight and continued well into the future. Several examples of this process are provided below:

- Boeing produced 75 Model 247 monoplanes for airlines associated with the company beginning in 1933 [54].
- Douglas designed the DC-2 for Transcontinental and Western Air in the 1930s, and the company manufactured 156 monoplanes in 20 versions for both domestic and international airlines [52].
- A request to Douglas from American Airlines to create a sleeper version of the DC-2 led to "the epitome of the mature, propeller-driven airplane", the DC-3 [52]. From its introduction in 1936 to the shutdown of production after World War II, 803 DC-2s were produced for commercial airlines.
- Boeing developed custom 707 jet airplanes to meet the unique needs of Qantas Airways and Braniff International Airways [54]

Companies, such as Boeing and Douglas, used product platforms to further meet the wants and needs of their clients, while controlling development and production costs. In the airplane industry, product platforms have been used for quite some time. Boeing's Model 40 mail transport biplane introduced in 1925 had two variants: the Model 40A introduced in 1927 and the Model 40B-4 introduced in 1928 [54]. The process of developing product families continued into the jet age and today. Boeing's 707, 727, and 737 airplanes shared the upper-lobe fuselage, and Boeing's 737 in 1991 had three models: the -300, -400, and -500 [54]. During development of its 777 jet airplane, Boeing focused even more on product platforms by "embracing both commonality in components and systems, and planning in advance a multiple product family" [2]. Consequently, the company was able to create an airplane that used more common parts and less unique parts than previous Boeing planes. In addition to using platforms for the same type of client (airlines), airplane manufacturers used platforms to produce slightly different aircraft for both airline and military clients. Similar to platforms for one client, multiple-client platforms have a rich history in airplane industry. Douglas' DC-3 propeller-driven airplane had military variants that allowed it be used as a troop transport and cargo plane [2], and out of the total 10,926 that were manufactured during its lifetime, 10,123 were produced for the US military [52]. Similarly, Douglas' DC-9 jet airplane, which "was the most successful Douglas transport since the DC-3," had three variants for the US military [54]. From this discussion, product platforms have clearly been used in the airplane industry to support a variety of customer preferences.

Recent developments with Boeing's 787 Dreamliner have advanced the pursuit of mass customization in the airplane industry closer to Davis' definition. Instead of only selecting a platform-based airplane and having Boeing directly design and integrate components to meet their interior needs, airlines can now customize their interior from a set of modular options; Boeing employs an assemble-to-order approach [55]. Options include colors and patterns, seat styles, galley designs, entertainment devices, lavatory configurations, and an assortment of appliances, such as coffee makers and ovens [56]. The variety of these interior options allows airlines to find the best components that satisfy their needs, and the modularity enables easier component replacement and interior reconfiguration. Prior to this new system, component replacement and interior reconfiguration could take a long time and even delay flights, potentially affecting revenue [55]. For example, changing a damaged seat in the past could have delayed a flight, while this new system can allow the seat to be replaced while the airplane is at the gate. Through common interfaces between components and the plane's frame, in particular the revolutionary harper fittings for the seats [57], Boeing has embedded flexibility into the 787s product architecture for customization purposes. In this way, the company is moving closer to Davis' definition of mass customization and is transforming the airplane industry into one that is similar to the automobile industry by allowing customers to "select a basic model and then add options meeting their specific tastes and budgets" [2].

Based on the above discussion, airplanes have evolved from craft-produced products to products being produced with mass customization in mind. This progression is shown in the below figure:

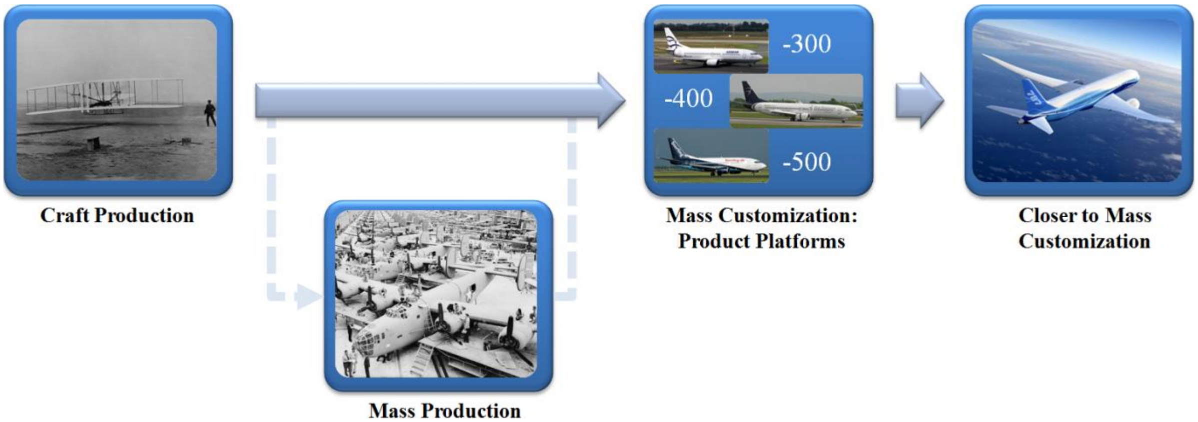


FIGURE 2.9: AIRPLANE PRODUCT DEVELOPMENT SUMMARY

Figure 2.9 shows a different trend than displayed in the other six products. Since this product is not targeted at the general population, it has only experienced periods of mass production during World War I and II. Instead, airplanes transitioned almost directly from the craft production days of the Wright Flyer I to the current pursuit of mass customization. After craft production, airplanes were customized in small quantities for airline and military clients, and these quantities became larger as the airplane industry grew, particularly with the increased popularity of air transportation. To respond to needs of the air transportation industry, airplane manufacturers developed product families, such as the Boeing 737-300, -400, and -500 jet planes. In addition to using platforms for their airline clients, manufacturers employed platforms to transform a commercial plane into a military one, as was seen with the Douglas DC-3. As the air transportation industry has continued to grow, customization techniques have developed past a match-to-order approach and towards an assemble-to-order approach, similar to the automobile industry. With Boeing's 787 Dreamliner, airline clients can quickly and efficiently customize the interior of their planes from a set of modular options. Though airplanes have progressed in a slightly different fashion than the other six products, they have undoubtedly evolved in a way that moves them closer to Davis' definition of mass customization.

2.9: Conclusions

In this chapter, six consumer products with varying levels of complexity and one industrial product were analyzed in terms of product development to support the proposed product development strategy outlined in Chapter 1. To recap, this strategy proposes that some products evolved, in terms of product development, from craft production to mass production and finally towards mass customization. During their pursuit of mass customization, firms either followed a match-to-order approach and then an assemble-to-order approach or both approaches simultaneously. In the broadest terms, the strategy proposes that some products, when appropriate, evolve with time in their company's pursuit of Davis' definition of mass customization. From the above analysis and discussion of the seven products, the proposed product development strategy outlined in Chapter 1 is adequately supported for the purpose of this thesis. A review of all seven products is given below, and additional observations are discussed.

Soft drinks were first craft-produced by a soda jerk mixing soda water and syrup to the customer's liking. Then, soft drinks were mass-produced when American bottle manufacturing techniques matured and self-serve soft drink machines replaced soda jerks. To meet the heterogeneous needs of drinkers, soft drink companies began creating different syrups and mixing them with a platform, soda water. When consumers desired healthier soft drinks, the manufacturers used the base model as the platform, such as Coke, to create a diet version, such as Diet Coke. Today, Coca-Cola has continued their pursuit of mass customization by offering in-store customization options with their Freestyle machine. Now, consumers can design their own soft drink from a wide variety of Coca-Cola flavors. Perhaps in the future, customers will be able to create their own bottled soft drink based on name brand flavors.

As early as Egyptian times, shoes were hand-crafted by skilled artisans who were to become known as cordwainers. Craft production was gradually replaced by mass production as sewing machines, such as the Goodyear Welt, were implemented to create standardized shoes. A shift to mass customization was made when platforms were used to offer product variety. Recall the Reebok ZigLite product family that had four different variants that looked similar but had different features. To give consumers even more design freedom, some modern shoes companies, such as Nike and Adidas, are offering customized shoes via the Internet. Customers use an online configuration tool to design their custom shoe at the point-of-purchase by specifying size, colors, materials, cushioning, and logos. In the future, shoe scanners, such as the iStep, may be used to allow consumers to create even more personalized shoes.

Prior to modern-day metal grills, grills were nothing more than a hand-crafted fire pit or fire rack. As people continued to enjoy outdoor cooking, grills shifted from craft production to mass production with metal grills, such as the brazier charcoal grills and the permanent backyard, natural gas grills. Recently, grills have progressed towards mass customization, as product platforms have been used to offer a variety of grills to satisfy the heterogeneous preferences of outdoor cooks. For example, Weber offers a family of charcoal grills, the One-Touch product family. The products within this family are distinguished by size and secondary features, such as thermometers and ash collectors. To get closer to Davis' definition of mass customization, grill manufacturers, like Weber, could begin offering customization options. Perhaps one day, an online configuration, similar to that used by Nike and Adidas, will allow consumers to customize their own grill.

In a rustic fashion similar to grills, portable drills were once rudimentary mechanical devices hand-crafted from raw materials. Examples of these craft-produced drills include the bow and pump drills. As people continued to drill holes for construction purposes, portable drills shifted from craft production to mass production with the geared hand drill. This process of mass producing drills continued after the invention of the electric drill, as can be seen from Black & Decker's history. Within the past few decades, portable drills have shifted away from mass production and towards mass customization. In Black & Decker's case, this transition started with the adoption of product platforms to accommodate new electric motor regulations. Today, the company continues to utilize product platforms to offer product variety, as was evidenced by their MAX Lithium Cordless Drill/Driver product family presented in Section 2.5. In their pursuit of Davis' definition of mass customization, Black & Decker has embedded flexibility into a few of their product's architectures for customization with SmartSelect technology and the Matrix Quick Connect System. The SmartSelect technology allows consumers to customize their portable drill's performance after the point-of-purchase, and the Matrix Quick Connect System enables customers to purchase modular components to meet their portable tool needs. Only the future will tell how Black & Decker and other portable drill manufacturers will push closer towards Davis' definition of mass customization.

Computers have a unique history in that they were craft-produced from hand-held, simplistic devices to room-sized, complex machines. The abacus and the Harvard Mark I computers illustrate this distinctive history. With technology improvements and an increased attraction in computers from businesses and individual consumers, the computer industry evolved from craft production to mass production. This transition began with the UNIVAC computer and quickly gained momentum with IBM's PC. The standardization and modularization of computer parts enabled Michael Dell to progress the computer industry from mass production towards mass customization. Today, Dell offers platform-based computers to customers via the Internet and telephone via a match-to-order approach, and they even allow consumers to modify some of the computer's components through a set of customization options via an assemble-to-order approach. Puget Systems allows customers to customize even more features than Dell, and the future may allow even more customization.

Even the industry that developed mass production started out following the tenets of craft production. Automobiles were first created by skilled artisans who manufactured car parts and assembled them by hand through an arduous process of hand filing. Vehicles created by companies like P&L illustrate this era in the automobile industry. Soon after Henry Ford entered the industry, mass production replaced the paradigm of craft production with his Model T. For decades after its introduction in the early 20th century, mass production was the dominant paradigm in the industry. Then, American automobile preferences began changing and foreign competitors employing methods of lean production, such as Toyota, began attracting American customers away from American-made automobiles. Through lean production and product platforms, these foreign manufacturers were able to create a variety of products to meet the heterogeneous needs of Americans. Eventually, American manufacturers began using platforms to meet these needs, though they initially had difficulties with distinguishing products in a product family. Today, both domestic and foreign automobile manufacturers use product platforms, and they offer customization options, sometimes in the form of packages, to allow consumers to further modify their vehicle's design. Similar to the shoe and computer industries, the Internet has again shown its usefulness for mass customization as automobile companies employ online configuration tools for vehicle customization. In the future, online computer-aided design systems may allow consumers greater freedom in their customization efforts.

Finally, in the industry's infancy, airplanes were hand-crafted from raw materials, such as wood and cloth. The Wright Flyer I is an example of such a hand-crafted plane. In contrast to the above six products, airplanes did not transition in a linear fashion from craft production to mass production and towards mass customization. Instead, airplanes experienced periods of mass production during the world wars, but, in general, transitioned from craft production towards mass customization. Airplanes were customized for clients, and platforms were used to offer product variety as air transportation grew in popularity. With Boeing's 787, customization options have been added in the pursuit of Davis' definition of mass customization. Airlines can now customize the interior of their planes in a quick, efficient manner. Though airplanes do not follow the linear pattern from craft production towards mass customization that the other six products experienced, it still follows the basic flavor of the product development strategy proposed in Chapter 1.

From this study, it can be concluded that products appropriate for customization evolve in a way that pushes their product development strategy closer to Davis' definition of mass customization. The history of the seven products discussed in this chapter, along with Smith et al.'s findings ([14], see Section 1.3), serve as initial validation of Figure 1.2. Building on this conclusion, the next chapter provides background into the key marketing and engineering tools needed to facilitate customization option assessment and selection.

CHAPTER 3: KEY TECHNOLOGIES FOR MASS CUSTOMIZATION

3.1: Introduction

As mentioned in Chapter 1, consumers desire products with more variety, more features, and better quality [7], [8]. Moreover, a 2007 report detailing the results of a study interviewing 72 senior engineering managers of industrial, electrical and transportation companies showed that (1) consumers desire customized products and (2) this desire has been increasing since 2002 [58], [59]. Concerning consumer satisfaction, experimental research has provided some evidence for customization increasing consumer satisfaction. Huffman & Kahn showed that consumers were more satisfied when they were able to select product features [60], and Bauer et al. demonstrated that consumers benefited differently based on the type of customization [61]. Stylistic customization was capable of producing emotional and symbolic benefits, while functional customization could produce quality and comfort benefits. From a business perspective, customized products have shown to directly increase a consumer's willingness to pay (WTP) [62]. To address these consumer desires, provide more consumer satisfaction, and increase consumers' WTP, the business strategy of mass customization has been suggested.

Mass customization is the new business paradigm in which companies strive to provide individually customized products while simultaneously striving for mass production costs [9]. For over twenty-five years, research has been conducted in mass customization with respect to the marketing, engineering, and manufacturing domains [63]. This thesis is concerned with the marketing and engineering domains of mass customization, and thus research related to these domains is discussed. In particular, research related to approaches for gathering consumer preferences, achieving product variety, and managing product change is presented. At the end of this chapter, the limitations of the current research are discussed in the context of this thesis. For a more detailed review of the current advances in MC, the interested reader is directed to [10] and [14].

3.2: Approaches for Gathering Consumer Preferences

Many approaches exist for gathering consumer preference information, and examples include archival searches of previously collected consumer data, interviews with focus groups, personal interviews, mail or phone surveys, and conjoint analysis [64], [65]. Conjoint analysis has become a popular approach for gathering consumer preference information in numerical form [65]. As a result of its popularity and ability to obtain consumer preference data in numerical form, this section focuses solely on this method.

Conjoint analysis originated in psychology in the mid-1960s before entering the marking community by the early 1970s [65]. In conjoint analysis, a respondent is asked to complete a set of tasks in which several product profiles are presented to the respondent for evaluation. These product profiles represent a product hierarchically with attributes and levels. An example of a task question for a discrete choice conjoint survey (see Section 3.2.1) is shown below:

TABLE 3.1: DISCRETE CHOICE CONJOINT ANALYSIS TASK EXAMPLE

	Laptop 1	Laptop 2	Laptop 3	None
Hard Drive	500GB	750GB	1TB	I would not select any of these products
Memory	16GB	4GB	8GB	
Processor	2.8GHz	2.6GHz	3.0GHz	
Screen	17.3"	15.6"	14"	
Your Selection	○	○	○	○

In Table 3.1, three product profiles are listed (Laptop 1, Laptop 2, and Laptop 3), and each product profile is composed of four attributes (Hard Drive, Memory, Processor, and Screen). Within these attributes, a number of levels can exist, and these levels differentiate the product profiles from each other. By having a respondent evaluate product profiles for several tasks, the respondent's preference (or part-worth) for each level and importance for each attribute can be estimated [65]–[68]. With this numerical preference data, product profiles composed of level combinations not shown in the tasks can be evaluated to obtain the respondent's total preference (or utility) for the product profiles. By using the part-worths of several respondents, a market-level analysis for a product profile can be conducted. The first step in obtaining this numerical preference data is creating tasks and having respondents evaluate product profiles in a traditional or discrete choice conjoint analysis framework.

3.2.1: Traditional and Discrete Choice Conjoint Analyses

In traditional conjoint analysis, tasks typically contain a single product profile [65]. By having one profile per task, respondents are encouraged to evaluate each product profile independently and without consideration of other profiles. To design these tasks, Green and Srinivasan recommend product profiles with no more than six attributes [66]. Additionally, only a few, well-designed tasks are required to obtain accurate preferences for a respondent, and thus traditional conjoint analysis can be administered with pencil-and-paper studies [65]. During administration of the traditional conjoint study, a respondent evaluates each product profile to indicate his/her likelihood of purchase [65]. Typically, each profile is rated on a scale, from 0 to 100, for example. By rating a few product profiles, a respondent's part-worths can be obtained for the tested levels with a mathematical model (usually linear regression) as well as his/her importance scores for the attributes.

As opposed to traditional conjoint analysis, tasks in discrete choice conjoint analysis (or choice-based conjoint analysis) contain a group of product profiles and a None, or walk-away option [65]. By grouping products together with a walk-away option, the real world purchase process is modeled better than it would be with traditional conjoint analysis. In further contrast with traditional conjoint analysis, task design in discrete choice conjoint analysis is more difficult and respondents spend more time to complete each task.

Computer software has been developed to combat this added complexity through automated task design and web-based survey administration and distribution. During survey administration, a traditional None option or a Dual-Response None option can be employed [69]. With a traditional None option, a respondent selects the product profile he/she would most likely purchase or the None option if no product profiles are desirable. This setup is shown in Table 3.1. With a Dual Response None option, a respondent selects the product profile he/she would most likely purchase and then answers a separate question about actually purchasing the chosen product profile. As a result of this setup, the None option is likely selected more than it would be with the traditional None option setup, which some researchers argue better reflect realistic purchase scenarios. In addition to this benefit, the estimation precision of the other levels is not jeopardized if the None option is selected often, as it could be with the traditional None option setup.

However, these benefits come at a cost; the time to complete each task is increased in comparison to the traditional None option setup. Regardless of the None option setup, part-worths for the tested levels can be determined with a mathematical model [65]. However, unlike traditional conjoint analysis, discrete choice conjoint analysis has traditionally calculated part-worths at the group-level and not the individual-level. For companies pursuing mass customization, individual-level preference data is important since each consumer is assumed to have a unique preference structure. Therefore, mathematical methods, such as latent class or hierarchical Bayes, have been developed to obtain individual-level preference data for discrete choice conjoint analysis. Since discrete choice conjoint analysis will be used in this thesis due to its ability to mimic the real world purchase process and the availability of computer software, these mathematical methods are discussed in the next section.

3.2.2: Mathematical Estimation of Consumer Preferences

To mathematically estimate consumer preferences, multinomial logit (MNL) models are typically used [70]–[73]. These models determine a respondent's utility for a product profile by summing the part-worths of the present attribute levels. The mathematical expression for this definition is shown below:

$$\boldsymbol{U_{ik}} = \sum_{\boldsymbol{j}} \boldsymbol{X_{ijk}\beta_j} + \boldsymbol{\varepsilon_{ik}} \qquad (\mathbf{3.1})$$

In Equation 3.1, $\boldsymbol{U_{ik}}$ is the i^{th}respondent's utility for the k^{th} product profile, $\boldsymbol{X_{ijk}}$ is the i^{th} respondent's rating of the j^{th} attribute level for the k^{th} product profile, $\boldsymbol{\beta_j}$ is the importance of the j^{th} attribute level, and $\boldsymbol{\varepsilon_{ik}}$ is an error term accounting for the difference between the respondent's actual utility and that modeled by this equation.

To obtain the $\boldsymbol{\beta_j}$ values, the MNL model makes two assumptions that enable a respondent's probability of choosing a product profile to be estimated [70]–[74]. The model assumes that a respondent selected the product profile that maximized his/her utility (known as the principle of utility maximization) and that the error term, $\boldsymbol{\varepsilon_{ik}}$, follows an extreme value distribution. With these assumptions, the following mathematical expression can be developed for predicting a respondent's probability of choice:

$$\boldsymbol{p_i^l} = \frac{\boldsymbol{exp}\,(\sum_j \boldsymbol{X_{ijl}\beta_j})}{\sum_{\boldsymbol{k=1}}^{\boldsymbol{K}} \boldsymbol{exp}\,(\sum_j \boldsymbol{X_{ijk}\beta_j})} \qquad (\mathbf{3.2})$$

In Equation 3.2, $\boldsymbol{p_i^l}$ is the probability of the i^{th} respondent selecting the l^{th} product profile from a set of alternative profiles, $k = 1, \ldots, K$. With Equation 3.2 developed, the $\boldsymbol{\beta}_\mathbf{j}$ values can be determined by maximizing the log-likelihood function, shown below:

$$\boldsymbol{log\, L} = \sum_{\boldsymbol{i}} \boldsymbol{log}\,(\boldsymbol{p_i}) \qquad (\mathbf{3.3})$$

In Equation 3.3, $\boldsymbol{p_i}$ is the probability, determined from Equation 3.2, that the i^{th} respondent selects the l^{th} product profile. By maximizing Equation 3.3, the market-level, or aggregate, $\boldsymbol{\beta_j}$ values are determined, thus ignoring any market heterogeneity. To capture market heterogeneity, latent class and hierarchical Bayes models can be utilized.

The latent class model represents market heterogeneity at a group-level, while the hierarchical Bayes (HB) model represents heterogeneity at the individual-level [65]. From the respondent population, the latent class model identifies homogeneous groups and then calculates part-worths for each attribute level for all identified groups. In contrast to latent class, HB uses data from other respondent's to estimate individual-level part-worths. Since the ultimate goal of mass customization is to offer individually-customized products, a HB model would be appropriate for obtaining individual-level part-worth data. The next section discusses this mathematical model in more detail.

3.2.2.1: Hierarchical Bayes Model of Consumer Preferences

To determine individual-level part-worths, hierarchical Bayes assumes that the individual-level part-worths exhibit a multivariate normal distribution [71]. This distribution is described in the following equation:

$$\boldsymbol{\beta_i} \sim \boldsymbol{Normal}(\boldsymbol{\alpha}, \boldsymbol{D}) \qquad (\mathbf{3.4})$$

In Equation 3.4, $\boldsymbol{\beta_i}$ is a vector containing all the part-worths for the i^{th} respondent, $\boldsymbol{\alpha}$ is a vector containing mean values of the distribution of part-worths for all respondents, and $\boldsymbol{D}$ is a matrix containing variances and covariances of the distribution of part-worths across all respondents. With this formulation, $\boldsymbol{X_{ijk}}$ in Equations 3.1 and 3.2 becomes binary and represents the presence or absence of an attribute level. Consequently, $\boldsymbol{X_{ijk}}$ becomes independent of the respondent and can be written as $\boldsymbol{X_{jk}}$. Moreover, $\boldsymbol{\beta_j}$ becomes the individual-level part-worth of the j^{th} attribute level and can be written as $\boldsymbol{\beta_{ij}}$.

After making this assumption, the parameters $\boldsymbol{\beta_i}$, $\boldsymbol{\alpha}$, and $\boldsymbol{D}$ are estimated with an iterative process, called Gibbs sampling or Monte Carlo Markov Chain, so that Equation 3.3 is maximized [71], [75]. The iterative process that determines these parameters begins by initializing all three parameters and then using two parameters at a time to estimate the third one. For the interested reader, a more detailed description of this estimation process is given in [75] and [71].

3.2.2.2: Properties of Part-Worths

In this thesis, Sawtooth Software's CBC/HB module is used to fit a hierarchical Bayes model to the gathered discrete choice conjoint data. Therefore, a discussion of the properties of the part-worth data obtained from this software is relevant. Regardless of the mathematical model, part-worths are interval data measured in units of utiles, and, for each attribute, they are scaled to an arbitrary additive constant [65]. Sawtooth Software's CBC/HB module employs zero-centered difference, thus the part-worths for each attribute sum to zero [69]. As a result of scaling part-worth data, the actual part-worth values are meaningless, and only the differences in part-worths are meaningful [65], [71]. Furthermore, part-worths cannot be compared across attributes for a single respondent, and they cannot be compared across multiple respondents. The following example, based on similar examples in [65] and [76], helps illustrate these points:

TABLE 3.2: PART-WORTH EXAMPLE

	Hard Drive	Part-Worth	Screen Size	Part-Worth
Respondent 1	500GB	40	14"	-30
	750GB	-10	15.6"	10
	1TB	-30	17.3"	20
Respondent 2	500GB	10	14"	0
	750GB	-30	15.6"	10
	1TB	30	17.3"	-10

In Table 3.2, the negative part-worth values do not mean that the levels are undesirable, but that they are less desirable than the positive part-worth values. Hence, for

Respondent 1, a 1TB hard drive is not necessarily undesirable; it is just 70 utiles less desirable than a 500GB hard drive.

In terms of comparing part-worths for a single respondent, it is valid to conclude that Respondent 2 prefers a 1TB hard drive 20 utiles more than a 500GB hard drive. However, since interval data does not support ratios, it is invalid to conclude that a 1TB hard drive is three times as preferred as a 500GB hard drive (30/10). Additionally, it is invalid to conclude that Respondent 2 prefers a 500GB hard drive equally to a 15.6" screen size. Lastly, concerning comparing part-worths between respondents, it is invalid to conclude that Respondent 1 prefers a 1TB hard drive as much as Respondent 2 prefers a 750GB hard drive.

3.2.3: Brief Discussion of Product Architecture

Based on the proposed product development strategy discussed in Chapter 1 and supported in Chapter 2, a product is defined prior to entering the paradigm of mass customization. Therefore, in developing customization options, a product architecture is at least partially defined. Ulrich defined a product architecture as "(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; and (3) the specification of the interfaces among interacting physical components" [77]. With the first two points of this definition at least partially completed, a firm could determine the attributes and levels for a discrete choice conjoint study. For example, consider the laptop product profile shown in Table 3.1. To generate such a profile, a firm would need to know some key functions of the laptop (store data long term and short term, process data, and display data) and some of the components that performed these functions (hard drive, memory, processor, and screen). Other functions, such as play sound or capture photo/video, and related components, such as speakers and built-in camera, could be ignored.

However, to finalize a product's design, a complete product architecture is required. For a complete product architecture, all the functions will be identified and mapped to physical components, and the interfaces between physical components will be defined. If a one-to-one mapping exists between functions and physical components and interfaces are decoupled, then the product architecture is considered modular. However, if no one-to-one mappings exist between functions and physical components and/or interfaces are coupled, then the product architecture is considered integral.

To help finalize and visualize a product architecture, tools, such as functional models and Design Structure Matrices (DSMs), can be used [78], [79]. With an architecture completely defined, a firm can focus on product variety and product change, as Ulrich argues that product architecture plays an important role in a firm's success since it affects these two categories [77]. The following sections discuss research related to product variety and product change.

3.3: Approaches for Achieving Product Variety

As discussed in the Section 3.1, consumers desire a variety of products, and even customizable products, so that their unique, individual wants and needs can be fulfilled. One solution to this consumer request is to offer a lot of different products. However, offering a large variety of products can have negative consequences, both from the firm's and the consumers' perspective. From the firm's point-of-view, a large, diverse product portfolio is likely to increase product development and production costs, especially when commonality between products is not a focal point of product design [12]. Concerning the consumers' perspective, a phenomenon known as the "too much choice" paradox exists. By being exposed to too much product variety, consumers likely perceive customized products with little market appeal [80] and experience a decreased sense of well-being from having to choose from a large set of products [81]. To combat increased costs and the "too much choice" paradox, product family design can be employed.

3.3.1: Introduction to Product Family Design

Product family design (PFD) is a product development strategy in which a set of related products, instead of a single product, is designed from one or more product platforms as a way to offer product variety and fulfill a diverse set of consumer preferences [12]. Since members of the product family are designed from one or more product platforms, they are called variants or derivatives [82]. Product platforms are defined in a number of ways, but these definitions can be classified into two categories. One category defines a product platform in a purely physical way: a collection of elements (features, components, subsystems) shared among product family members. The other category does not limit a product platform to the physical domain: "a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced" [2]. Regardless of the definition used, product platforms enable the creation of product families, thus providing benefits to consumers and the firm.

3.3.1.1: Advantages and Disadvantages of Product Family Design

From the consumers' point-of-view, product family design (also known as platform-based product development) limits the amount of available products for purchase while still providing variety. Therefore, platform-based product development can combat the "too much choice" paradox while satisfying consumers' desire for more product variety. From the firm's perspective, PFD allows cost savings while providing the ability to offer a variety of products [12]. In particular, product family design allows a reduction in product development and production costs. The automobile company, Volkswagen, saved billions of dollars through platform-based product development [83]. Additionally, PFD enables a decrease in product development time, a reduction in product complexity, an enhanced capability for product upgrades, and an improved flexibility and responsiveness in manufacturing routines [12], [82]. By using platforms to create a family of electric motors, Black & Decker was able to produce one product per week [84].

Though PFD provides several benefits both to consumers and the firm, it also provides a few disadvantages to both groups. With respect to consumers, PFD can limit the amount of customization available. If a product family is created and offered to consumers in a match-to-order fashion, the consumers' ability to customize their product is limited. Offering customization options in an assemble-to-order fashion is one way to combat this limitation, and some companies are pursuing this option (see Chapter 2). Concerning the firm, platform-based product development may inhibit and delay future innovations [2]. Consider a product family has been on the market for some time, and now future innovations are required to maintain the family's competitive advantage. If the platform is not updated periodically, especially as new technologies emerge, the product family may lose its competitive advantage due to an outdated platform. Sony avoided this potential pitfall of platform-based product development by periodically performing generational changes to its Walkman platform [85]. In addition to potentially inhibiting future innovations, PFD is more time-consuming than single product development, and thus market launches of the first few family members may be delayed [86]. Finally, platform-based product development is more complex and challenging than single product design. To combat this difficulty, the design community has conducted numerous research in developing systematic approaches for PFD. Basic approaches to platform-based product development are presented next followed by a more detailed overview of current PFD research.

3.3.1.2: Basic Approaches to Product Family Design

At the most basic level, Robertson and Ulrich identified three steps for product family design [87]. These steps include developing a (1) product plan, (2) differentiation plan, and (3) commonality plan. The product plan identifies what concepts a firm will offer as products to consumers, the differentiation plan determines how these products will be distinguished from one another in the product family, and the commonality plan determines what product elements will be shared among family members. At another level of granularity, the first step can be broken down into two approaches.

These two approaches to PFD include a top-down, or proactive approach, and a bottom-up, or reactive approach [12]. In top-down PFD, a set of new products are designed from one or more product platforms to form a product family. An example of a top-down

PFD method is Design for Mass Customization, which develops a product family architecture from building blocks based on functional requirements and design variables [88]. As opposed to top-down product family design, bottom-up PFD begins with a set of existing products and redesigns them such that they are related to each other through one or more product platforms. An example of a bottom-up PFD method is the research conducted by Farrell & Simpson in which they determined a product platform for a set of highly customized products by determining which components to redesign and make common among the product family members [89]. Upon selecting either a top-down or bottom-up PFD approach, platform leveraging strategies can be used to help complete the differentiation and commonality plans.

The four platform leveraging strategies introduced by Meyer and Lehnerd include horizontal leveraging, vertical leveraging, beachhead leveraging, and no leveraging [2]. These leveraging strategies are commonly visualized with a market segmentation grid (MSG), shown below [2]:

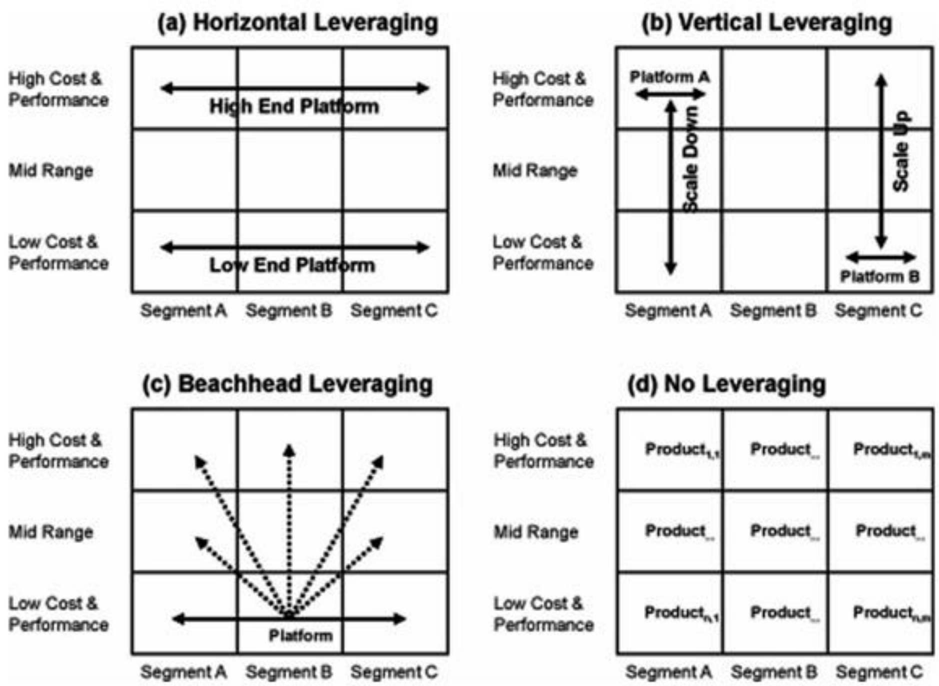


FIGURE 3.1: PLATFORM LEVERAGING STRATEGIES

As shown in Figure 3.1, a MSG is a qualitative tool that organizes products based on their cost and performance versus their target market segment. To create product variety via product families, one of the shown leveraging strategies, excluding the no leveraging strategy, can be adopted. Horizontal leveraging uses platforms in a single performance level to target multiple market segments, vertical leveraging uses platforms in a segment to reach different performance levels, and beachhead leveraging is a combination of both leveraging strategies.

To implement any of these three leveraging strategies, modular, scalable, or a combination of modular and scalable platforms can be used. Product family members from a modular platform are created by combining unique modules with the platform, while product family members from a scalable platform are created by combining components with a scaled version of the platform [82]. An example of a modular product family is the desktop computer, whose motherboard may be the platform and additional modules, such as the hard drive and memory, can be changed to create family members. An example of a scalable product family are Boeing commercial airplanes, whose fuselage section can be considered the platform that is scaled to accommodate various amounts of passengers [12]. In addition to modular and scalable platforms, generational platforms allow these leveraging strategies to be implemented over time [82]. Though the basic approaches presented in this section provide firms with a high-level understanding of product family design, detailed systematic approaches can provide firms with more direction in conducting platform-based product development. In the next section, an overview of current PFD research is presented.

3.3.2: An Overview of Research in Product Family Design

Research in this area can be classified into the five following categories: evaluation and selection techniques, PFD based on platform type, approaches for determining platform extent, PFD with marketing and manufacturing considerations, and approaches for flexible platform development. An overview of the research conducted in these categories is now presented. For a more comprehensive review of product family design, the interested reader is referred to the literature reviews of Pirmoradi et al. [90], Jiao et al. [82], Simpson et al. [91], and Simpson [12].

3.3.2.1: Evaluation and Selection Techniques

Several techniques exist for evaluating product families, especially in the form of metrics. Simpson reported that metrics related to product family design focus on measuring a product's similarity and distinctiveness with the products in the product family [12]. Numerous commonality indices have been developed to assess the degree of commonality between products in the product family, and common ones include DCI, TCCI, PCI, %C, CI and $CI^{(C)}$ [90]. For more specific information on these metrics, the interested reader is directed to the review done by Thevenot and Simpson [92]. In addition to commonality indices, metrics exist for measuring the amount of interaction between components. Examples of such metrics include the Design for Variety GVI and CI indices, which measure the difficulty of redesign for future development and the amount of coupling between components, respectively [93].

As well as metrics, methods exist for evaluating and selecting product platform designs for PFD. Examples of such methods include the work of Moon et al. [94] and Simpson et al. [95]. Moon et al. used a multiobjective particle swarm optimization algorithm "to select the best platform design strategy from a set of Pareto-optimal solutions based on commonality and design variation within the product family" [94]. Simpson et al. developed a technique, called the Product Variety Tradeoff Method, to assess scalable platforms based on commonality [95]. Though these metrics and techniques can be used to evaluate and select a platform-based product design strategy, they cannot used to develop such design strategies. The following sections discuss some methods that can be used to generate product family designs, starting with methods that are based on platform type.

3.3.2.2: PFD based on Platform Type

Numerous methods have been created for product family design by utilizing a modular or scalable platform. A few examples are presented below to demonstrate the work in this area. Modular architectures have been very successful in allowing companies to offer a diverse set of products [91], [96]. For modular PFD, research has focused on module identification and optimization. Examples of research in modular PFD include the work of Fujita et al. [97] and Gonzalez-Zugasti et al. [98]. Fujita created two frameworks to optimize module attributes and module selection [97]. Gonzalez-Zugasti et al. expanded upon an earlier version of Fujita et al.'s work [99] by considering existing and new modules, and not just existing modules, for modular platform-based product development [98]. For more details on modularity and modular platform-based product development, the interested reader is directed to the literature reviews of Fixson [100] and Jose and Tollenaere [101].

In addition to modular PFD, scalable PFD research has been conducted, and work in this area has focused on identifying the common and unique design variables (DVs) for a product concept and then optimizing these DVs to maximize one or more performance goals [82]. Examples of scalable platform-based product development research include the works of Simpson et al. [102], [103] and Li et al. [104]. Simpson et al. developed an approach, entitled Product Platform Concept Exploration Method, to design a scale-based product family [102], [103]. The method involves using a MSG, mathematical models of product performance based on product parameters and DVs, and a compromise Decision Support Problem (DSP) to create a scale-based product family. Li et al. developed a multiobjective optimization to design a scalable platform and its variants [104]. The first stage optimized the products individually with respect to the two objectives (cost and performance) and then determined the common DVs based on small deviations. Once the common DVs were identified and their values were set, the remaining DVs were optimized with respect to the two objectives to form the product variants.

3.3.2.3: Approaches for Determining Platform Extent

The approaches mentioned thus far did not explicitly consider platform extent (the distribution of variants among platforms) and typically considered one platform for a product family. Since only a single platform is designed, these methods are computationally simplistic, but individual products in the product family could be over-design or under-designed [82]. By using a single platform, low end products could be over-designed, while high end products could be under-designed. To address this concern, several researchers have developed methods to determine multiple platforms.

A few researchers have used cluster analysis to determine multiple platforms for PFD. Examples include Dai and Scott [105], Freeman et al. [106], and Chen and Wang [107]. Dai and Scott used sensitivity and cluster analyses to design multiple, scalable product platforms and variants [105]. Products were individually optimized for performance, a sensitivity analysis of the DVs on performance was conducted, a cluster analysis was implemented on the sensitivity data to identify common DVs and their values, and the product variants were optimized for performance. Freeman et al. used fuzzy c-means to identify potential platforms for a product family [106]. They clustered components based on their similarity to each other, and, as a result, were able to identify one or more product platforms. Chen and Wang used fuzzy clustering and Shannon's entropy to design multiple platforms [107]. However, instead of a two-stage approach that first determines the product platforms and then the product variants, a two-level chromosome genetic algorithm was used to simultaneously optimize product platforms and variants for performance. Other researchers have also recognized the potential sub-optimality of two-stage approaches to platform-based product development. For example, Messac et al. developed a one-stage approach using physical programming to a scale-based product family utilizing a single platform [108]. The method showed some computational saving and similar results when compared to two-stage approaches, but did not consider multiple platforms as Chen and Wang did.

Other methods do not use cluster analysis to design multiple platforms for a product family. Examples include methods developed by Seepersad et al. [109] and de Weck et al. [110]. Seepersad et al. created a quantitative approach to determine (1) the number of scalable platforms for a market segment and (2) the product distribution among these platforms [109]. This approach formulated the design problem as a compromise DSP and used physical programming to solve it. Another method that used a two-stage approach and considered platform extent like Dai and Scott's method [105] was created by de Weck et al. [110]. Their approach created platforms and variants for maximum product family profit by first optimizing the number of platforms and then optimizing the variant configurations for a given number of variants. Unlike the other methods, the approach developed by de Weck et al. utilized marketing domain information; it used actual sales volume information in the two-stage, product family design optimization. Other researchers have recognized the importance of marketing information, as well as manufacturing information, being incorporated into the product design process, and research in this area is discussed next.

3.3.2.4: PFD with Marketing and Manufacturing Considerations

Though approaches described above consider the engineering domain with little attention to the marketing or manufacturing domains, some research has been conducted to include these other areas. Tseng and Jiao advocated the inclusion of all three domains in product family design and argued that maximizing reusability over these domains is a challenge in achieving mass customization [111]. Specifically, they argue that "the synergy of commonality and modularity needs to be tackled starting from the functional domain characterized by customer needs or functional requirements [marketing domain], and needs to encompass both the physical [engineering domain] and process [manufacturing domain] domains of design" [111].

A few researchers have worked on combining the engineering and marketing domains. In the management literature, Moon et al. used conjoint analysis to determine platforms and variants such that a market performance metric (preference share, contribution, or profit) was maximized [112]. They showed that different products were obtained based on the market performance metric being considered, and that platforms were advantageous in designing products to maximize a market performance metric as opposed to considering products individually. Similar research conducted by Riesenbeck et al. explored the profitability of platform-based product variety compared to the profitability of product variety without platforms [113]. By combining consumer preference data from conjoint analysis with the platform concept, they could identify important attributes and levels, reduce the variable costs of these attributes and levels, and increase profitability.

Though not directly considering product family design, a few researchers in the engineering design community have conducted research that explored combining the marketing domain with the engineering domain. Examples include the works of Ferguson et al. [70], Porterfield et al. [76], and Michalek et al. [114]. Ferguson et al. offered "food for thought" regarding integration of marketing information into engineering design problems [70]. They showed that a discrete choice conjoint survey could be used to design a mass customized product, and they explored the ability of hierarchical Bayes and latent class models at representing consumer preferences. Porterfield et al. developed a metric based on consumer preference information obtained from a discrete choice conjoint survey to measure the utility difference between a consumer's ideal product and their best available alternative [76]. This metric, called Sacrifice Gap, was then successfully used to determine a set of optimal product designs while considering firm-centric and consumer-centric objectives. Michalek et al. developed a technique using analytical target cascading (ATC) to design a single product based on marketing requirements and engineering capabilities [114]. To design this product, two sub-problems were formulated, one for the marketing domain and one for the engineering domain, and solved iteratively until convergence. The marketing sub-problem used conjoint analysis to identify product levels that maximized profits, while the engineering sub-problem used DVs to find a feasible design that minimized deviation from the marketing product.

In addition to exploring the possibility of integrating the marketing domain with the engineering domain and using the combination of domains to design a single product, engineering design researchers have developed methods using both domains for product family design. Two examples include the work of Kumar et al. [115] and ElMaraghy and AlGeddawy [116]. Kumar et al. created a method, entitled Market-Driven Product Family Design, to design a product family while considering their position in the MSG [115]. The method involves creating a MSG showing the firm's products and their competitors' products, estimating a demand model using a nested logit, constructing product performance models using product design variables and a cost structure, and running a profit maximization model to determine the optimal product configuration, optimal number and configuration of platforms, and the optimal product positioning. ElMaraghy and AlGeddawy developed a technique, called Product Variants Design Model, "to integrate market domain requirements with product modularity and spatial constraints between components" [116]. They used functional analysis to map customer product requirements to primary components and cladistics to determine new configurations of components to create modules.

Not only has some research combined the marketing and engineering domains, but also some research has combined these two domains with the manufacturing domain. Two examples include Michalek et al. [117] and Farrell and Simpson [118]. Michalek et al. modified their aforementioned ATC method by formulating a manufacturing sub-problem and designing a product line as opposed to a single product [117]. They showed that compromising a product design to reduce manufacturing costs was worthwhile until revenue losses due to poor market performance outweighed the cost savings. Farrell and Simpson expanded upon their previous work on determining platforms for highly customized products [89] by representing the manufacturing costs with an activity-based (ABC) model [118]. The ABC model considers the fixed and variable costs of manufacturing by modeling tooling costs, overhead costs, new material costs, and machining costs.

As can be seen from the above discussion, several methods exist that consider the marketing and manufacturing domains along with the engineering domain for product design and product family design. However, these approaches, and the ones mentioned before them, do not consider the effect of future changes on product design. The next section discusses research related to flexible platform development.

3.3.2.5: Approaches for Flexible Platform Development

To address the disadvantage of platforms inhibiting future innovation, some research has focused on flexible platforms to accommodate expected and unexpected changes. Khadke and Gershenson developed a method, called Planned Product Innovation Method (PPIM), to explore and plan for technology change [119]. This approach analyzed technologies in a product with respect to three aspects (principle of operation, performance level, and technological architecture) and compared this analysis with technology forecast information to determine a technology's potential for change. By clustering similar change potentials, engineers could focus on the important technologies for innovation. In a later work, these authors developed four heuristics, based on the three aforementioned technological aspects and standardization, to identify the technologies to include in a product platform so as to minimize the effect of technology change [120]. These heuristics and PPIM were then incorporated into an approach, entitled Technology-Driven Platform Development, to determine technology-based platform elements in an existing platform [121]. By determining these platform elements, potentially frequent and costly changes to a product platform due to technology changes could be avoided. It is worth noting that this approach does not identify platform elements.

Though Technology-Driven Platform Development does not identify platform elements, other approaches have been developed to identify platform elements while considering time-dependent changes. Seepersad et al. created an approach to design multiple product platforms to accommodate time-dependent product changes by formulating the design problem as a utility-based compromise DSP in which product design changes are considered to occur probabilistically over time [122]. Sered and Reich used Design for Variety indices and a DSM to calculate the total design effort in terms of cost for the current and future generations of a platform and then used this information to determine which components to standardize and modularize [123]. Madni proposed adaptable product line architectures as a way to avoid developing a platform that would inhibit product evolution [124]. These architectures would incorporate change absorbers or some adaption mechanism to accommodate future changes. Similar to the work of Khadke and Gershenson, Suh et al. identified critical platform elements and used them to create a flexible platform [125]. However, instead of identifying platform elements from technology change potentials, Suh et al. determined uncertain DVs and mapped these DVs to physical elements with a change propagation analysis. As recognized by Suh et al., product change research could be used to support flexible platform development, and thus product variety. The next section discusses product change research.

3.4: Approaches for Managing Product Change

In addition to affecting product variety, the paradigm of mass customization affects product change. Eckert et al. first identified mass customization as a factor of design change [126], and they later classified types of change into two categories: emergent and initiated [127]. Emergent changes are unexpected changes that arise during the product design process, and initiated changes are expected changes that arise from new requirements. Mass customization creates initiated changes as consumers desire more product variety to satisfy their individual requirements. To accommodate changes caused by mass customization among other factors, research in product change has focused on flexibility and change propagation analysis. An overview of the research conducted in these areas is discussed below. For a more comprehensive review of the engineering change literature, the interested reader is directed to the literature review of Jarratt et al. [128].

3.4.1: Overview of Research in Flexibility

Upton defined flexibility as "the ability to change or adapt with little effort, time, or penalty" [129]. With regard to product design, research in flexibility has focused on determining flexibility heuristics, quantifying a product's flexibility, and designing a product so that it could "adapt with little effort" [129] to expected and unexpected changes. Keese et al. developed twenty-four flexibility guidelines for future evolution by examining a large variety of products [130]. In a similar fashion, Fricke and Schulz identified a set of principles which could be used to design a product architecture capable of handling foreseen and unforeseen changes, and they developed a design method around these principles called Design for Changeability [131]. Three basic and six extending principles based on four aspects of changeability (flexibility, agility, robustness, and adaptability) were identified. Therefore, this method is not only concerned with a product's ability to adapt to change easily (flexibility), but also it is concerned with a product's ability to change quickly (agility), to be insensitive to change (robustness), and to adjust to change (adaptability).

As well as qualitative heuristics for flexibility, quantitative measures have been developed. Palani Rajan et al. created an approach, entitled Change Mode & Effects Analysis, to measure the inherent flexibility within a product [132]. For this method, a product is broken into components, or functional blocks, and then a potential change is analyzed based on the product's current flexibility, the likelihood of the change, and the firm's readiness for the change. Upon completion of the method, a Change Potential Number is determined that indicates the product's current flexibility for the assessed change. Another method developed by Cormier et al. measured a product's flexibility in the early stages of mass customization product design with three metrics based on the product's functionality [133]. These three metrics were related to the flows, geometry, and interfaces of a product, and they allowed the designer to consider a product's flexibility before functional elements were mapped to physical components.

Lastly, qualitative and quantitative methods have been developed to design flexible products. Examples include the work of Tilstra et al. [134] and Dong et al. [135]. Tilstra et al. applied the flexibility guidelines identified by Keese et al. [130] to a real design problem and showed that a product designed with the guidelines in mind was more prepared for change than a system designed without the guidelines [134]. Dong et al. developed a flexible optimization decision model for modular product design that allowed small and large adjustments to be made to a product, and they showed that this model found a product that was more beneficial to the firm [135].

3.4.2: Overview of Research in Change Propagation Analysis

In addition to analyzing a product's flexibility, research in change propagation analysis has been conducted to understand a change's influence on a product. Research in this area has focused on developing methods to describe and quantitatively examine change propagation to support design decisions. The discussion below focuses on the change propagation descriptions and related metrics. Eckert et al. determined four classifications for components in relation to change propagation: multiplier, absorber, carrier, and constant [127]. A multiplier changes more components than the number of components that changed it, an absorber changes fewer components than the number of components that changed it, a carrier changes the same number of components as the number of components that changed it, and a constant experiences no change. Suh et al., who was already discussed using change propagation to map DVs to physical components for flexible platform design, quantified these classifications with a metric called Change Propagation Index (CPI) [125]. Giffin et al.

improved the CPI by bounding its range and incorporating self-changes into the definition [136]. Moreover, Giffin et al. created two metrics to classify changes as acceptors or reflectors, and they developed a motif method to represent and analyze change propagation patterns using parent, child, and sibling relationships of proposed and executed changes.

Besides these change propagation descriptions and metrics, more complex methods have been developed to quantitatively analyze design dependencies and change propagation. Examples of such methods include those developed by Asikoglu and Simpson [137], Hamraz et al. [138], and Clarkson et al. [139]. Asikoglu and Simpson created a method that quantified design dependencies by considering direct and indirect connections [137]. The method breaks down a product into components, uses DSMs and Ohm's Law to capture design dependencies with a MATLAB Simulink model, and quantifies these dependencies with a change resistance value at each interface. These values can be averaged to obtain a component-level, and product-level, change resistance value. A small resistance value indicates that changes would easily propagate. Though this method is not solely designed for change propagation analysis, it can be used to examine change propagation by modifying the interface connections and comparing new resistance values with the values before the change was implemented. A method specifically developed for change propagation analysis was developed by Hamraz et al. [138]. This method used matrix calculations instead of an exhaustive search algorithm common to other methods. Lastly, Clarkson et al. developed the Change Prediction Method (CPM) [139]. The CPM breaks down a product into subsystems and uses a series of DSMs and propagation tree structures to "predict that risk of change propagation in terms of likelihood and impact of change" due to change propagating through direct and indirect connections [139]. Keller et al. applied the CPM to assist the conceptual design of a diesel engine [140] and later for customization planning [141]. By considering several change requests independently in terms of change propagation and the resulting cost of redesign, Keller et al. was able to identify which requests to offer and how to offer them so to minimize change propagation [141]. Originally, the CPM could only handle changes initiated by one subsystem [139], but Ahmad et al. suggested a modification that allowed the method to accommodate changes initiated by multiple subsystems in terms of combined likelihood [142]. Upon suggesting this modification, Ahmad et al. proposed a framework using the CPM and cross-domain DSMs to consider the effects of multiple changes on product requirements, functions, components, and detail design processes. Similarly, Koh et al. built on Ahmad et al.'s modification and used the CPM and house of quality to explore the effect of multiple change options on product requirements during the redesign of a jet engine fan [143]. From this analysis, it is clear a lot of research has been conducted with respect to change propagation.

3.5: Limitations of Current Research

As indicated by the literature review above, numerous research efforts have focused on gathering consumer preferences, achieving product variety, and managing product change. Though a lot of research has been conducted in mass customization, limitations to current research still exist. Research in product variety focuses on product family design through platform and variant development. This approach to product variety could limit the amount of customization when a firm designs a product family such that consumers can only select from standardized variants (a match-to-order approach, as discussed in Chapter 1). By offering customization options and employing an assemble-to-order approach, a firm can increase the amount of customization available to consumers. A top-down approach for PFD to enable such customization has been developed by Hernandez et al. [144] and improved by Williams et al. [145]. This approach, entitled Platform Constructural Theory Method, designs a platform by formulating the design problem "as a problem of access in geometric space" [144] and solving it with constructural theory [144], [145]. Though such an approach can be used to design a product family with customization options, a bottom-up approach for PFD does not exist.

A further limitation of research in product variety is that very little attention has been given to integrating the marketing and engineering domains. This fact is seen from the small amount of research presented in Section 3.3.2.4 and the Market Driven Studies section of a very recent PFD literature review [90]. The literature review indicates that integrating the marketing and engineering domains is an area of future work.

Finally, research in product change has focused minimally on customization planning. Cormier et al.'s flexibility metrics [133] and Keller et al.'s CPM [141] are the only examples found for product change research being explicitly used for customization planning. For bottom-up approaches to PFD with customization options, change propagation research could be very useful.

This thesis partially addresses these three current limitations in mass customization research. It proposes a bottom-up approach for a single product that considers marketing and engineering product change information for the evaluation of customization options. The specifics to this approach are discussed in the next chapter.

CHAPTER 4: APPROACH FOR CUSTOMIZATION OPTION ASSESSMENT

4.1: Introduction

As shown in Smith et al. and Chapter 2, several companies pursuing mass customization offer customization options via an assemble-to-order approach [14]. Though customization options appear to be the next step towards Davis' definition of mass customization, Chapter 3 showed that there is a gap in the literature for customization option assessment. This thesis aims to fill this gap by proposing a customization option assessment and selection approach that can be implemented during the early stages of product redesign. This chapter outlines the steps of this proposed approach.

4.2: Overview of Proposed Approach

The proposed approach for customization option assessment during the early stages of redesign consists of five steps. These steps and sub-steps are outlined in the below diagram:

1

- Identify potential subsystems for redesign based on average changes
  - Break product down into subsystems
  - Create subsystem dependency DSM
  - Create direct likelihood and impact DSMs
  - Calculate combined likelihood, impact, and risk DSMs
  - Determine potential subsystem(s)

2

- Develop conceptual-level customization options
  - Identify consumer suggestions for base product
  - Map consumer suggestions to one or more subsystems
  - Select consumer suggestions that are mapped to potential subsystem(s)
  - Develop conceptual-level customization options for selected suggestions
  - If desired, develop additional customization options

3

- Conduct change analysis for the options
  - Select customizaiton options for analysis
  - Map customization options to base product's subsystems
  - Determine direct likelihood and impact values for each option
  - Replace these values with the ones created in Step 1
  - Calculate combined likelihood, impact, and risk DSMs
  - Compute total redesign effort for the customization options

4

- Gather and evaluate consumer preferences for the options
  - Create discrete choice conjoint survey attributes and levels from the options
  - Determine discrete choice conjoint survey design, including any additional questions
  - Field discrete choice conjoint survey, gather data, & create consumer preference model
  - Evaluate current market scenario
  - Evaluate potential market scenarios from offering the customization options

5

- Consider tradeoffs between results from Steps 3 & 4

FIGURE 4.1: PROPOSED APPROACH

Prior to implementing the approach shown in the above figure, an existing product is selected with the intent of redesigning it in order to offer customization options. In Chapter 1, customization options were broadly defined as options that allow a consumer to modify his/her product's final design within constraints. For the proposed approach, this definition is further refined to reflect the current practice of companies pursuing mass customization with an assemble-to-order approach (see Chapter 2 for examples, such as Dell).

Customization options are defined as options that allow a consumer to modify his/her product's final design by invoking changes to the existing (or base) product offering, whether that be subsystem-level changes to the base product, emotion-focused system-level changes (such as color), or changes to the accessory items that are bundled with the base product. As an example, consider Dell's approach for allowing a consumer to customize their laptop purchase. After selecting their base product, a consumer can select his/her hard drive, amount of memory, etc. as well as laptop color for some models and any accessory items, such as a mouse and carrying case [45].

Step 1 - Identify potential subsystems for redesign based on average changes

For the proposed approach, the selected base product is assumed to be currently available on the market, and detailed drawings of this product are assumed to exist. Once a product is selected, the first step of the proposed approach uses an engineering change tool to explore change propagation within the product and identify potential subsystems for customization option development based on average changes. Ideal potential subsystems would be those subsystems that are easy to change and have a low risk for change propagation when changed. The identification of such subsystems can be used as a starting point during the redesign process because it is likely that one or more customization options can be offered due to the small amount of required redesign effort. Ideally, these potential subsystems would not only be easy to redesign, but also the redesigns would be attractive to consumers.

Step 2 - Develop conceptual-level customization options

After one or more potential subsystems are identified in Step 1, conceptual-level customization options are developed by considering changes that could be made to the potential subsystem(s). If consumer feedback data is available on the base product, or any other related marketing data is accessible, this information can be used to assist in conceiving ideas for customization options. Concept generation techniques such as brainstorming, brain-ball, the gallery method, or the 6-3-5 method can also be employed [78].

Ideally, all consumer feedback would map to one or more potential subsystems. However, it is likely that some feedback will map to non-potential subsystems. In these situations, the redesign team must decide whether to ignore the feedback or include non-potential subsystems in the analysis. Depending on the situation, either choice may be desirable. If budgets are tight and only potential subsystems can be changed, then it might be necessary to ignore such consumer feedback. However, if such rigid constraints do not exist, the feedback associated with non-potential subsystems can be considered so that possible profit will not be lost.

If marketing data does not exist, the redesign team must solely use concept generation techniques to develop customization options for the potential subsystem(s) in their pursuit of mass customization. Similar to the argument presented above, customization options for non-potential subsystems can be developed at the decision of the redesign team.

Before discussing the third step of this approach, it is prudent to discuss the level of detail necessary for developing customization options. The general rule of thumb is that more detail is better because the changes and their propagation can be more easily understood. However, a lot of detail may not be desired or available during the early stages of redesign. Yet, too little detail can render this approach meaningless.

Therefore, customization options are more actionable when they contain conceptual-level detail; designers and consumers should know, at a high level, how one or more subsystems change in relation to a characteristic of the subsystem.

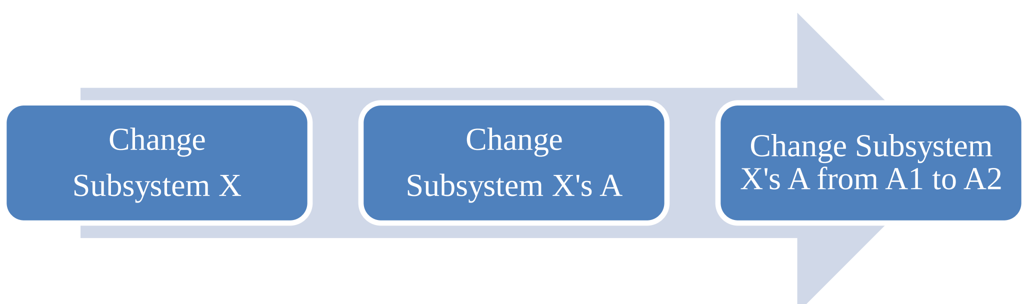


FIGURE 4.2: LEVEL OF CHANGE DETAIL

In Figure 4.2, X is the subsystem's name, A is a characteristic of Subsystem X, and A1 and A2 are values of the characteristic. Consider an automobile with the subsystem of interest being the entertainment system. The entries in Figure 4.2 could be 'Change the Entertainment System' → 'Change the Entertainment System's Musical Inputs' → 'Change the Entertainment System's Musical Inputs from Cassette Tape to CD.' With the last entry, designers and consumers would conceptually understand how the entertainment system changes even though the details of the change are not defined.

During the early stages of redesign, such information may not be available and may only become available as the redesign process enters the detailed design phase. Even without this information, the redesign team can estimate the redesign effort required to change the entertainment system's musical inputs from cassette tape to CD. Also, they can gather market desirability of such a change. Redesign effort and market desirability can be estimated because the change to the entertainment system is understood at a conceptual-level. Such estimates at the same level of reliability could not be made with the second entry of 'Change Entertainment System's Musical Inputs.' Of course, if more details of the change are available, then they can be included such that the estimates are even more reliable. The final level of detail before proceeding to Steps 3 and 4 is dependent upon the redesign team.

Step 3 - Conduct change analysis for the options

In Step 3, an engineering change tool is needed to evaluate the conceptual-level customization options developed in Step 2. This tool is used to predict the change and change propagation associated with the customization options. From this step, the redesign effort associated with offering one or more customization options can be predicted. With this information, Step 4 can be completed.

Step 4 - Gather and evaluate consumer preferences for the options

In Step 4 of the proposed approach, a marketing tool is needed to evaluate the conceptual-level customization options developed in Step 2. Specifically, the tool is used to gather consumer preference data on the customization options. By using the information from Step 3 to set prices for each customization option, the desirability of one or more customization options can be evaluated.

Step 5 - Consider tradeoffs between results from Steps 3 & 4

Finally, in Step 5, the tradeoffs between the results obtained from Steps 3 and 4 are considered before selecting customization options to pursue further in the redesign process. The premise for presenting a tradeoff analysis is that the redesign team should consider both the engineering and marketing domains since product redesign is a collaborative process between these two disciplines. Furthermore, insights can be gained from a tradeoff analysis that would be lost if not considered.

With the overview of the proposed approach complete, the remainder of this chapter delves into the specifics of the approach. First, the engineering change and marketing tool selections are presented. Then, the specifics of the approach are discussed.

4.3: Engineering Change Tool Selection

For Steps 1 and 3, one or more engineering change tools are required. Six selection requirements are developed and used to select the appropriate tool. These six selection requirements are listed below:

1. To simplify the proposed approach and ensure that change results obtained for Steps 1 and 3 can be compared, it is desired that the same engineering change tool is used for both steps.
2. To avoid developing a new engineering change tool, it is desirable to use an existing and proven tool that represents change and its propagation quantitatively.
3. This tool should be able to predict change propagation for conceptual-level changes since the customization options are defined at the conceptual level.
4. It is desired that the tool realistically represent change propagation by considering change propagation through direct and indirect connections and feedback loops.
5. The tool should be able to handle multiple changes since multiple customization options can be offered.
6. It is desired that the tool be easy to implement.

With these requirements, an engineering change tool is selected by examining the current engineering change literature (see Chapter 3). The Change Prediction Method (CPM) tool is selected for the proposed approach [139]. From Chapter 3, the CPM uses subsystems to predict change propagation. Since customization options can be associated with subsystems, the CPM should be valid to use for Steps 1 and 3. This assumption will be further explored in Sections 4.5.1 and 4.5.3, as well as through the case studies. Regarding the second selection requirement, the CPM is a proven tool that represents change and its propagation quantitatively; it has been used for aircraft and automobiles [116], [139], [141]. Also, the Change Prediction Method is deemed able to predict change propagation for conceptual-level changes since it was designed to predict change propagation for "average change experienced during a complete redesign process" [139]. Along similar lines, an argument can be made that the CPM is a good tool for predicting change propagation for conceptual-level changes since the quantitative data is given a probabilistic fashion.

In relation to the fourth requirement, the CPM was designed to account for change propagation through both direct and indirect connections, but it was not designed with feedback loops. Since the CPM has had success in predicting past changes, this deviation from the requirement will be neglected. With regard to the fifth selection requirement, some work has been done to allow the CPM to handle multiple changes from a likelihood point-of-view, but not from an impact perspective [142]. For this thesis, only one customization option is considered at a time due to this limitation of the CPM. Further information on this issue is presented in Section 4.5.3.1. Finally, to fulfill the last requirement, free software is available for academic use called the Cambridge Advanced Modeller (CAM) [146]. With this program and the CPM toolbox, the tool can be easily implemented to analyze a variety of change cases. The procedure for using this tool is described by Clarkson et al. [139] and is reviewed in Section 4.5.1.

4.4: Marketing Tool Selection

For Step 4, one or more marketing tools are required. Seven selection requirements are developed and used to select the appropriate tool. These seven selection requirements are listed below:

1. To simplify the proposed approach, it is desired that one marketing tool be used for Step 4.
2. To avoid developing a new marketing tool, it is desired that an existing and proven tool that quantitatively estimates consumer preferences be used.
3. Since customization options can be changes to subsystems of a product, the marketing tool should be able to estimate consumer preferences for parts of a product and the whole product.
4. The motivation behind this thesis is mass customization, which views consumers as individuals with varying preferences. Therefore, the marketing tool should estimate individual-level consumer preferences.
5. The marketing tool should be capable of realistically modeling consumer purchase scenarios.
6. Since market scenarios can change, the tool should be able to handle several different market scenarios.
7. It is desired that the tool be easy to implement.

With these selection requirements, a marketing tool is selected by examining the literature (see Chapter 3). Discrete choice conjoint analysis (DCA) with a hierarchical Bayes (HB) estimation is selected for the proposed approach. With this tool, Step 4 of the proposed approach can be completed; consumer preferences can be gathered and modeled. To address the second requirement, DCA has been successfully used in both academia and industry [10], [65], [70], [76], [147]–[151]. As discussed in Chapter 3, DCA allows heterogeneous part-worths to be estimated for product attributes. Concerning the fourth requirement, traditional conjoint analysis can be used to obtain individual preferences [65]. However, this type of conjoint analysis is not as realistic (the fifth requirement) as discrete choice conjoint analysis because it does not include a 'walk-away' option (recall Section 3.2.1). Therefore, DCA was chosen for its ability to represent realistic purchase scenarios, and it was coupled with HB estimation to obtain individual preference data.

With respect to the sixth requirement, DCA with HB estimation can analyze numerous market scenarios as long as the tested attributes and levels can represent the market scenarios. If a product enters the market with attributes different than those tested in the survey, then a new survey would have to be fielded. This downside was deemed acceptable because this thesis will not consider products with different attributes than those tested. Finally, to address the last requirement, commercial software, specifically Sawtooth Software's SSI Web and CBC/HB modules, is available to gather and model consumer preferences. The details for using this software package are described in Section 4.5.4.

4.5: Specifics of Proposed Approach Given Tool Selection

This subsection of Chapter 4 will refine the five steps introduced in Section 4.2 given the engineering and marketing tools selected in the previous section.

4.5.1: Step 1: Identify potential subsystems for redesign based on average changes

Given the choice of the Change Prediction Method as the engineering tool, the sub-steps associated with Step 1 are almost identical to those developed by Clarkson et al. [139]. The addition to this procedure comes in Step 1.5, where the exploration of change propagation leads to the identification of subsystems potentially well-suited for redesign. These sub-steps are summarized in the following diagram:

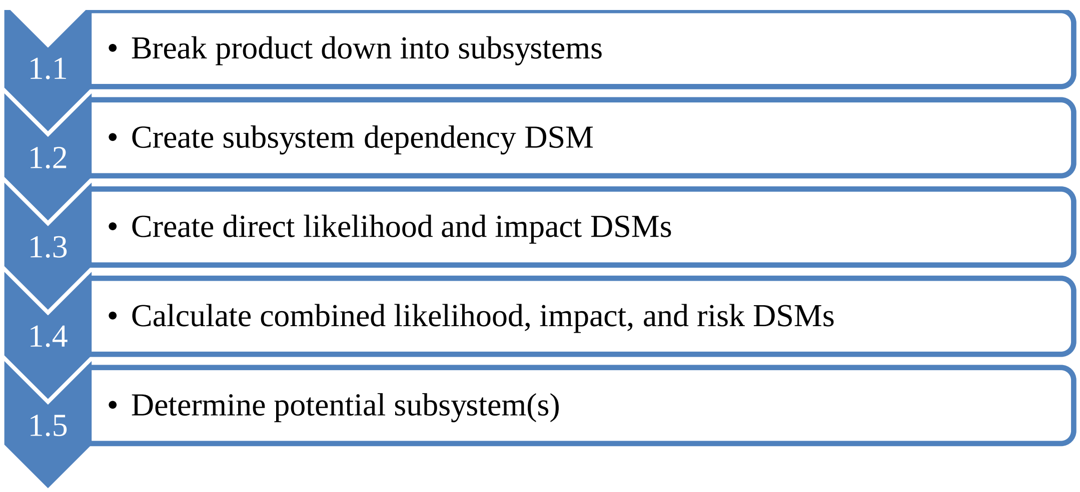


FIGURE 4.3: APPROACH STEP 1 SUB-STEPS

Step 1.1 - Break product down into subsystems

The first sub-step in Step 1 is to break the product down into subsystems based on some distinction, such as function, location, etc. Clarkson et al. recommends that a product is broken down into less than 50 subsystems [139].

Step 1.2 - Create subsystem dependency DSM

After the product is decomposed into subsystems, a subsystem dependency Design Structure Matrix (DSM) is created. In this DSM, the columns represent the initiating subsystems (or the subsystems that initiate change), and the rows represent the affected subsystems (or the subsystems whose design may be affected by changes from the initiating subsystems) [139]. An example of a subsystem dependency DSM is shown below:

TABLE 4.1: SUBSYSTEM DEPENDENCY DSM

		Initiating Subsystems								
		A	B	C	D	E	F	G	H	I
Affected Subsystems	A		X		X			X		
	B	X						X		
	C					X			X	X
	D	X				X		X		
	E			X	X			X	X	X
	F							X		X
	G	X			X	X	X			
	H			X		X				X
	I			X		X	X		X	

In Table 4.1, the X's represent direct change relationships between two subsystems. As an example, consider changing Subsystem A's design. From looking at the column associated with Subsystem A, Subsystem A has direct change relationships with Subsystems B, D, and G. Phrased another way, by changing Subsystem A's design, the designs of Subsystem's B, D, and G may change through change propagating across their interface(s) with Subsystem A. Notice that the diagonals are blacked out because an initiating subsystem obviously affects itself. Also, recognize that this DSM is non-symmetric, though for another product, it could be symmetric.

Step 1.3 - Create direct likelihood and impact DSMs

With the subsystem dependency matrix defined, the direct likelihood and direct impact DSMs are created by replacing the X's in Table 4.1 with numerical values. According to Clarkson et al., the likelihood represents "the average probability that a change in the design of one sub-system will lead to a design change in another by propagation across their common interface", while impact represents "the average proportion of the design work that will need to be redone if the change propagates" [139]. Overall, both DSMs represent the "average change experienced during a complete redesign process" [139]. In both matrices, the values are between 0 and 1, and the values can be determined from a group of engineering experts and/or historical change documentation. For the case studies presented in Chapter 5, a group of engineering graduate and undergraduate students in the Department of Mechanical and Aerospace Engineering at NC State are used to elicit these values, and the scales shown in Table 4.2 are used to help determine the appropriate values:

TABLE 4.2: DIRECT LIKELIHOOD & IMPACT SCALES

Scale		Likelihood	Impact
	1	100% chance change will propagate	100% of design work will be redone
High	0.9		
	0.8	80% chance change will propagate	80% of design work will be redone
	0.7		
Medium	0.6		
	0.5	50% chance change will propagate	50% of design work will be redone
	0.4		
Low	0.3		
	0.2	20% chance change will propagate	20% of design work will be redone
	0.1		
	0	0% chance change will propagate	0% of design work will be redone

Examples of direct likelihood and impact DSMs are shown below:

TABLE 4.3: DIRECT LIKELIHOOD DSM

		Initiating Subsystems								
		A	B	C	D	E	F	G	H	I
Affected Subsystems	A		0.3		0.4			0.2		
	B	0.4						0.3		
	C					0.2			0.8	0.6
	D	0.1				0.4		0.4		
	E			0.2	0.2			0.4	0.4	0.8
	F							0.6		0.8
	G	0.2			0.3	0.3	0.6			
	H			0.2		0.2				0.6
	I			0.4		0.5	0.8		0.6	

TABLE 4.4: DIRECT IMPACT DSM

		Initiating Subsystems								
		A	B	C	D	E	F	G	H	I
Affected Subsystems	A		0.2		0.3			0.3		
	B	0.3						0.2		
	C					0.2			0.8	0.5
	D	0.2				0.3		0.3		
	E			0.2	0.2			0.3	0.4	0.6
	F							0.5		0.6
	G	0.2			0.2	0.2	0.2			
	H			0.4		0.5				0.5
	I			0.6		0.7	0.6		0.6	

By examining Tables 4.3 and 4.4, it is clear that the direct likelihood and impact values are independent of each other. A high likelihood value does not necessarily mean a high impact value, and vice versa.

<u>Step 1.4 - Calculate combined likelihood, impact, and risk DSMs</u>

Upon completing the two matrices shown in Tables 4.3 and 4.4, the CAM software with the CPM toolbox is used to create the combined likelihood, combined impact, and combined risk matrices [146]. The software considers change propagating through both direct and indirect change relationships by using propagation trees to determine the combined likelihood and impact DSMs [139]. For example, consider changing Subsystem A and its affect on Subsystem G. The software considers the change propagating directly from Subsystem A to Subsystem G (notice the X in Table 4.1), and indirectly through Subsystem D (Subsystem A affects Subsystem D which affects Subsystem G). The software also determines the combined risk matrix, which is simply the combined likelihood matrix multiplied by the combined impact matrix [139]. To obtain these three matrices, the direct likelihood and direct impact matrices are input into the software and then the following settings are used [146]:

- Algorithm: Forward CPM
- Path Length: 6
- View as: Numeric (percentages)

All of these settings are default except for the 'View as' setting, which allows the combined likelihood, impact, and risk values to be obtained. The following figure shows the result of Step 1.4:

Combined Likelihood		Initiating Subsystems								
		A	B	C	D	E	F	G	H	I
Affected Subsystems	A		0.3	0.28	0.47	0.37	0.44	0.48	0.45	0.46
	B	0.44		0.24	0.29	0.32	0.39	0.43	0.39	0.4
	C	0.14	0.04		0.3	0.67	0.73	0.57	0.91	0.86
	D	0.21	0.06	0.38		0.55	0.59	0.62	0.6	0.63
	E	0.17	0.05	0.55	0.39		0.79	0.68	0.82	0.91
	F	0.16	0.05	0.49	0.34	0.64		0.7	0.75	0.86
	G	0.23	0.07	0.42	0.42	0.6	0.74		0.66	0.71
	H	0.12	0.04	0.48	0.27	0.57	0.64	0.5		0.73
	I	0.15	0.05	0.55	0.33	0.69	0.83	0.63	0.81	

Combined Impact		Initiating Subsystems								
		A	B	C	D	E	F	G	H	I
Affected Subsystems	A		0.2	0.38	0.32	0.35	0.37	0.34	0.4	0.37
	B	0.3		0.3	0.29	0.29	0.29	0.27	0.31	0.31
	C	0.76	0.72		0.76	0.72	0.76	0.76	0.81	0.74
	D	0.3	0.29	0.4		0.35	0.4	0.37	0.43	0.4
	E	0.52	0.51	0.57	0.43		0.63	0.54	0.65	0.65
	F	0.6	0.59	0.69	0.63	0.66		0.59	0.73	0.66
	G	0.21	0.21	0.29	0.23	0.26	0.27		0.32	0.28
	H	0.6	0.59	0.55	0.61	0.58	0.59	0.6		0.57
	I	0.71	0.7	0.68	0.73	0.75	0.65	0.7	0.74	

Combined Risk		Initiating Subsystems								
		A	B	C	D	E	F	G	H	I
Affected Subsystems	A		0.06	0.11	0.15	0.13	0.16	0.16	0.18	0.17
	B	0.13		0.07	0.08	0.09	0.11	0.12	0.12	0.12
	C	0.11	0.03		0.23	0.48	0.55	0.43	0.74	0.64
	D	0.06	0.02	0.15		0.19	0.24	0.23	0.26	0.25
	E	0.09	0.03	0.31	0.17		0.50	0.37	0.53	0.59
	F	0.10	0.03	0.34	0.21	0.42		0.41	0.55	0.57
	G	0.05	0.01	0.12	0.10	0.16	0.20		0.21	0.20
	H	0.07	0.02	0.26	0.16	0.33	0.38	0.30		0.42
	I	0.11	0.04	0.37	0.24	0.52	0.54	0.44	0.60	

FIGURE 4.4: COMBINED LIKELIHOOD, IMPACT, AND RISK DSMS

Step 1.5 - Determine potential subsystem(s)

Finally, the last sub-step in Step 1 of the proposed approach is to identify potential subsystems for redesign based on average changes. As mentioned in Section 4.2, potential subsystems are as those subsystems that are easy to change and have a low risk for change propagation when changed. To determine if a subsystem is easy to change, a measure of the average difficulty to change a subsystem, such as average rework cost, can be estimated from historical change data and/or engineering experts. Assume for the product shown in Table 4.1, the following average rework costs are estimated:

TABLE 4.5: SUBSYSTEM AVERAGE REWORK COST ESTIMATES

Subsystem	Average Rework Cost Estimate
A	$15
B	$5
C	$20
D	$10
E	$30
F	$25
G	$5
H	$20
I	$30

In Table 4.5, the average rework cost estimates for Subsystems A through I are shown. Assuming an arbitrary cutoff point of $10, Subsystems B, D, and G are good candidates for redesign based solely on average rework cost (their easiness to change). However, change propagation must also be considered when identifying potential subsystems.

To determine if a subsystem has a low risk for propagating changes to other subsystems, risk portfolio and case risk plots can be created. For the risk portfolio plot, each subsystem's combined outgoing risk is plotted on the X-axis, while each subsystem's combined incoming risk is plotted on the Y-axis [140]. For a subsystem, the combined outgoing risk is the average of the column values in the combined risk matrix, and the combined incoming risk is the average of the row values in the combined risk matrix. An un-scaled and scaled version of a risk portfolio plot is shown below:

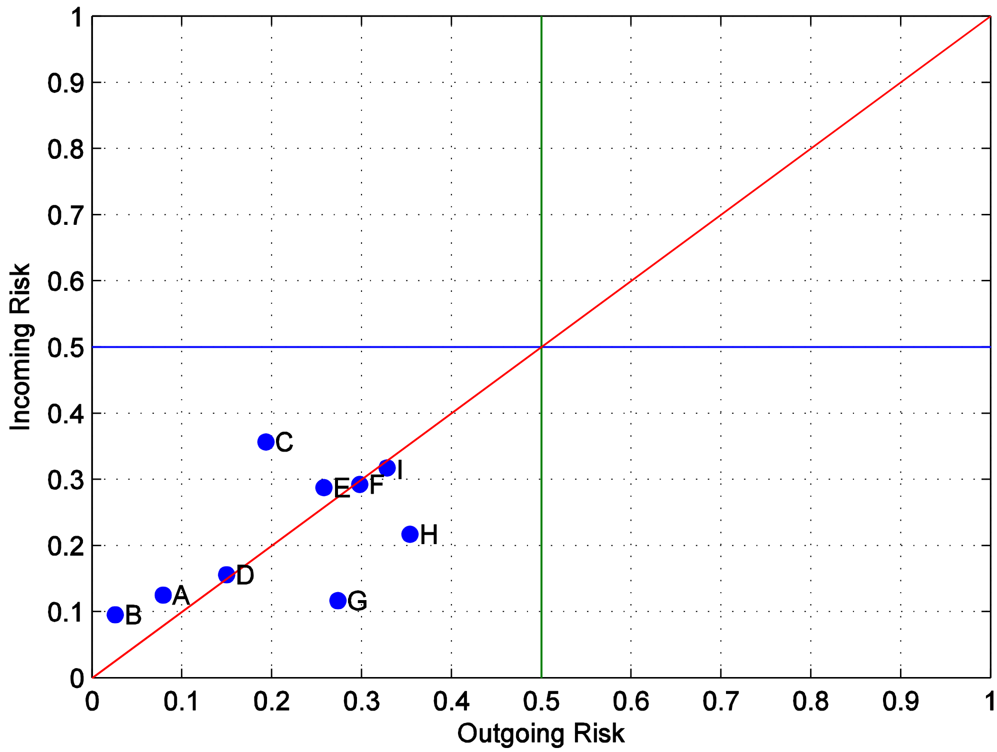


FIGURE 4.5: RISK PORTFOLIO - UN-SCALED

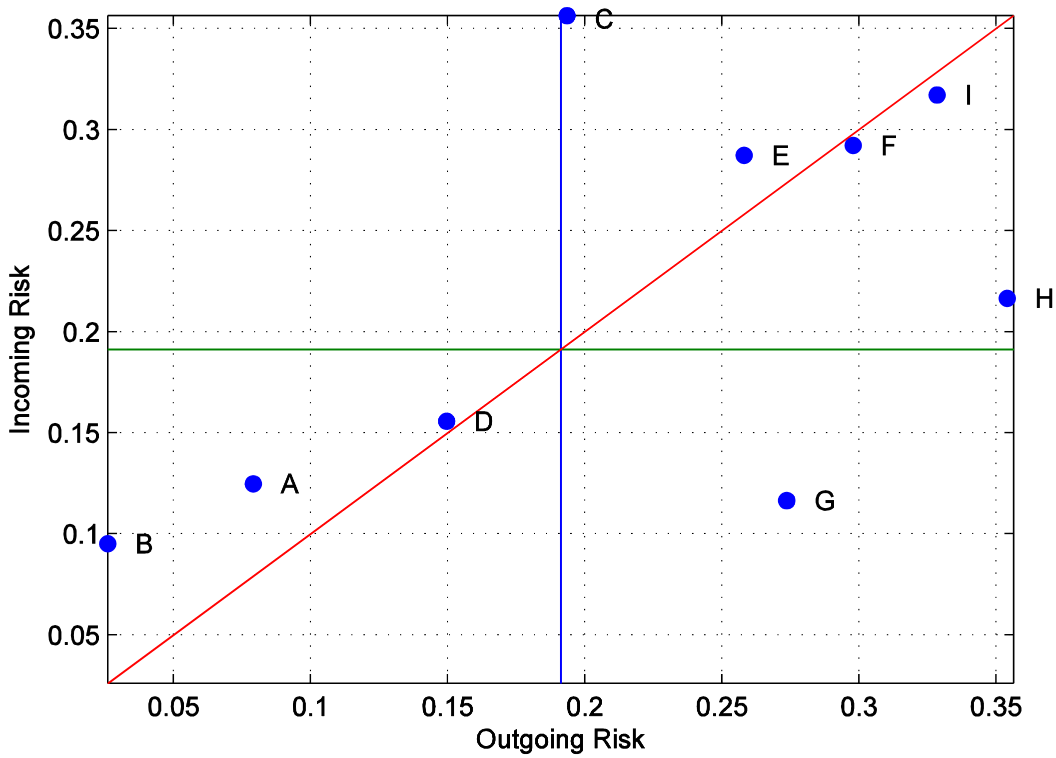


FIGURE 4.6: RISK PORTFOLIO - SCALED

In Figures 4.5 to 4.6, the bottom left quadrant contains subsystems with low incoming and outgoing risks, while the top right quadrant contains subsystems with high incoming and outgoing risks. The other two quadrants can be used to classify subsystems as change absorbers or change multipliers (recall Eckert et al.'s classification scheme, [127]). The top left quadrant represents change absorbers (subsystems that have more incoming risk than outgoing risk), while the bottom right quadrant represents change multipliers (subsystems that have less incoming risk than outgoing risk). The diagonal line represents change carriers, or subsystems that have the same amount of incoming risk as outgoing risk. Potential subsystems for redesign will exist towards the bottom left corner because they are low risk, while subsystems near the top right corner should be avoided due to their high risk nature.

In Figure 4.5, the un-scaled figure, it is clear that, on average, the product's subsystems do not exhibit high incoming or outgoing risk with respect to the absolute risk scale (between 0 and 1). Since this plot is not scaled based on the risk values of the product of interest, deceptive conclusions can be drawn. Based solely on this figure, the worrisome conclusion that all subsystems could be candidates for redesign (based solely on change propagation considerations) is made since they all exist in the bottom left quadrant. Therefore, a scaled version of Figure 4.5 is created and used to identify potential subsystems. For the case studies in Chapter 5, scaled versions of risk portfolio plots are only presented because of this worrisome conclusion.

Figure 4.6 is created by scaling Figure 4.5 with the minimum and maximum values of incoming/outgoing risk. Based on this new figure, Subsystems C and E-I are high risk subsystems and likely should not be selected as candidates for redesign. Subsystem G is a change multiplier, Subsystems F and I are high risk change carriers, and Subsystems C, E and H are high risk in general. In contrast to these subsystems, Subsystems A, B, and D can be considered low risk subsystems suitable as candidates for redesign based solely on change propagation.

In addition to exploring change propagation using risk portfolio plots, case risk plots can be analyzed to gain further insight and to identify potential subsystems for redesign. In contrast to the risk portfolio plots, case risk plots can be created for each subsystem [139]. These graphs plot the combined likelihood and impact values of affected subsystems given an initiating subsystem(s). Two case risk plots for the "average change experienced during a complete redesign process" [139] with initiating Subsystems (ISs) B (a low risk subsystem) and F (a high risk subsystem) are shown below as examples:

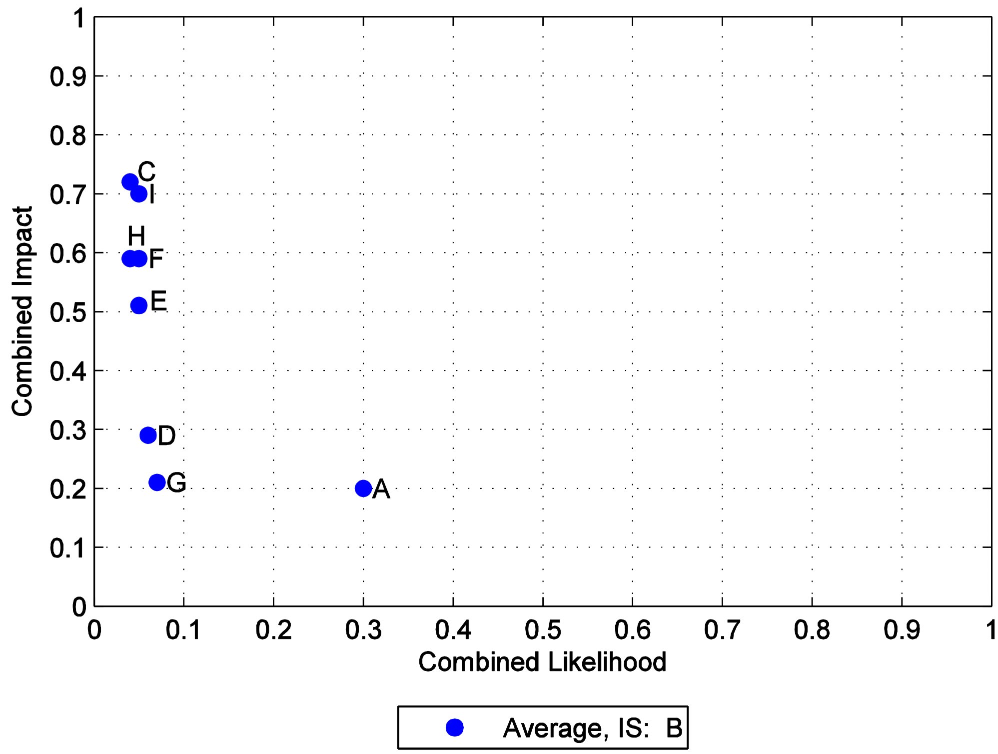


FIGURE 4.7: AVERAGE CASE RISK PLOT, IS=B

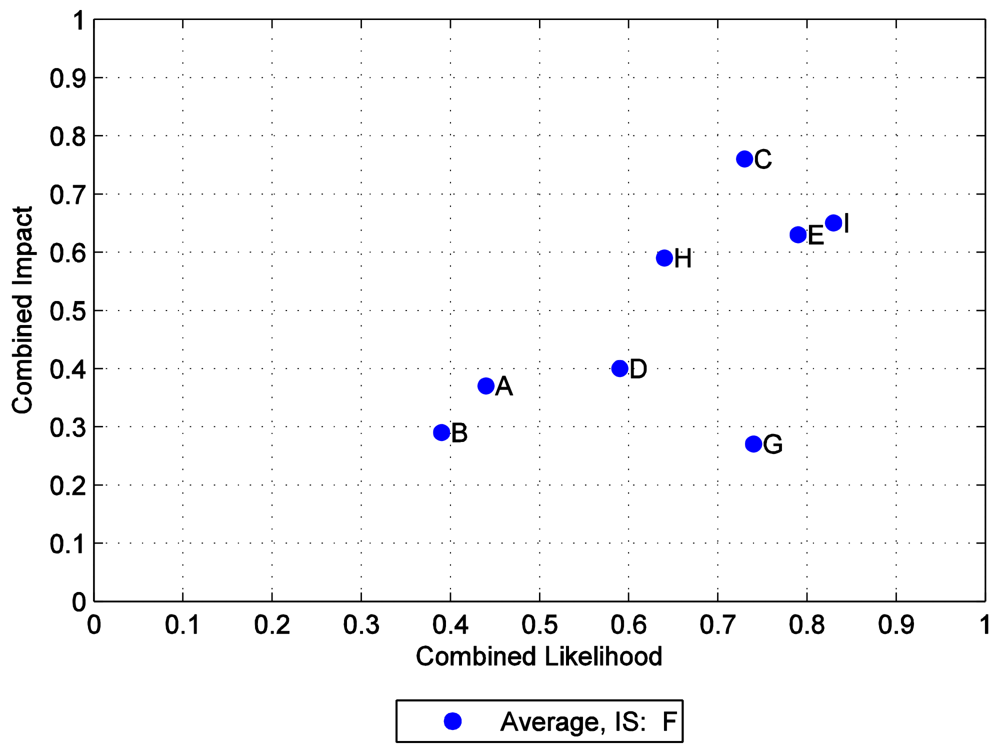


FIGURE 4.8: AVERAGE CASE RISK PLOT, IS=F

By examining Figures 4.7 and 4.8, the risk of changes from Subsystems B or F propagating to other subsystems can be observed. From observing the overall picture, the range of the combined impact values is very similar between the two subsystems, yet the range of the combined likelihood values is very different. For Subsystem B, all the combined likelihood values are less than 40%, while most of these values are greater than 50% for Subsystem F. Based on this observation and considering only change propagation for average changes, Subsystem B is a better candidate for redesign than Subsystem F because it is the less risky subsystem. Similar analysis can be done when comparing all the subsystems.

The case risk plots shown in Figures 4.7 and 4.8 can be combined into one plot by independently mapping the combined likelihood and impact values for each initiating subsystem to a 0→1 log scale [139]. Such a plot is shown below:

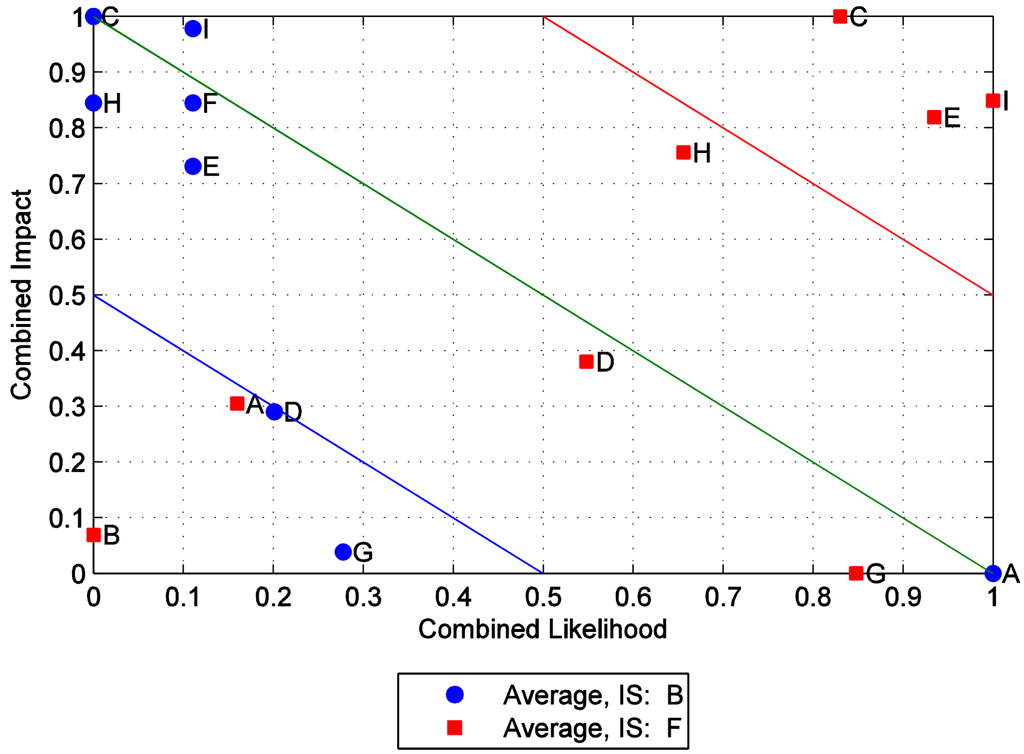


FIGURE 4.9: AVERAGE CASE RISK PLOT-SCALED, IS=B,F

In Figure 4.9, the diagonal lines indicate equal risk. By comparing the two initiating subsystems, it is clear that Subsystem F has more high risk components (upper right corner) than Subsystem B. Therefore, in terms of change propagation, Subsystem B should be chosen over Subsystem F as a potential subsystem because it has lower risk. Again, similar analysis can be done when comparing all the subsystems.

By considering both the easiness to change a subsystem and the risk of change propagation from changing a subsystem, potential subsystems for redesign can be obtained. From Table 4.5, Subsystems B, D, and G are identified as potential subsystems based on their easiness to change, while from Figure 4.6, Subsystems A, B, and D are identified as potential subsystems based on their low risk for change propagation. Through considering Table 4.5 and Figure 4.6, as well as assuming a very conservative redesign team, Subsystem B is considered a potential subsystem. This subsystem is used as the chosen subsystem for redesign for the remainder of this approach.

4.5.2: Step 2: Develop conceptual-level customization options

In this step of the proposed approach, conceptual-level customization options are developed. The sub-steps for Step 2 are shown below:

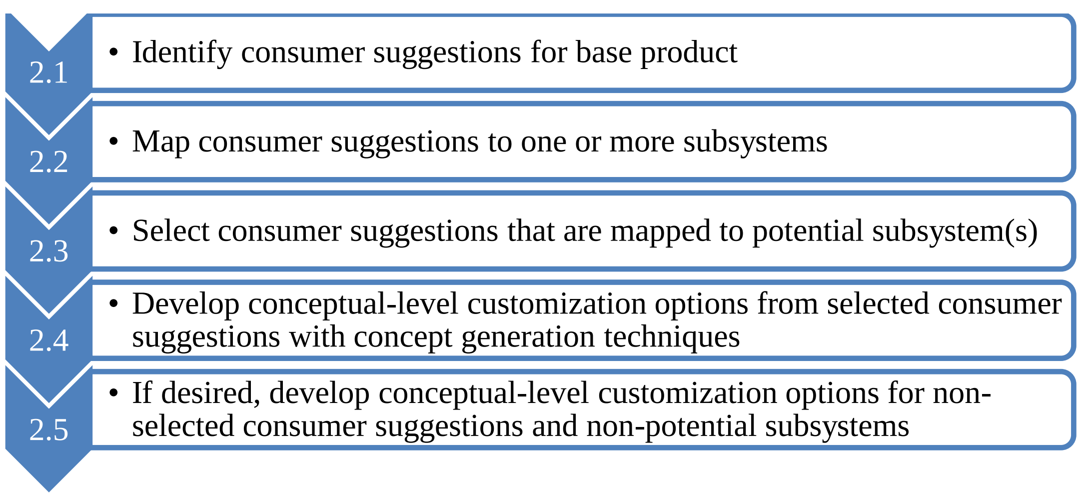


FIGURE 4.10: APPROACH STEP 2 SUB-STEPS

Step 2.1 - Identify consumer suggestions for the base product

The first sub-step of Step 2 is to identify consumer suggestions for the base product from gathered consumer feedback. Since the base product has been on the market, it is assumed that some data has been collected about consumers' acceptance of the base product and any suggestions for improvement on the base product's design.

Step 2.2 - Map consumer suggestions to one or more subsystems

With consumer suggestions identified, the relevant suggestions are mapped to the base product's subsystems. A relevant suggestion is one in which the design of one or more subsystems needs to be changed in order to satisfy the suggestion. The mapping done in Step 2.2 should identify which subsystems require change. An example mapping is shown below:

TABLE 4.6: CONSUMER SUGGESTIONS TO SUBSYSTEMS MAPPING

		Subsystems								
		A	B	C	D	E	F	G	H	I
Consumer Suggestions	Suggestion 1		X							
	Suggestion 2		X							
	Suggestion 3	X	X		X	X	X	X		X
	Suggestion 4						X			

In Table 4.6, the X's identify which subsystems require change for each consumer suggestion. It should be noted that the X's should only identify direct changes caused by a consumer suggestion. For example, Suggestion 3 requires Subsystems A, B, D-G, and I to be directly changed. It does not, for instance, require Subsystem A to change, which then requires the other subsystems to change.

Before moving onto Step 2.3, it is noted that consumer suggestions that do not require changing one or more subsystems do not have to be ignored, but they can be considered in Step 2.5.

Step 2.3 - Select consumer suggestions that are mapped to potential subsystem(s)

For Step 2.3, the consumer suggestions mapped to the potential subsystem(s) are selected for initial customization option development. As shown by the highlighted cells in Table 4.6, Suggestions 1 and 2 would be selected because they are mapped to Subsystem B, which was identified in Step 1.5. The reasoning behind this selection criterion is that suggestions mapped to potential subsystems are likely to cost less to satisfy because the potential subsystem(s) should be easy to change and have a low risk for change propagation. Ideally, such suggestions enable the firm to gain a marketing advantage from developing and offering customization options based on them. This tradeoff between market desirability and engineering effort is a major part of the proposed approach and is considered in Step 5. However, for Step 2.3, the goal is to just consider those suggestions mapped to the potential subsystem(s).

Prior to moving to Step 2.4, it is prudent to discuss the two scenarios that exist when a suggestion is mapped to multiple subsystems. If a consumer suggestion is mapped only to potential subsystems, then this suggestion should be selected. However, if a consumer suggestion is mapped to multiple subsystems, and only a fraction of those are potential subsystems, then this consumer suggestion should not be selected. With consumer suggestions selected for initial customization option development, Step 2.4 is begun.

Step 2.4 - Develop conceptual-level customization options from selected suggestion(s)

The next step in Step 2 is to develop conceptual-level customization options from the selected consumer suggestions. In developing these customization options, concept generation tools can be used, and the discussion associated with Figure 4.2 in Section 4.2 should be remembered. At the end of Step 2.4, the selected consumer suggestions from Step 2.3 should be transformed into one or more customization options at the level of change detail illustrated by the third entry in Figure 4.2. Assume Options 1 and 2 are developed for potential Subsystem B.

Step 2.5 - If desired, develop additional customization options

After Step 2.4 is complete, the last sub-step can be done to complete Step 2. This sub-step is not required to move onto Step 3, but it can be completed if the redesign team wishes to consider a larger set of customization options. In this sub-step, any consumer suggestions not mapped in Step 2.2 or not chosen in Step 2.3 can be used to develop customization options. For the consumer suggestions not mapped in Step 2.2, these suggestions would be related to emotional system-level changes and changes to accessory items (base on the definition of customization options given in Section 4.2).

Additionally, the redesign team can use concept generation techniques to develop customization options for non-potential subsystems. The three types of customization identified by Ferguson et al. in their definition of mass customization can be used along with concept generation techniques to develop customization options ([10]; see Section 1.2.3). Recall, the three types of customization are functional (or performance), anthropological (fit and comfort), and emotional (style) [10]. Similar to Step 2.4, all customization options developed in Step 2.5 must exist at the level of change detail present in the third entry of Figure 4.2. Assume Options 3 and 4 are developed for non-potential Subsystem F. With Step 2.5 completed, Step 3 is begun.

4.5.3: Step 3: Conduct change analysis for the options

The purpose of Step 3 is to analyze the change required to the base product in order to offer customization options related to subsystem-level changes. The sub-steps of this step are shown below:

- 3.1 • Select customization options for change analysis
- 3.2 • Map customization options to base product's subsystems
- 3.3 • Determine direct likelihood and impact values for the customization options
- 3.4 • Replace direct likelihood and impact values created in Step 1 with these new values
- 3.5 • Calculate the combined likelihood, impact, and risk DSMs
- 3.6 • Compute total redesign effort for the customization options

FIGURE 4.11: APPROACH STEP 3 SUB-STEPS

Step 3.1 - Select customization options for analysis

The first sub-step shown in Figure 4.11 is to select the customization options for change analysis. Customization options related to potential subsystem(s) should be selected because they are likely to be low risk changes. However, other customization options may also be selected for change analysis to (1) broaden the scope of options considered by the redesign team, (2) consider options that may be require little engineering effort even though they are not mapped to a potential subsystem and (3) ponder options that may be more desirable to consumers than the options mapped to the potential subsystem(s).

Concerning customization options that are mapped to multiple subsystems, this thesis only considers one customization option with a 1-to-1 mapping to a subsystem of the base product at a time. Therefore, if multiple customization options with 1-to-1 mappings are selected, each option is analyzed independently.

From an engineering perspective, only one customization option that is mapped to one subsystem is considered because more research is required in engineering change prediction for multiple subsystem changes. A brief discussion concerning this fact is given below.

4.5.3.1: ***A Note about Change Prediction for Multiple Changes***

Customization options can cause multiple subsystems to change in three ways. First, several customization options are offered that affect one subsystem each. Second, a customization option is offered that affects multiple subsystems. Finally, several customization options are offered that affect multiple subsystems. To predict change propagation for such scenarios with the CPM, likelihood and impact values must be considered for all initiating subsystems. As mentioned in Section 3.4.2, some research has been conducted to allow the CPM to accommodate multiple initiating subsystems. This modification is discussed in more detail below.

A modification to the Change Prediction Method has been suggested by Ahmad et al. that allows the method to accommodate multiple initiating subsystems from a likelihood perspective [142]. The modification follows the same procedure outlined by Clarkson et al. [139] to obtain the combined likelihood DSM and then uses the following equation to merge the combined likelihood values for two initiating Subsystems X and Y:

$$\boldsymbol{f(x,y) = min\left(1, \sqrt{x^2 + y^2}\right)} \qquad \textbf{(4.1)}$$

In Equation 4.1, $\boldsymbol{x}$ is the combined likelihood value for Subsystem X in a row, and $\boldsymbol{y}$ is the combined likelihood value for Subsystem Y in the same row. This equation is applied to every row in the combined likelihood DSM, and a new column containing the resultant values is added to the combined likelihood DSM. If there are three initiating subsystems (X, Y, and Z), then Equation 4.1 is first applied to Subsystems X and Y. Then, the results become the $\boldsymbol{x}$ or $\boldsymbol{y}$ values, and the remaining variable is used for the combined likelihood values of Subsystem Z. A similar approach is followed for more than three initiating subsystems. Figure 4.12 below, taken from Koh et al. [143], is presented to clarify this modification for an option (O5) that requires changes to two subsystems (C1 and C2) [143]:

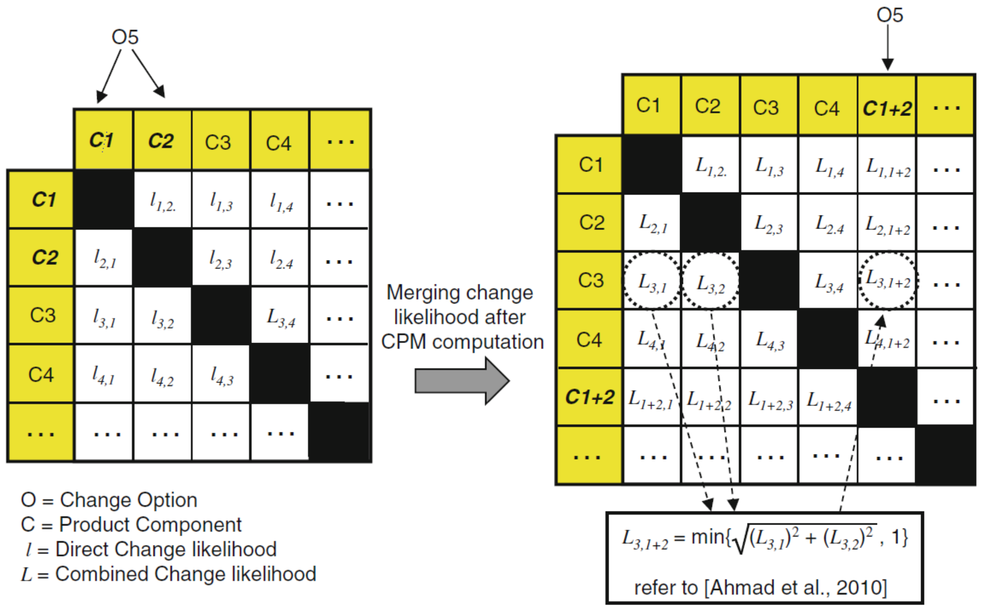


FIGURE 4.12: CPM MODIFICATION FOR MULTIPLE CHANGES

Though Equation 4.1 was suggested, more research is needed to fully consider multiple changes from several subsystems. Two specific areas of future research are identified. First, though Equation 4.1 was used by Ahmad et al. [142] and Koh et al. [143], more research is needed to validate its accuracy in predicting multiple changes. Change prediction of previous, documented changes could be used to validate this equation. Second, a similar equation is needed for combined impact in order to obtain combined risk values for multiple changes. Once an equation for this method is developed, its accuracy should be validated in a way similar to that for combined likelihood. As a result of these research needs, this thesis will not consider customization option offerings that cause multiple initiating subsystems. However, if the Equation 4.1 is validated and a similar equation for impact is developed and validated, the proposed approach will be able to handle multiple changes, especially for customization options that affect one subsystem each but are being offered at the same time. However, an engineering team may have difficulty in Step 3.3 if a single customization option affects multiple subsystems because it may be difficult to understand how each subsystem changes.

Step 3.2 - Map customization options to base product's subsystems

After the customization options are selected, they are mapped to the base product's subsystems in a fashion similar to that used in Step 2.2. The subsystem that requires changing from offering a customization option is identified. In other words, the initiating subsystem for a customization option is identified in this sub-step. An example mapping is shown below:

TABLE 4.7: CUSTOMIZATIONS OPTION TO SUBSYSTEMS MAPPING

		Subsystems								
		A	B	C	D	E	F	G	H	I
Options	Option 1		X							
	Option 2		X							
	Option 3						X			
	Option 4						X			

As shown in Table 4.7, each customization option is mapped with one subsystem. With this mapping complete, Step 3.3 is begun to analyze the change propagation for the selected customization options.

Step 3.3 - Determine direct likelihood and impact values for the options

For each customization option, new direct likelihood and impact DSM values are determined. The first step in determining these values is to use the column of the subsystem dependency DSM (see Table 4.1) for the subsystem identified in Step 3.2. For example, if Option 1 from Table 4.7 is considered, then the column associated with Subsystem B is selected. The selected column identifies most of the change relationships for which direct likelihood and impact values are needed. However, depending on the customization option considered, change relationships may need to be removed or added. In Step 1, average changes during a typical redesign process were considered, and thus change relationships present during such a process were identified. When more specific changes are considered, change relationships may need to be removed or added.

Once all the change relationships are identified for the initiating subsystem, direct likelihood and impact values are determined the same way as in Step 1. As a reminder, these values can be obtained from historical change data and/or engineering experts. As was the case with Step 1, a group of engineering students is used in this thesis along with the scales presented in Table 4.2 to obtain this data.

In determining these values, the more concrete nature of the change caused by the customization option (in comparison with average changes considered in Step 1) should help experts determine accurate direct likelihood and impact values. To further assist in determining accurate values, customization options that affect the same subsystem can be compared. Consider determining the direct likelihood values for Options 1 and 2 that affect Subsystem B:

TABLE 4.8: COMPARE ACROSS CUSTOMIZATION OPTIONS

Direct Likelihood	Options	1	2
	Initiating Subsystem	B	B
Affected Subsystems	A	0.2	0.4
	B		
	C		
	D		
	E		
	F		
	G		
	H		
	I		

In Table 4.8, the direct likelihood values for affected Subsystem A due to Options 1 and 2 are determined by comparing the affect of these options on Subsystem A. Option 2 has a higher likelihood of affecting Subsystem A than Option 1, and the values reflect this trend. The same technique is suggested for determining the direct impact values.

In addition to comparing customization options to help determine accurate direct likelihood and impact values, the relationship between values of affected subsystems can be compared. Consider determining the direct likelihood values for Options 3 and 4 that affect Subsystem F:

TABLE 4.9: COMPARE DOWN AFFECTED SUBSYSTEMS

Direct Likelihood	Options	3	4
	Initiating Subsystem	F	F
Affected Subsystems	A		
	B		
	C		
	D		
	E		
	F		
	G	0.5	0.2
	H		
	I	0.5	0.2

Assume that the redesign team following this proposed approach considers the direct likelihood that Option 3 would propagate change to Subsystem G to be the same as the direct likelihood that Option 3 would propagate change to Subsystem I. They draw the same conclusion about Option 4, but, using the technique illustrated in Table 4.8, they deem Option 3 to have a greater likelihood for change propagation. As shown in Table 4.9, the redesign team would fill in the same direct likelihood values for Subsystems G and I for each option, with the likelihood values larger for Option 3. This same technique of comparing values of affected subsystems for an option is suggested for determining the direct impact values. Once the direct likelihood and impact values for all the selected customization options are determined, the next sub-step of Step 3 is begun.

Step 3.4 - Replace these values with the ones created in Step 1

For Step 3.4, the new direct likelihood and impact values are input into the direct likelihood and impact DSMs from Step 1.3. As stated in Step 3.1, each customization option is analyzed independently, so only one column from each DSM is replaced (recall only customization options that have one initiating subsystem are considered in this thesis). This step is illustrated in Figure 4.13 below with Option 3 and the direct likelihood DSM:

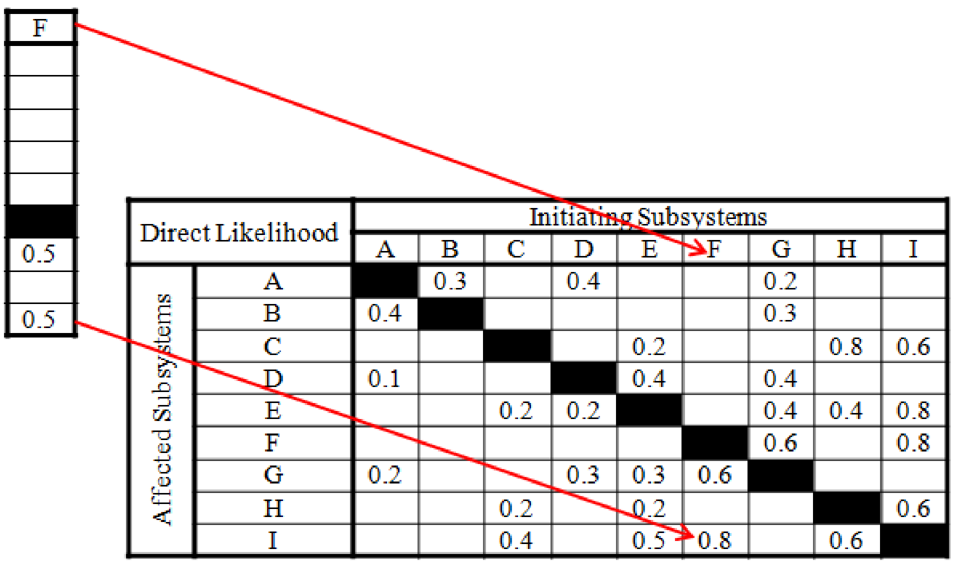


FIGURE 4.13: REPLACE AVERAGE VALUES WITH SPECIFIC VALUES

The justification regarding the value replacement shown in Figure 4.13 is discussed below. When a subsystem-level change is induced by a customization option at the level of detail shown in the third entry of Figure 4.2, the direct likelihood and impact values can be updated from the average values used in Step 1. These values can be updated because the subsystem-level change has transformed from the abstract level of average change to a more concrete level of change associated with a specific customization option. Though the direct likelihood and impact values associated with the initiating subsystem can be updated, the values associated with the remaining subsystems cannot be updated because more detailed change information for these subsystems is not known. Therefore, the initiating subsystem should be the only column updated in the direct likelihood and impact DSMs. Further proof of this sub-step will be evaluated in the case studies.

Step 3.5 - Calculate the combined likelihood, impact, and risk DSMs

After new direct likelihood and impact DSMs are constructed, the combined likelihood, impact, and risk DSMs are calculated using the same approach and CAM software settings outlined in Step 1.4. Case risk plots, similar to the ones shown in Step 1.5, can be created for each analyzed customization option. The case risk plots for the options shown in Table 4.7 are shown below:

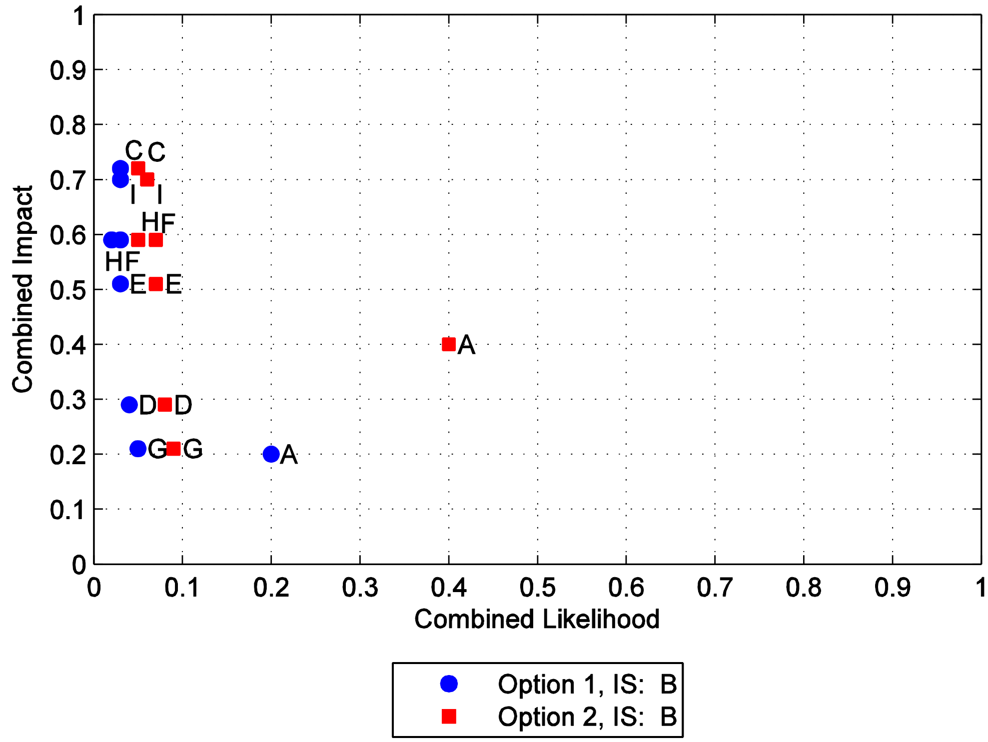


FIGURE 4.14: NEW CASE RISK PLOT, IS=B

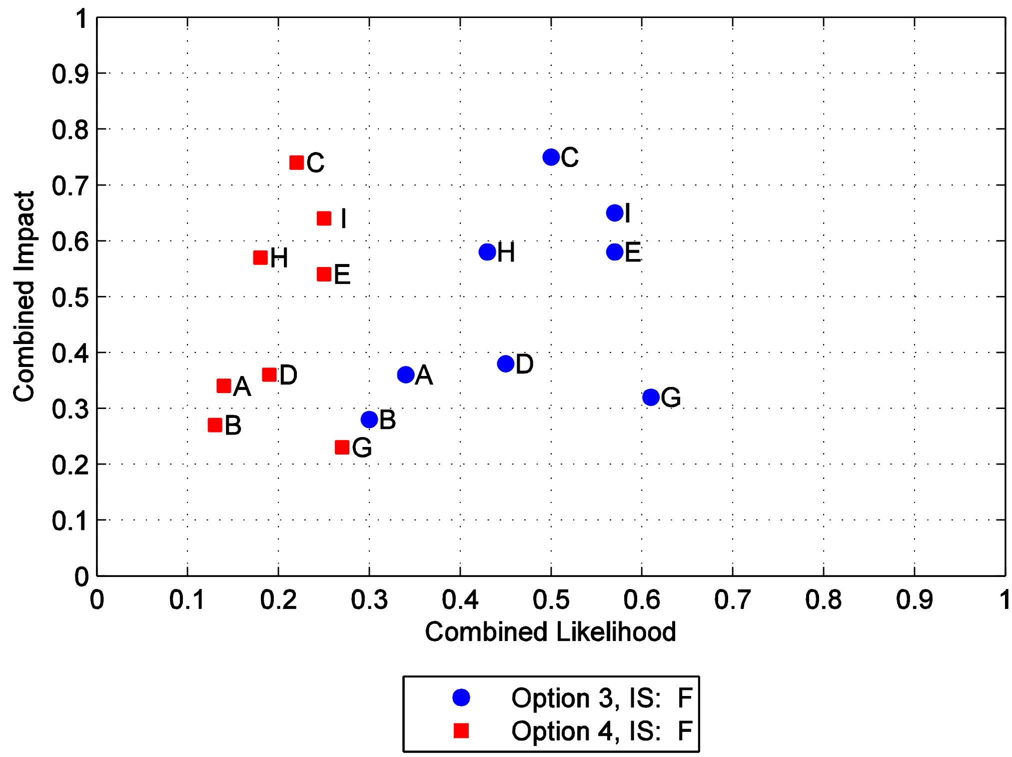


FIGURE 4.15: NEW CASE RISK PLOT, IS=F

By examining Figures 4.14 and 4.15, the trends used to create the direct likelihood values shown in Tables 4.8 and 4.9 are seen, as expected. For Subsystem B, there is a higher risk of change propagating to Subsystem A with Option 2 than with Option 1. For Subsystem F, Subsystem G is more likely to experience change than Subsystem I for both customization options, and there is a higher risk of change propagating to these subsystems with the Option 3. With risk values calculated for each customization option selected in Step 3.1, the last sub-step of Step 3 is begun.

Step 3.6 - Compute total redesign effort for the customization options

The last sub-step of Step 3 is to compute a value representing the total redesign effort associated with the customization option. To calculate the total redesign effort for a customization option, the type of customization option must be considered. The redesign effort formulation will change based on whether the customization option is initiated by a subsystem-level change, an emotional system-level change, or a change relating to accessory items.

For customization options that are initiated by changing an existing subsystem, this value should include the redesign effort associated with (1) changing the initiating subsystem and (2) the risks of change propagating to other subsystems. If cost information is available, then a total cost for redesign can be calculated. Using the cost framework introduced by Keller et al. [141] as a basis, the following formula is proposed:

$$\boldsymbol{ETC_{k,i}} = \sum_{j=1}^{N} \boldsymbol{fix_j} + \boldsymbol{rework_{k,i}} + \sum_{\substack{j=1 \\ j \neq i}}^{N} \boldsymbol{rework_j}\left(\boldsymbol{E_{k,i\rightarrow j}}\right)\left(\boldsymbol{r_k}(\boldsymbol{i} \rightarrow \boldsymbol{j})\right) \qquad (\mathbf{4.2})$$

In Equation 4.2, $\boldsymbol{ETC_{k,i}}$ is the estimated total cost to produce the product with customization option k initiated by changing subsystem i, $\boldsymbol{fix_j}$ is the total cost for subsystem j of the base product, $\boldsymbol{rework_{k,i}}$ is the estimated cost to change subsystem i in order to offer customization option k, $\boldsymbol{rework_j}$ is the estimated average cost to change subsystem j, $\boldsymbol{E_{k,i\rightarrow j}}$ is the expected number of changes initiated by subsystem i on subsystem j for customization option k, $\boldsymbol{r_k(i \rightarrow j)}$ is the risk of initiating subsystem i affecting subsystem j for customization option k, and $\boldsymbol{N}$ is the total number of subsystems. The term $\boldsymbol{fix_j}$ includes all design, material, and manufacturing costs associated with subsystem j of the base product, and the terms $\boldsymbol{rework_{k,i}}$ and $\boldsymbol{rework_j}$ capture any changes to these costs as a result of offering customization option k. Notice that the total cost of the base product can be obtained by making $\boldsymbol{rework_{k,i}}$, $\boldsymbol{rework_j}$, and $\boldsymbol{E_{k,i \rightarrow j}}$ zero.

The rework cost for initiating subsystem i, $\boldsymbol{rework_{k,i}}$, can be estimated by considering the specific change made to subsystem i for customization option k, and by using historical change data and/or engineering experts. The average rework cost for the affected subsystems from Step 1.5, $\boldsymbol{rework_j}$, is used because it is not known how the affected subsystems will change at this point in the redesign process. As already stated in Step 1.5, this average rework cost can be estimated using historical data and/or engineering experts. The expected number of changes, $\boldsymbol{E_{k,i \rightarrow j}}$, can also be estimated in this manner. For this thesis, all the terms, except for $\boldsymbol{r_k(i \rightarrow j)}$, will be subjectively estimated since historical change and cost data are unavailable for the case study products.

For customization options related to emotional system-level changes, the total redesign effort is estimated by considering the changes to the manufacturing processes. Similar to subsystem-level changes, cost information can be used, if available, to estimate this effort. In particular, additional manufacturing costs due to purchasing new machinery, increasing the workforce, production process complexity, switching out materials in machines (such as the type of dye for color customization options), etc. can be aggregated to obtain the total redesign effort for emotional system-level changes. In this thesis, redesign costs for emotional system-level customization options are subjectively estimated since industry cost data is unavailable.

For customization options related to accessory item changes, the total redesign effort is estimated by considering design, fixed (material procurement and manufacturing), and rework costs. If the customization option offers a new accessory item that is not previously available, then design and fixed costs must be estimated. If the customization option changes an existing accessory item via a subsystem-level change, then a formula similar to Equation 4.2 can be used after a change propagation analysis is performed. Finally, if the customization option changes an existing accessory item via an emotional system-level change, then additional manufacturing costs must be estimated. In this thesis, the redesign costs for such changes are estimated subjectively since industry cost data is unavailable.

An example redesign cost is given below for Options 1 through 4 presented in Table 4.7:

TABLE 4.10: REDESIGN COST ESTIMATES

Customization Option	$\boldsymbol{TRC_i}$
Option 1	\$14.00
Option 2	\$14.50
Option 3	\$16.00
Option 4	\$15.50

From Table 4.10, the total redesign cost for each customization option is obtained. Based solely on engineering change, the best option is Option 1 at \$14.00. With the redesign costs estimated, Step 4 is begun to determine the market desirability of each customization option.

4.5.4: Step 4: Gather and evaluate consumer preferences for the options

With Step 3 complete, Step 4 in the proposed approach is begun. The sub-steps of this step are outlined below:

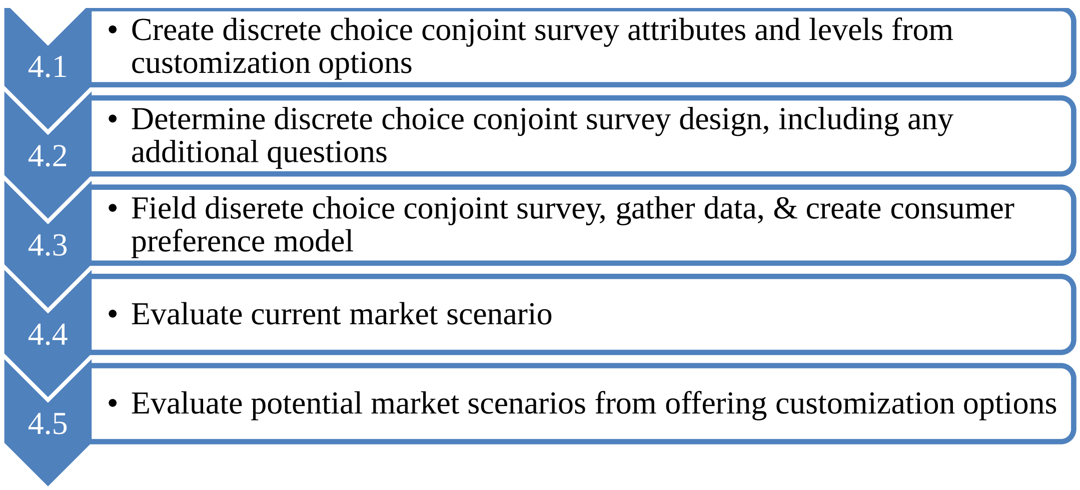


FIGURE 4.16: APPROACH STEP 4 SUB-STEPS

Step 4.1 - Create discrete choice conjoint survey attributes and levels from options

The first sub-step of Step 3 is to create the discrete choice conjoint survey attributes and levels based on the customization options developed in Step 2. To complete this subs-step, similar customization options are grouped together such that the attributes represent broad changes to one or more subsystems, and the levels are the customization options developed in Step 2. Additionally, to be able to complete Step 4.4, levels that reflect the base product are added to each attribute. Moreover, to capture price information from respondents, a price attribute and levels are created. For this attribute, the levels should reflect the expected range of prices resulting from offering customization options. The redesign costs estimated from Step 3.6 can be used along with any marketing data to estimate these price ranges. Finally, the following recommendations from Sawtooth Software's SSI Web module are considered concerning attribute and level creation [69]:

- Attributes should be independent.
- Number of attributes cannot be greater than 10 (due to license restrictions).
- Number of attributes should be kept small (around 6) to avoid respondents focusing on just a few attributes.
- Levels should be mutually exclusive.
- Levels should clearly convey information to respondents. If words cannot convey information without unintended ambiguity, then graphics should be used. For example, for a level in a color attribute, instead of stating red, show the color.
- Number of levels cannot be greater than 15 (due to license restrictions).
- Number of levels across all attributes should be similar to avoid Number-of-Levels Effect, where attributes with more levels get a greater importance.
- Prohibitions, or restrictions between attribute levels, should be avoided.

An example discrete choice conjoint survey with attributes and levels is shown in Table 4.11. Here, there are two attributes comprised of three levels each. Also, the price attribute is shown with three levels.

TABLE 4.11: DISCRETE CHOICE CONJOINT SURVEY ATTRIBUTES & LEVELS

		Attributes		
		Attribute 1	Attribute 2	Price ($)
Levels	1	Option 1	Base	10
	2	Option 2	Option 3	30
	3	Base	Option 4	50

Step 4.2 - Determine discrete choice conjoint survey design, including additional questions

After the attributes and levels are defined, the design of the survey, including any questions not used for modeling consumer preferences, is done to complete Step 4.2. Before or after the task questions (see Section 3.2), questions relating to demographics or the base product can be asked. The Sawtooth license allows 10 questions to be asked. The redesign team must decide whether to ask these questions or not. Concerning the design of the task questions, the following considerations should be given:

- Number of product profiles per task
- Creation of product profiles
- Inclusion of the None option, and if so, which None option (traditional vs. Dual Response)

- Inclusion of holdout tasks
- Total number of tasks

With regard to these considerations, Sawtooth Software's SSI Web manual recommends the following [69]:

- 3 to 5 product profiles per task
- Balanced Overlap over Random Enumeration or Complete Enumeration
- Include either type of None option, though some researchers argue Dual-Response is better (see Section 3.2.1)
- Include holdout tasks as a way to check model validity
- Reliable data can be obtained from respondents for at least 20 tasks

Step 4.3 - Field discrete choice conjoint survey, gather data, & create preference model

From these considerations, a discrete choice conjoint survey can be created, uploaded onto a web server, and used to gather respondent data. The data is downloaded from the web server after enough responses have been obtained. In terms of the number of respondents required to obtain an accurate preference model, the following formula has been suggested [65]:

$$\boldsymbol{n} \geq \frac{\mathbf{500}\boldsymbol{c}}{\boldsymbol{ta}} \tag{4.3}$$

In Equation 4.3, $\boldsymbol{n}$ is the number of respondents required to give an accurate consumer preference model, $\boldsymbol{c}$ is the largest number of levels in an attribute, $\boldsymbol{t}$ is the total number of tasks, and $\boldsymbol{a}$ is the number of product profiles per task.

Once enough responses are obtained, a consumer preference model can be created to complete Step 4.3. For this thesis, a hierarchical Bayes model is used (see Section 3.2.2.1) to model consumer preferences, and Sawtooth Software's CBC/HB module is used to create it. After respondent data is gathered and the .dat file is downloaded, the .dat file is opened in SSI Web, and a .cho file is created to import into CBC/HB. With the file loaded into CBC/HB, the model fit settings are chosen, and the program is run to obtain individual-level part-worths in a .csv format. An example .csv file is shown in Table 4.12:

TABLE 4.12: RESPONDENT PART-WORTH DATA

	Attribute 2		
Respondent #	**Base**	**Option 3**	**Option 4**
1	-1.26	2.03	-0.77
2	3.62	-4.93	1.31

Recall from Section 3.2.2.2 that Sawtooth uses zero-centered difference, and part-worths for an attribute sum to zero. Notice that this characteristic is true for the values presented in Table 4.12.

Step 4.4 - Evaluate current market scenario

Once individual part-worth data is obtained for the tested levels, the current market scenario can be evaluated. Market scenarios can be evaluated in terms of aggregate contribution margin (a surrogate for profit), revenue, or market share of preference. For the purposes of this thesis, market scenarios are evaluated with respect to market share of preference. Market share of preference information can be determined for the base product(s), competitor product(s), and the None option (if present). The formula for market share of preference (MSP) for the l^{th} product profile is shown below:

$$\boldsymbol{MSP_l = \frac{\sum_{i=1}^{N} p_i^l}{N}} \qquad (\mathbf{4.4})$$

In Equation 4.4, the l^{th} product profile can define the base product, a competitor product, or the None option. $\boldsymbol{N}$ is the total number of respondents, i is the i^{th} respondent, and $\boldsymbol{p_i^l}$ is the i^{th} respondent's individual share of preference, whose definition is presented in Equation 3.2 in Section 3.2.2. In Equation 3.2, $\boldsymbol{K}$ would represent all the alternatives present in the current market scenario. Therefore, it would represent the base product(s), competitor product(s), and the None option (if included). The tested levels would define the product profiles representing the actual base product(s) and competitor product(s). For independent attributes, the tested levels (for discrete attributes) or an interpolation of the tested levels (for continuous attributes) would be used to define the product profiles representing the actual products. If any dependent attributes existed, then a mapping should be developed, where possible. Specifically, a scheme should be developed to map the chosen levels of independent attributes to determine the values of dependent attributes. For any dependent attribute, mapping schemes should be developed so that they are as realistic as possible.

To determine the price scheme, the redesign team should consider the total redesign costs associated with each customization option and the price sensitivity of consumers. For this thesis, the price is assumed to be a multiple of cost. An example price scheme is shown below:

TABLE 4.13: ATTRIBUTE PRICE SCHEME

		Base Price: $20	
		Attributes	
		Attribute 1	Attribute 2
Levels	1	$6	$2
	2	$7	$4
	3	$8	$3

In Table 4.13, notice that a base price of $20 is defined and that the total prices associated with the customization options are double the redesign cost values shown in Table 4.10.

With such mappings defined, Equation 4.4 can be used to determine the market share of preference (MSP) for products in the current market scenario. For the case studies presented in this thesis, the base product (for which customization options are being developed and assessed) and the None option define the current market scenario. Equation

4.4 can be used to determine the base product's and the None option's MSP. Assume these values to be 30% and 70%, respectively, for the example.

Step 4.5 - Evaluate potential market scenarios from offering the customization options

The final sub-step of Step 4 is to evaluate new market scenarios resulting from offering customization options. Equation 4.4 can be used to evaluate the MSP of all alternatives in new market scenarios resulting from customization options. In this thesis, offered customization options are assumed to create new products in the market. If more than one customization option is offered, then the alternatives must include all possible combinations of customization options as products. For example, if Options 1 and 3 in Table 4.7 are offered along with the base product, then the market contains the base product, the None option, the base product with Option 1, the base product with Option 3, and the base product with Options 1 and 3. These five alternatives would then be considered in Equation 4.4 for the new market scenario. Of course, infeasible products from combining options that cannot be offered simultaneously would not be considered. Due to the combinatorial nature of this problem, this thesis only considers one customization option being offered at a time. For the options shown in Table 4.7, assume the following MSP values:

TABLE 4.14: MSP VALUES FOR MARKET SCENARIOS

Market Scenario	Option Product MSP (%)	Base Product(s) MSP(%)	Competitor Product(s) MSP (%)	% Change in Competitor Product(s)	% Change in Base Product(s)
Current	0	30	70	N/A	N/A
Option 1	16	15	69	-1.43	-50
Option 2	20	30	50	-28.57	0
Option 3	5	25	70	0	-16.67
Option 4	25	20	55	-21.43	-33.33

As seen in Table 4.14, for each market scenario created from a customization option, the MSP values for the new product created from the customization option, the base product(s), and competitor product(s), including the None option, are listed. If the current market scenario includes multiple products for the firm, then the third column in Table 4.14 contains the sum of the MSP values of each product. Similarly, the fourth column contains the sum of the MSP values of all competitor products, including the None option.

In addition to determining MSP values, percent change in MSP values for the competition and base product(s) can be calculated to gain insight on the affect of offering customization options. Percent changes are calculated by comparing the MSP values of the new market scenarios with the current market scenario. Such values are presented in Table 4.14. A negative percent change for the competition indicates that the competition lost MSP from the customization option being offered, while a negative percent change indicates that the firm lost MSP from the customization option being offered (an indication of cannibalization). Due to the formulation of MSP, a positive percent change in MSP for the competition or the firm cannot occur.

Overall, the largest negative percent change for the competition and the smallest negative percent change for the firm (zero percent change is ideal) are desired. However, the percent change in the competition MSP is deemed more important because it indicates the total gain in MSP for the firm. From Table 4.14, Option 2 fits is the best option because it has the largest negative percent change for the competition and zero percent change for the firm. However, customization options that meet this criterion should not automatically be pursued; both the market desirability and the engineering redesign effort should be considered, as is done in Step 5.

4.5.5: Step 5: Consider tradeoffs between results from Steps 3 & 4

The final step of the proposed approach shown is to consider the tradeoffs between the engineering and marketing domains when deciding which customization options to offer. Specifically, this step allows tradeoffs to be considered between the amount of engineering redesign effort required to offer customization options and the market desirability of offered customization options. A fever chart, such as the one shown below, can be created to consider such tradeoffs:

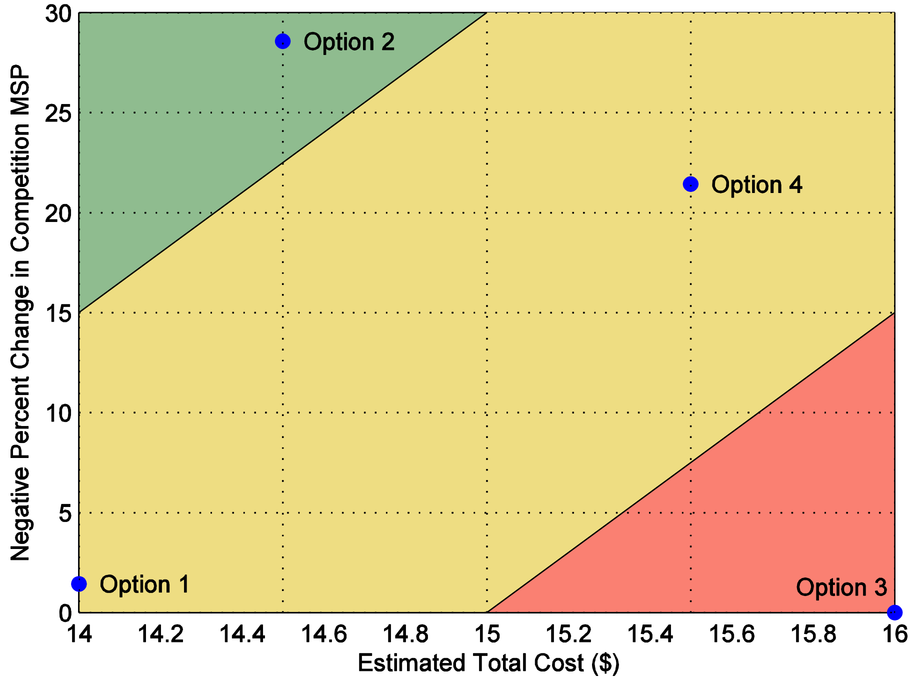


FIGURE 4.17: TRADEOFF PLOT

As shown in Figure 4.17, the X-axis is the engineering impact, and the Y-axis is the marketing impact. Each point in this figure represents one or more customization options being offered by the firm. As previously mentioned, this thesis will only consider one customization option being offered by the firm due to the combinatorial nature of the marketing problem and the limited work done in engineering change research for multiple changes. The color scheme indicates that customization options near the upper left hand corner are desirable (low estimated total cost, high negative percent change in the competition MSP), while customization options near the lower right hand corner are undesirable (high estimated total cost, low negative percent change in the competition MSP).

To obtain the chart obtained in Figure 4.17, the results from Steps 3 and 4 are used. For the X-axis values, the redesign effort score obtained for each customization option from Step 3.6 is used. For the Y-axis, the percent change in the competition in MSP from Step 4.5 is multiplied by negative one and used. Therefore, negative Y-values indicate a loss in MSP for the firm.

With a complete fever chart, both the engineering and marketing domains can be considered when determining which customization option to pursue for further development in the detail design phase. Notice that Options 1 and 2 are the lowest cost options as might be expected since they relate to potential Subsystem B, while Options 3 and 4 are the highest cost options as might be expected since they relate to non-potential Subsystem F. From the above figure, Option 3 should not be pursued because it only impacts the marketing domain a little while requiring the most amount of rework. The other customization options are more likely to be pursued. Option 1 might be pursued because it has the lowest redesign cost out of all the options and a small increase in the marketing domain. If the firm is willing to pay a larger redesign cost, then Option 4 could be pursued because it results in a larger increase in MSP than Option 1. However, Option 2 is likely the best option to pursue because it has the largest increase in MSP for the firm and its redesign cost is only slightly more than Option 2. As can be seen, the tradeoff plot can help the redesign team consider both marketing and engineering tradeoffs before selecting a customization option to pursue in the detailed design phase.

4.6: Summary

This chapter outlined the proposed approach for customization option development during the early stages of redesign. First, the chapter outlined the five-step approach and explained these steps in broad terms. Then, the engineering change and marketing tools were selected based off of a set of selection criteria. Finally, the sub-steps of the five-step approach were explained. With the approach fully explained, the case studies are presented in the next chapter.

CHAPTER 5: CASE STUDIES

5.1: Introduction

In this chapter, the proposed approach outlined in Chapter 4 for customization option assessment is demonstrated with two products. First, the product selection process is discussed, and the two products chosen are presented in Sections 5.2. Then, the approach shown in Chapter 4 is applied to each product in Sections 5.3 and 5.4. The chapter is wrapped up with a discussion of the results in terms of initial approach validation in Section 5.5 and a chapter summary in Section 5.6.

5.2: Product Selection

Prior to product selection, some criteria are developed to help choose appropriate products to implement the approach outlined in Step 4. These criteria are presented in the following list:

- The products should be mass market products because (1) mass customization focuses on products sold to the general product and (2) gathering consumer preferences is likely easier for mass market products.
- The products should be electromechanical or mechanical in nature. In comparison to non-electromechanical or non-mechanical products, these types of products typically have more complex product architectures with constraints that will affect the amount of redesign work required to offer a

customization option. In general, it is believed that these products will reveal more information about the proposed approach as opposed to non-electromechanical and non-mechanical products.

- The physical products or documentation should be available for deconstruction. Recall from Chapter 4 that a product deconstruction is necessary for Steps 1 and 3.
- The two products should have different complexities in order to learn how a product's complexity influences the implementation of the proposed approach.

With these criteria established, an electromechanical and a mechanical, mass market product is chosen. For the electromechanical product, a desk fan is chosen, particularly one modeled after a Lasko fan. For the mechanical product, a gas grill is chosen; particularly a Master Forge 2-burner liquid propane (LP) grill is selected. More information regarding this product is presented in Section 5.4.

5.3: Desk Fan

The desk fan used for this case study is modeled after the Lasko desk fan shown below [152]:

FIGURE 5.1: DESK FAN

For the purposes of this thesis, the characteristics of the desk fan shown in Figure 5.1 are listed below:

- Black fan with a flat base that produces 48dB of noise and weighs 3lb
- Powered through a 6ft power cord
- 10" diameter fan blade with 0.5" radius clearance with grill whose clearance with the base is 5"
- 3 speed settings (low, medium, high)
- Non-oscillating, 90° side-to-side adjustment range (±45°)
- 60° up-and-down adjustment range (±30°); At -30°, grill touches stand
- Price: $30

With the desk fan fully defined, the steps of the proposed approach are now implemented.

5.3.1: Step 1 - Identify potential subsystems for redesign based on average changes

The first step of the approach is to identify potential subsystems for customization option development from a change analysis. The five sub-steps for the desk fan are presented below.

Step 1.1 - Break product down into subsystems

For this step, the desk fan is decomposed into nine different subsystems based on a combination of function and location. This decomposition is shown below [152]:

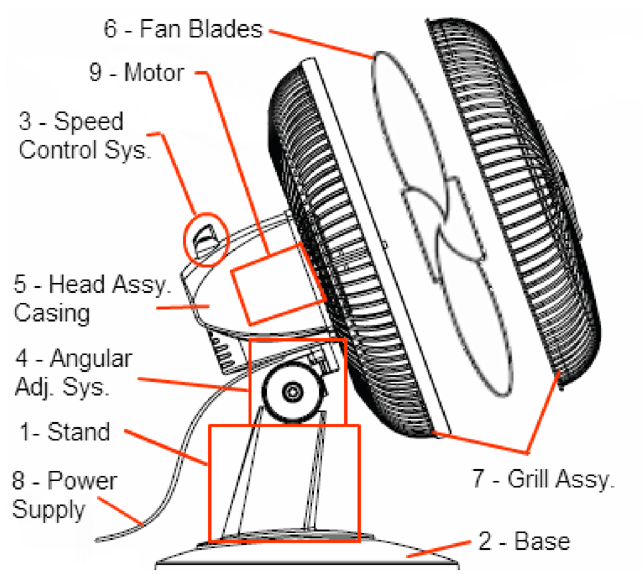


FIGURE 5.2: DESK FAN BREAKDOWN

Before moving onto Step 1.2, a few comments about the desk fan breakdown shown in Figure 5.2 are necessary. Subsystem 3, the Speed Control Subsystem, consists of the speed selector switch and the assumed circuit board that attaches to Subsystem 5. Subsystem 4, the Angular Adjustment System, consists of the parts that allow the fan to move side-to-side and up-and-down and attaches to Subsystems 1 and 5. Lastly, Subsystem 5 consists of the plastic casing that encompasses Subsystems 3 and 9 and that interacts with Subsystems 4, 7, and 8.

<u>Step 1.2 - Create subsystem dependency DSM</u>

After the fan is decomposed into the nine subsystems shown in Figure 5.2, the subsystem dependency DSM is created. This matrix is shown below in Table 5.1:

TABLE 5.1: DESK FAN SUBSYSTEM DEPENDENCY DSM

		Initiating Subsystems								
		1	2	3	4	5	6	7	8	9
Affected Subsystems	1		X		X			X		
	2	X						X		
	3					X			X	X
	4	X				X		X		
	5			X	X			X	X	X
	6							X		X
	7	X			X	X	X			
	8			X		X				X
	9			X		X	X		X	

Step 1.3 - Create direct likelihood and impact DSMs

The values in the direct likelihood and impact DSMs are determined by interviewing a group of graduate and undergraduate students in the Department of Mechanical and Aerospace Engineering at NC State with the guidance of the scales presented in Table 4.2. The values decided upon are shown in the below tables:

TABLE 5.2: DESK FAN DIRECT LIKELIHOOD DSM

		Initiating Subsystems								
		1	2	3	4	5	6	7	8	9
Affected Subsystems	1		0.3		0.4			0.2		
	2	0.4						0.3		
	3					0.2			0.8	0.6
	4	0.1				0.4		0.4		
	5			0.2	0.2			0.4	0.4	0.8
	6							0.6		0.8
	7	0.2			0.3	0.3	0.6			
	8			0.2		0.2				0.6
	9			0.4		0.5	0.8		0.6	

TABLE 5.3: DESK FAN DIRECT IMPACT DSM

		Initiating Subsystems								
		1	2	3	4	5	6	7	8	9
Affected Subsystems	1		0.2		0.3			0.3		
	2	0.3						0.2		
	3					0.2			0.8	0.5
	4	0.2				0.3		0.3		
	5			0.2	0.2			0.3	0.4	0.6
	6							0.5		0.6
	7	0.2			0.2	0.2	0.2			
	8			0.4		0.5				0.5
	9			0.6		0.7	0.6		0.6	

Step 1.4 - Calculate combined likelihood, impact, and risk DSMs

With the direct likelihood and impact matrices defined, the CAM software with the CPM toolbox and the settings discussed in Chapter 4 are used to determine the combined likelihood, impact, and risk DSMs. These DSMs are shown in Figure 5.3 below:

Combined Likelihood		Initiating Subsystems								
		1	2	3	4	5	6	7	8	9
Affected Subsystems	1		0.3	0.28	0.47	0.37	0.44	0.48	0.45	0.46
	2	0.44		0.24	0.29	0.32	0.39	0.43	0.39	0.4
	3	0.14	0.04		0.3	0.67	0.73	0.57	0.91	0.86
	4	0.21	0.06	0.38		0.55	0.59	0.62	0.6	0.63
	5	0.17	0.05	0.55	0.39		0.79	0.68	0.82	0.91
	6	0.16	0.05	0.49	0.34	0.64		0.7	0.75	0.86
	7	0.23	0.07	0.42	0.42	0.6	0.74		0.66	0.71
	8	0.12	0.04	0.48	0.27	0.57	0.64	0.5		0.73
	9	0.15	0.05	0.55	0.33	0.69	0.83	0.63	0.81	

Combined Impact		Initiating Subsystems								
		1	2	3	4	5	6	7	8	9
Affected Subsystems	1		0.2	0.38	0.32	0.35	0.37	0.34	0.4	0.37
	2	0.3		0.3	0.29	0.29	0.29	0.27	0.31	0.31
	3	0.76	0.72		0.76	0.72	0.76	0.76	0.81	0.74
	4	0.3	0.29	0.4		0.35	0.4	0.37	0.43	0.4
	5	0.52	0.51	0.57	0.43		0.63	0.54	0.65	0.65
	6	0.6	0.59	0.69	0.63	0.66		0.59	0.73	0.66
	7	0.21	0.21	0.29	0.23	0.26	0.27		0.32	0.28
	8	0.6	0.59	0.55	0.61	0.58	0.59	0.6		0.57
	9	0.71	0.7	0.68	0.73	0.75	0.65	0.7	0.74	

Combined Risk		Initiating Subsystems								
		1	2	3	4	5	6	7	8	9
Affected Subsystems	1		0.06	0.11	0.15	0.13	0.16	0.16	0.18	0.17
	2	0.13		0.07	0.08	0.09	0.11	0.12	0.12	0.12
	3	0.11	0.03		0.23	0.48	0.55	0.43	0.74	0.64
	4	0.06	0.02	0.15		0.19	0.24	0.23	0.26	0.25
	5	0.09	0.03	0.31	0.17		0.50	0.37	0.53	0.59
	6	0.10	0.03	0.34	0.21	0.42		0.41	0.55	0.57
	7	0.05	0.01	0.12	0.10	0.16	0.20		0.21	0.20
	8	0.07	0.02	0.26	0.16	0.33	0.38	0.30		0.42
	9	0.11	0.04	0.37	0.24	0.52	0.54	0.44	0.60	

FIGURE 5.3: DESK FAN COMBINED LIKELIHOOD, IMPACT, & RISK DSMS

<u>Step 1.5 - Determine potential subsystem(s)</u>

Finally, the last sub-step of Step 1 is to determine potential subsystems. As mentioned in Chapter 4, ideal potential subsystems are as those subsystems likely to be easily changed with a low risk for change propagation. For the first part of this definition, the average rework cost for each subsystem is subjectively estimated since historical change data and cost information is unavailable. To estimate these costs, the following procedure is used:

- Estimate total cost of base product from price.
- Estimate cost for each subsystem as a percentage of the total cost.
- Estimate average rework cost from these subsystem costs.

For the desk fan, a 100% markup is assumed, so the total cost is 50% of the base price ($30*0.50 = $15). The percentages listed in Table 5.4 for each subsystem are subjectively determined based on the perceived complexity (number and type of interfaces). These subsystem costs, the $\boldsymbol{fix_j}$ values for Equation 4.2, are then multiplied by 2/3 to obtain an estimate for the average rework cost for each subsystem, $\boldsymbol{rework_j}$. The subsystem costs are multiplied by 2/3 to account for the cost saving associated with redesigning a subsystem as opposed to designing it from scratch.

TABLE 5.4: DESK FAN SUBSYSTEM AVERAGE REWORK COST ESTIMATES

Subsystem #	**Percentage (%)**	$\boldsymbol{fix_j}$	$\boldsymbol{rework_j}$
1	7	$1.05	$0.70
2	6	$0.90	$0.60
3	12	$1.80	$1.20
4	8	$1.20	$0.80
5	14	$2.10	$1.40
6	19	$2.85	$1.90
7	10	$1.50	$1.00
8	11	$1.65	$1.10
9	13	$1.95	$1.30

From Table 5.4, the subsystems with low average rework costs are likely good candidates for redesign based solely on easiness to change. Using an arbitrary cutoff amount of $1.25 (halfway between the minimum and maximum average rework costs), Subsystems 1-4, 7, and 8 could be potential subsystems for redesign depending upon their risk for change propagation (the highlighted cells in Table 5.4).

To determine a subsystem's risk for change propagation, recall that risk portfolio and case risk plots can be created. The scaled risk portfolio plot is presented below:

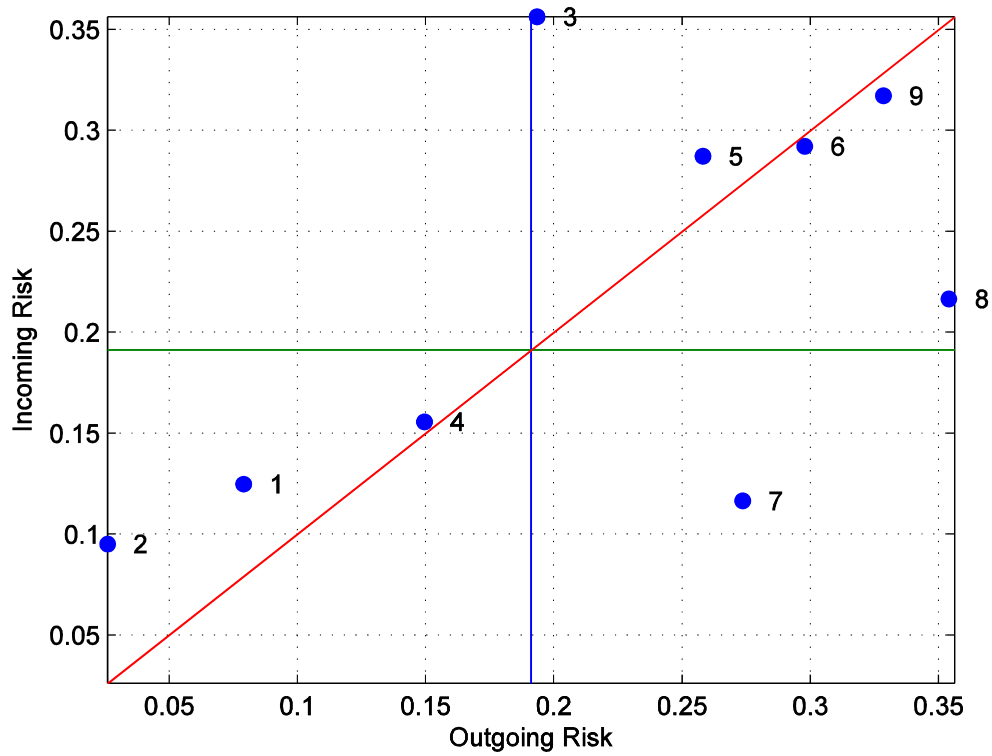


FIGURE 5.4: DESK FAN SCALED RISK PORTFOLIO

In analyzing Figure 5.4, subsystems that are close to the bottom left corner are potential subsystems for redesign. Therefore, the three Subsystems in the bottom left quadrant (1, 2, and 4) are likely good candidates for customization option development. However, the remaining subsystems are poor candidates because they are closer to the top right corner, indicating high risk. Subsystem 7, one that was a potential candidate based on Table 5.4, is a change multiplier and thus should not be selected as a potential subsystem.

As mentioned in Chapter 4, case risk plots can be used to further explore change propagation and identify potential subsystems for redesign. The case risk plots for each subsystem are presented in the following three figures with three subsystems presented per figure.

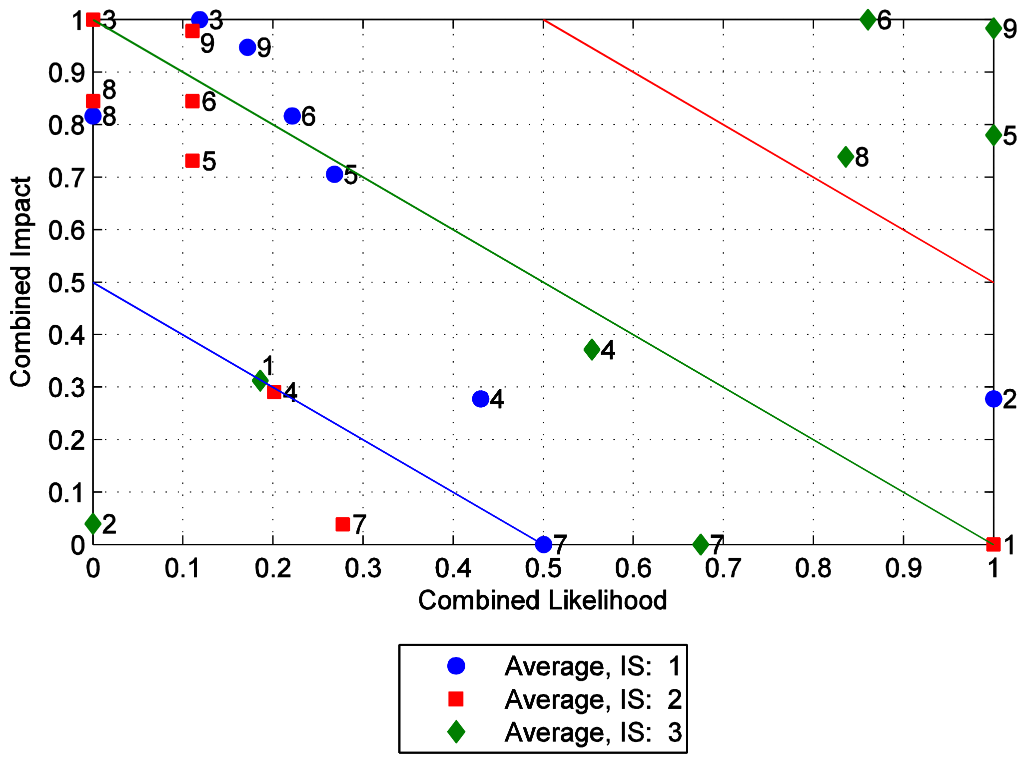


FIGURE 5.5: DESK FAN AVERAGE CASE RISK PLOT - SCALED, IS=1-3

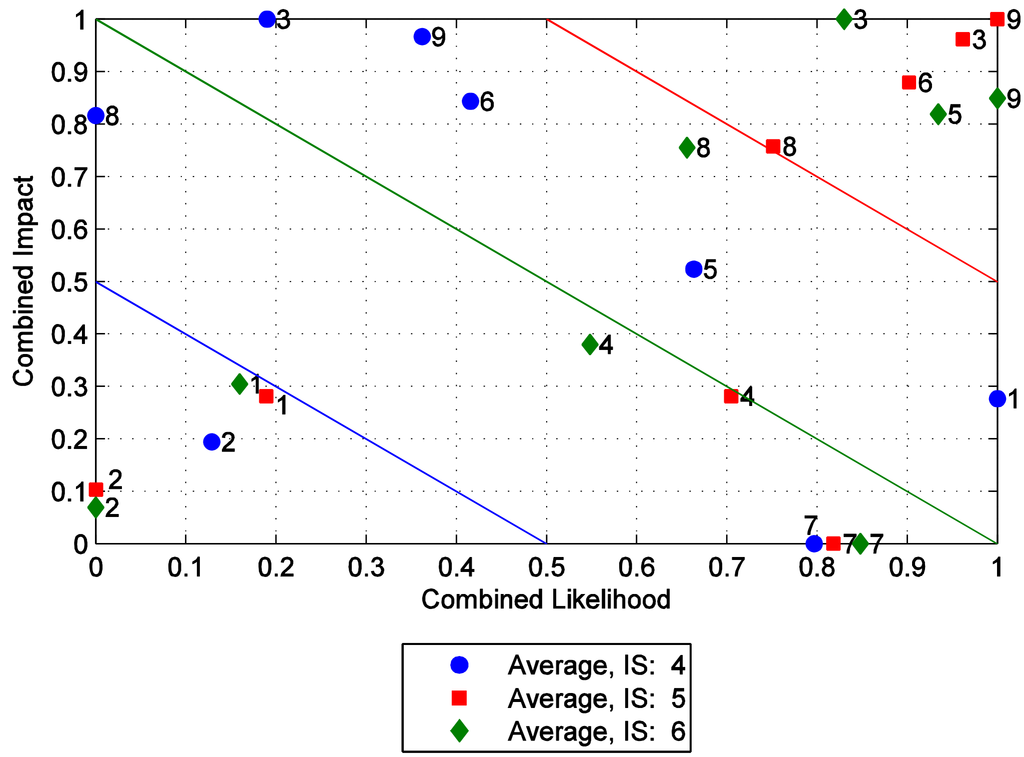


FIGURE 5.6: DESK FAN AVERAGE CASE RISK PLOT - SCALED, IS=4-6

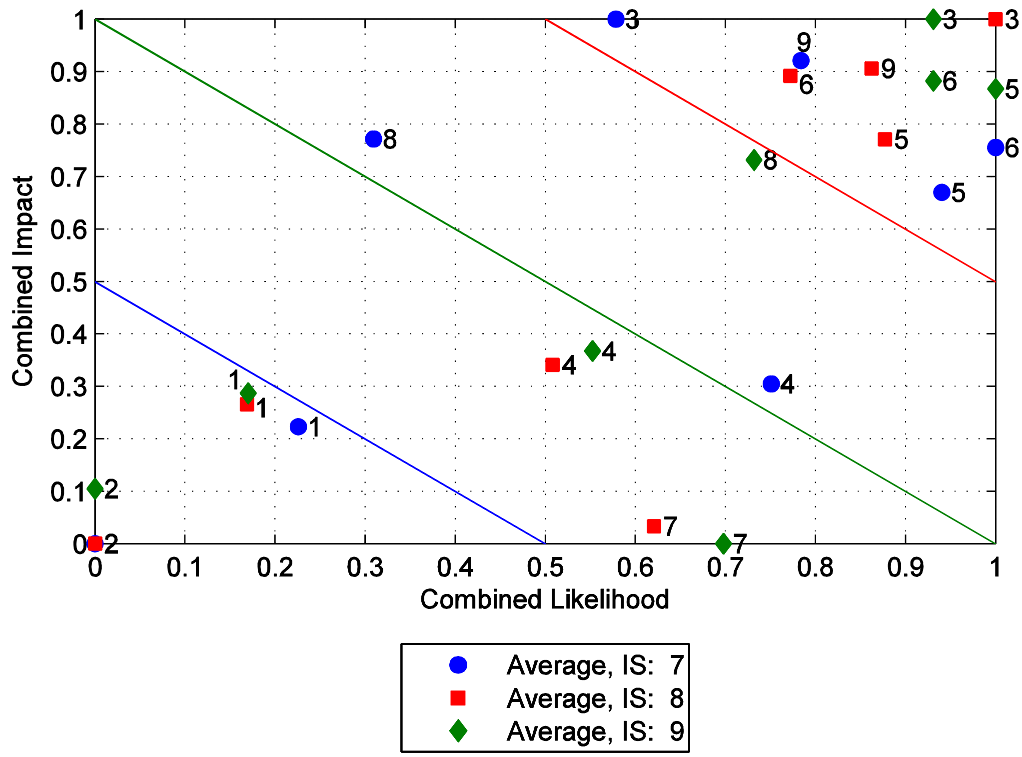


FIGURE 5.7: DESK FAN AVERAGE CASE RISK PLOT - SCALED, IS=7-9

From Figures 5.5 to 5.7, it is clear that Subsystems 1, 2 and 4 are low risk subsystems for change propagation, and thus they are potential subsystems for redesign. In Figure 5.5, Subsystems 1 and 2 have many subsystems at medium risk for being affected by change propagation (around the green line), while Subsystem 3 has a few subsystems at high risk for being affected by change propagation (above the red line). Additionally, Subsystem 2 has more low risk subsystems than Subsystem 1. In Figure 5.6, Subsystem 4 has one low risk subsystem (below the blue line) with some medium-high risk subsystems (between green and red lines). In comparison to Subsystems 5 and 6, Subsystem 4 has no high risk subsystems (above the red line). Lastly, in Figure 5.7, it is clear that Subsystems 7 through 9 have many high risk subsystems (above the red line). By examining Subsystems 7 and 8, they have more high risk subsystems (above the red line) than low or medium risk subsystems. From all three of these figures, the same conclusions can be reached from Figure 5.4; Subsystems 1, 2, and 4 are good candidates for redesign based on change propagation.

By considering the results presented in Table 5.4 and Figures 5.4 through 5.7, potential candidate subsystems for the desk fan are selected. Based on the easiness to change, Subsystems 1-4, 7 and 8 were identified as potential candidates. From the risk portfolio and case risk plots, Subsystems 1, 2, and 4 were chosen as potential candidates. With both of these results in mind, Subsystems 1, 2, and 4 are chosen as potential subsystems for customization option development because, with average changes, they are easy to change and have a low risk for change propagation.

5.3.2: Step 2 - Develop conceptual-level customization options

The second step is to develop conceptual-level customization options. For this case study, no marketing data containing consumer suggestions was available. Therefore, Steps 2.1 through 2.4 are skipped, and Step 2.5 is used. For this sub-step and for Step 3, a project report centered around a desk fan was used [153]. In this report, a variety of fans currently on the market were studied, and a market segmentation grid was created. Additionally, a desk fan was chosen and decomposed using a functional model. From these data sets, a requirements list was for a desk fan was developed, and a mind map was created to show the potential attributes of a desk fan. This mind map is recreated with a few modifications and shown below:

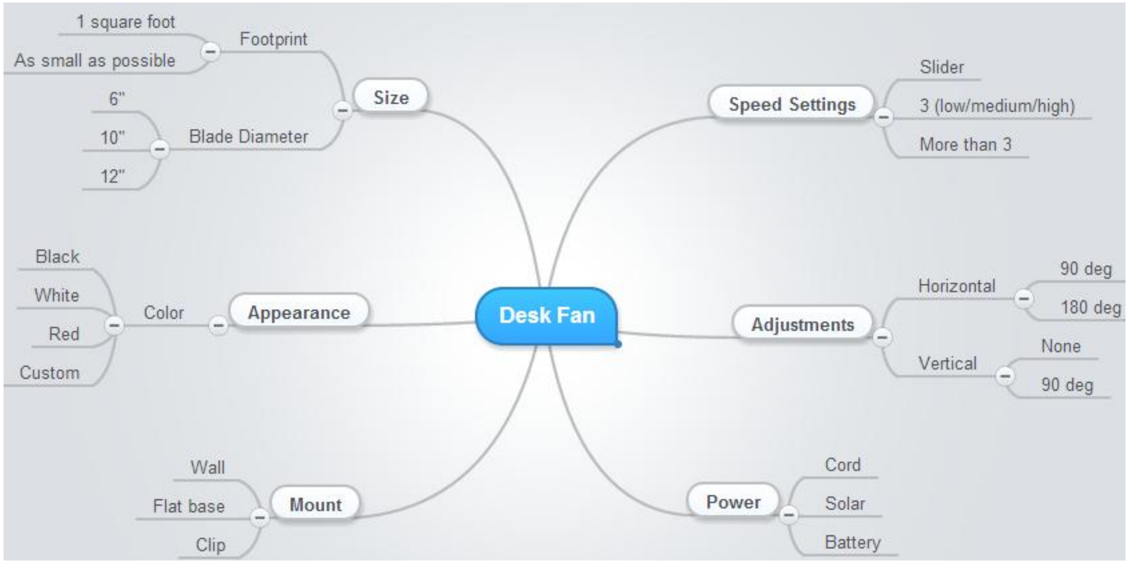


FIGURE 5.8: DESK FAN MIND MAP

From Figure 5.8, 23 customization options are developed for use in this case study such that they exist at the level of detail present in the third entry of Figure 4.2. The customization options are listed below:

- Change fan blade diameter from 10" to:
  - 4"
  - 6"
  - 8"
  - 12"
- Change mount type from flat base to:
  - Clip
  - Wall-mount
- Change number of speed settings from 3 to:
  - 1
  - 2
  - 4
  - 5

- Change side-to-side (horizontal) adjustment range from 90° to:
  - 0°
  - 60°
  - 150°
- Change up-and-down (vertical) adjustment range from 60° to:
  - 0°
  - 30°
  - 90°
- Change power supply from 6ft cord to:
  - 3ft cord
  - 10ft cord
  - Battery-powered
- Change fan's color from black to:
  - Red
  - Blue
  - White
  - Custom

These customization options are then mapped to the potential subsystems. Mount type, for example, is mapped to potential Subsystem 2. The options related to side-to-side (or horizontal) and up-and-down (or vertical) adjustment ranges are directly linked to potential Subsystem 4. In this case study, none of the generated customization options are considered for Subsystem 1 because the original project report did not consider this subsystem. The remaining customization options, excluding color, are related to non-potential subsystems, in particular Subsystems 3, 6, and 8. The system-level change of color is also included as several customization options.

5.3.3: Step 3 - Conduct change analysis for the options

The third step of the proposed approach is to conduct a change analysis for the customization options. The sub-steps for this step are presented below for the desk fan.

Step 3.1 - Select customization options for analysis

As discussed in Chapter 4, the customization options mapped to potential Subsystems 2 and 4 are selected for analysis because these subsystems were identified in Step 1.5 as being easy to change with a low risk for change propagation under average changes. However, the other customization options are also considered because they may require little engineering effort, while also being desirable to consumers.

Step 3.2 - Map customization options to base product's subsystems

The customization options listed above are mapped to the base desk fan shown in Figure 5.1. This mapping is shown in the below table:

TABLE 5.5: MAPPING CUSTOMIZATION OPTIONS TO DESK FAN SUBSYSTEMS

Customization Option	Subsystem #
4" blade	6
6" blade	6
8" blade	6
12" blade	6
Clip	2
Wall-mount	2
1 speed setting	3
2 speed settings	3
4 speed settings	3
5 sped settings	3
0° horizontal adjustment range	4
60° horizontal adjustment range	4
150° horizontal adjustment range	4
0° vertical adjustment range	4
30° vertical adjustment range	4
90° vertical adjustment range	4
3ft power cord	8
10ft power cord	8
Battery-powered	8
Red desk fan	1-9
Blue desk fan	1-9
White desk fan	1-9
Custom-color desk fan	1-9

From Table 5.5, all the customization options, excluding the desk fan color options, are each mapped to one subsystem. Since each option is linked to one initiating subsystem, the CPM can be used to evaluate these customization options induced by subsystem-level changes. The color options are considered emotional system-level changes, and thus the CPM method is not needed because these options do not propagate changes to other subsystems. However, the redesign cost for these customization options are still estimated in Step 3.6.

Step 3.3 - Determine direct likelihood and impact values for the options

With the mapping shown above, the direct likelihood and impact values for each customization option is determined to fulfill Step 3.3. Similar to Step 1.3, a group of engineering students were used to determine these values for each customization option by using the scales presented in Table 4.2. Also, as discussed in Section 4.5.3, related customization options are compared to each other and the relationships between values of affected subsystems are compared to help determine these values. These tables, along with a brief discussion of the thought process used to obtain them, are presented in Appendix A.

Step 3.4 - Replace these values with the ones created in Step 1

Once the direct likelihood and impact values are determined for each customization option, the old values from Step 1 are replaced with these values. The columns associated with the initiating subsystem are replaced in each matrix, as shown in Figure 4.13.

Step 3.5 - Calculate the combined likelihood, impact, and risk DSMs

After replacing the old direct likelihood and impact values with the ones determined in Step 3.2, the CAM software with the CPM toolbox is used to calculate the likelihood, impact, and risk DSMs for each customization option. These values are presented in Appendix B, and the $\boldsymbol{r_k}(\boldsymbol{i} \rightarrow \boldsymbol{j})$ values are the values shown in the risk DSMs.

Step 3.6 - Compute total redesign effort for the customization options

The last sub-step of Step 3 is to compute the total redesign effort for the customization options. To complete this step, the $\boldsymbol{fix_j}$ and $\boldsymbol{rework_j}$ values from Table 5.4 are used, and the $\boldsymbol{rework_{k,i}}$ and $\boldsymbol{E_{k,i \rightarrow j}}$ values are estimated. The $\boldsymbol{rework_{k,i}}$ values, shown in Table 5.6, are subjectively estimated by considering the changes to the design, material, and manufacturing costs of the base product from customization option k. These values are subjectively estimated because historical change data and cost information is unavailable. If the proposed approach is used in an industry setting, these types of information should be used to obtain better estimates. For this thesis, the procedure for estimating these values is listed below:

- Assume design, material, and manufacturing costs are each 1/3 of $\boldsymbol{fix_i}$.
- Estimate the impact, or the proportion of the total design work needing to be redone to offer customization option k, for initiating subsystem i. These values are shown in Appendix A.
- Assume the redesign cost for subsystem i is the design cost times the estimated impact.
- Subjectively estimate the change in manufacturing and material costs by considering the affects of customization option k on subsystem i's manufacturing process and material makeup.

Once the $\boldsymbol{rework_{k,i}}$ values are estimated, the $\boldsymbol{E_{k,i\rightarrow j}}$ are estimated for each customization option. If the $\boldsymbol{r_k(i\rightarrow j)}$ value is not zero, the value for $\boldsymbol{E_{k,i\rightarrow j}}$ is set to at least 1 in order to capture the risk of change propagating. If the $\boldsymbol{E_{k,i\rightarrow j}}$ value was set to 0 and the change does propagate, then the estimate total cost would be inaccurate and misleading. To avoid such a problem, $\boldsymbol{E_{k,i\rightarrow j}}$ is set to at least 1 if $\boldsymbol{r_k(i\rightarrow j)}$ is not zero ($\boldsymbol{E_{k,i\rightarrow j}}$ is obviously zero if $\boldsymbol{r_k(i\rightarrow j)}$ is zero). Values other than 1 for $\boldsymbol{E_{k,i\rightarrow j}}$ are obtained by subjectively considering the number of interfaces changed and shape changes. For all the customization options associated with the desk fan, $\boldsymbol{E_{k,i\rightarrow j}}$ is 1, except for the wall-mount and battery options. For the wall-mount option, $\boldsymbol{E_{wall-mount,2\rightarrow 1}}$ is 2 because it is expected that Subsystem 1's shape and interface with Subsystem 2 will change to support and correctly position the fan when mounted to the wall. For the battery option, $\boldsymbol{E_{battery,8\rightarrow 5}}$ is 2 because it is expected that Subsystem 5's shape and interface with Subsystem 8 will change for battery storage. With all the parameters estimated, Equation 4.2 is used to estimate the total cost for each customization option induced by a subsystem-level change.

To estimate the total cost for emotional system-level changes (i.e.: the color options), the material and manufacturing costs are considered. For this thesis, the basic color options (red, blue, and white) are assumed to add 5% of the base product's manufacturing and material costs to the overall cost of the base product ($15). The custom color option is assumed to be 25% more to account for the extra burden of a consumer-specified color.

With all these estimates complete, the total costs for all the customization options are shown in the below table:

TABLE 5.6: DESK FAN ESTIMATED TOTAL COSTS

Customization Option	$rework_{k,i}$	$ETC_{k,i}$
4" blade	\$0.19	\$18.66
6" blade	\$0.38	\$16.45
8" blade	\$0.57	\$16.01
12" blade	\$0.95	\$17.66
Clip	\$0.47	\$15.64
Wall-mount	\$0.14	\$15.66
1 speed setting	-\$0.28	\$16.06
2 speed settings	-\$0.08	\$16.06
4 speed settings	\$0.38	\$16.72
5 sped settings	\$0.58	\$17.13
0° horizontal adjustment range	\$0.02	\$15.43
60° horizontal adjustment range	\$0.13	\$15.60
150° horizontal adjustment range	\$0.18	\$15.65
0° vertical adjustment range	\$0.02	\$15.43
30° vertical adjustment range	\$0.13	\$15.60
90° vertical adjustment range	\$0.18	\$19.90
3ft power cord	-\$0.16	\$14.84
10ft power cord	\$0.43	\$15.43
Battery-powered	\$0.94	\$22.25
Red desk fan	N/A	\$15.50
Blue desk fan	N/A	\$15.50
White desk fan	N/A	\$15.50
Custom-color desk fan	N/A	\$15.63

Given the assumptions about the estimated cost data, the estimated total costs in Table 5.6 are analyzed, and a customization option is chosen based on engineering effort (recall that only one customization option is offered at a time). To visualize the range of the cost values, a scatter plot is created:

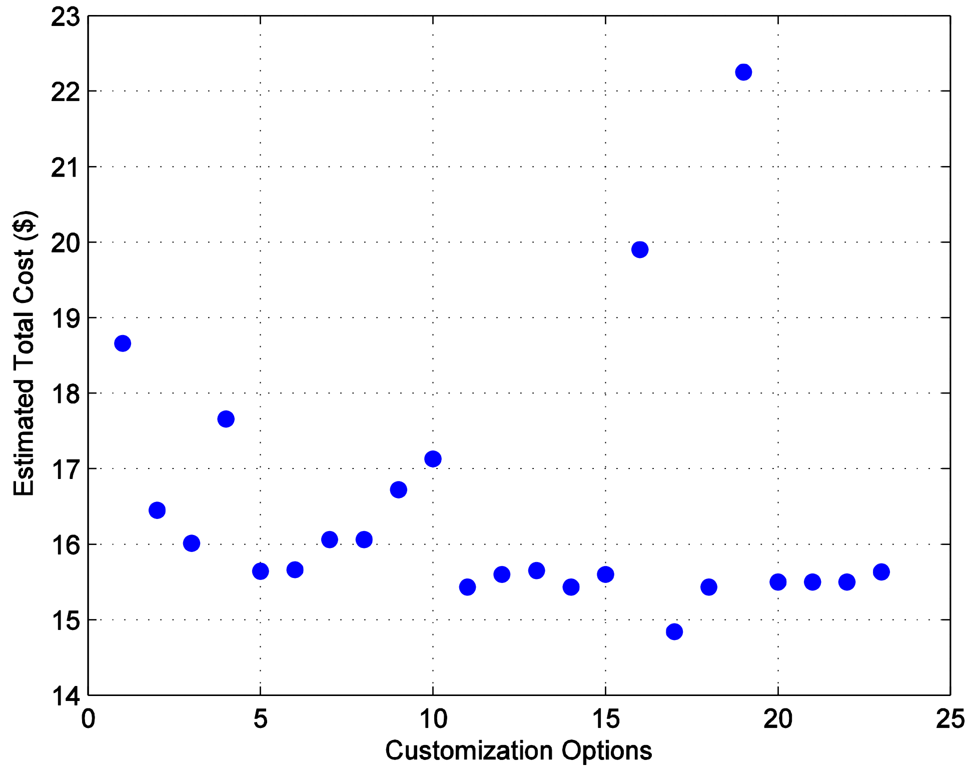


FIGURE 5.9: DESK FAN ETC SCATTER PLOT

By examining Figure 5.9, it is clear the majority of the customization options lie within the ranges of $15 to $17. On average, the redesign team should expect to pay $16.45 for a customization option ($1.45 greater than the cost of the base desk fan). If a redesign team is considering the best option from each grouping, the following options would be considered, listed in order from least expensive to most expensive:

- 3ft power cord at $14.84
- 0° horizontal adjustment range at $15.43
- 0° vertical adjustment range at $15.43

- Any color, except custom, at $15.50
- Clip mount at $15.64
- 8" fan blade at $16.01
- 1 or 2 speed settings at $16.06 each

From this list, it is clear that the best customization option to pursue, based solely on engineering effort, is the 3ft power cord option at $14.64 (less than the cost of the base desk fan). The next best customization options are the 0° horizontal adjustment range, the 0° vertical adjustment range, and the 10ft power cord options at $15.43. The worst option to pursue is the battery option at $22.25. However, these conclusions are drawn by considering only the engineering aspect of the problem. In defining the customization option to pursue, the marketing domain must also be considered, as is done in Step 4.

5.3.4: Step 4 - Gather and evaluate consumer preferences for the options

The fourth step of the proposed approach is to gather and evaluate consumer preferences for the developed customization options. The sub-steps for the desk fan are presented below.

Step 4.1 - Create discrete choice conjoint survey attributes and levels from options

The discrete choice conjoint survey used for the desk fan comes from the report mentioned above [153]. The attributes and levels for the discrete choice conjoint survey are shown in Table 5.7.

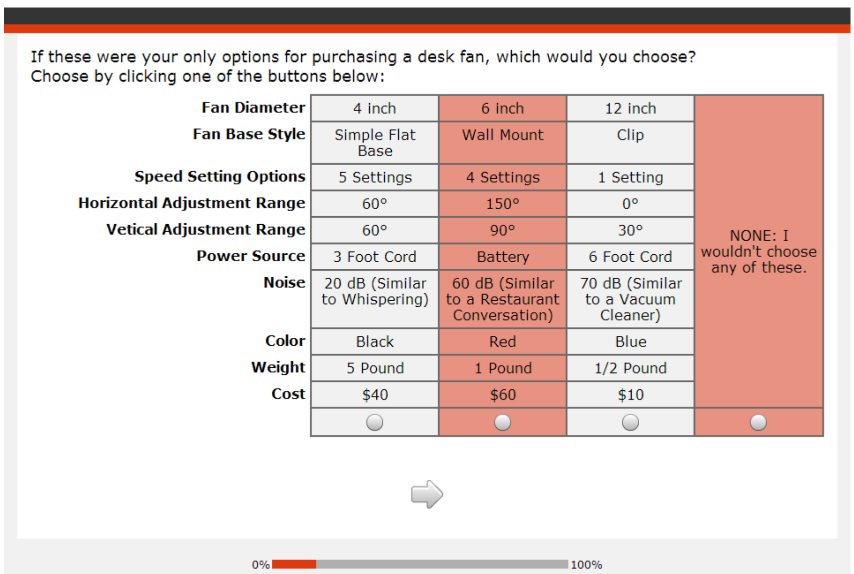
In this table, notice that there are three attributes not related to the 23 customization options. The price attribute is added to obtain price part-worth data for each respondent. The noise and weight attributes are remnants of the report from which the marketing data was obtained [153]. The levels in these two attributes are not considered customization options because they are system-level changes and do not fit the customization option definition outlined in Section 4.2. Finally, before moving onto Step 4.2, notice that the base product specifications are present in Table 5.7. These specifications are required for the market analyses in Steps 4.4 and 4.5.

TABLE 5.7: DESK FAN ATTRIBUTES & LEVELS

		Attributes									
		Blade Diameter (in)	Mount Type	Number of Speed Settings	Horizontal Adjustment Range	Vertical Adjustment Range	Power Supply	Noise (dB)	Color	Weight (lb)	Price ($)
Levels	1	4	Flat Base	1	0°	0°	3ft cord	20	Red	0.5	10
	2	6	Clip	2	60°	30°	6ft cord	40	Black	1	20
	3	8	Wall-mount	3	90°	60°	10ft cord	60	Blue	2.5	40
	4	10		4	150°	90°	Battery-powered	70	White	5	60
	5	12		5					Custom		

Step 4.2 - Determine discrete choice survey design, including additional questions

After the attributes and levels are defined, the survey design is chosen by considering Sawtooth's recommendations. Three product profiles are shown per task, a Balanced Overlap design scheme is used to create the tasks, a traditional None option is adopted, and a total of eleven tasks are asked including one holdout task [153]. A screen shot of a task question for the desk fan conjoint survey is shown in Figure 5.10 below:


If these were your only options for purchasing a desk fan, which would you choose?
Choose by clicking one of the buttons below:

Fan Diameter	4 inch	6 inch	12 inch	NONE: I wouldn't choose any of these.
Fan Base Style	Simple Flat Base	Wall Mount	Clip	
Speed Setting Options	5 Settings	4 Settings	1 Setting	
Horizontal Adjustment Range	60°	150°	0°	
Vetical Adjustment Range	60°	90°	30°	
Power Source	3 Foot Cord	Battery	6 Foot Cord	
Noise	20 dB (Similar to Whispering)	60 dB (Similar to a Restaurant Conversation)	70 dB (Similar to a Vacuum Cleaner)	
Color	Black	Red	Blue	
Weight	5 Pound	1 Pound	1/2 Pound	
Cost	$40	$60	$10	

0% 100%

FIGURE 5.10: DESK FAN TASK QUESTION EXAMPLE

From Figure 5.10, notice that the color attribute could be considered ambiguous since the colors are not clearly defined. Unfortunately, this characteristic of the desk fan survey is a remnant of the report from which it came [153]. A similar ambiguity is avoided for the gas grill survey discussed in Section 5.4.4.

Step 4.3 - Field discrete choice conjoint survey, gather data, & create preference model

After the survey was created and posted on the web, it was distributed through social media sites and e-mails to obtain as many responses as possible [153]. From this distribution, a total of 89 respondents are obtained. According to Equation 4.3, the minimum number of respondents to obtain an accurate consumer preference model is 76. Therefore, 89 respondents are enough to move forward with this thesis, though more may be desired if the proposed methodology is used in an industry setting. Sawtooth Software's CBC/HB module is used with a majority of the default settings to determine the individual-level part-worths. The only setting altered is the constraint setting, in which the price levels are constrained such that the lowest price is always favorable.

Step 4.4 - Evaluate current market scenario

With the part-worths calculated for each individual respondent, Step 4.4 evaluates the current market scenario. Before calculating market share of preference (MSP) values, mapping schemes are developed for the three dependent attributes (noise level, weight, and price). Since detailed noise level and weight data are not available, the mapping schemes for these two attributes are subjectively developed with physical trends in mind. The mapping scheme for noise level is shown below:

TABLE 5.8: DESK FAN ATTRIBUTE NOISE LEVEL SCHEME

		Base Noise: 40dB
		Attribute
		Blade Diameter
Levels	1	2dB
	2	4dB
	3	6dB
	4	8dB
	5	10dB

As seen in Table 5.8, the only independent attribute from Table 5.7 that is related to noise level is blade diameter. By assuming the same rotational velocity for each fan blade size, the noise level will increase with increasing fan blade size due to the increased tip speed [154]. Hence, this physical trend is represented in the above table. To obtain an overall noise level that is reasonable with desk fans, a base noise level of 40dB is set. In continuing with Step 4.4, the mapping scheme for weight is shown below:

TABLE 5.9: DESK FAN ATTRIBUTE WEIGHT SCHEME

		Base Weight: 1.1lb			
		Attributes			
		Blade Diameter	Mount Type	Number of Speed Settings	Power Supply
Levels	1	0.10lb	1.00lb	0.05lb	0.20lb
	2	0.20lb	0.50lb	0.15lb	0.30lb
	3	0.30lb	0.75lb	0.20lb	0.40lb
	4	0.40lb		0.25lb	1.00lb
	5	0.50lb		0.30lb	

Unlike the noise level attribute, the weight attribute has many independent attributes from Table 5.7 that can be mapped to it. The weight changes to Subsystem 4 (the Angular Adjustment System) due to the horizontal and vertical adjustment range attributes are deemed negligible, thus they are not included in the scheme shown above. Also, color is deemed to have no substantial influence on weight. Similar to the noise level mapping scheme, physical trends are represented in the weight mapping scheme. The weight increases with blade diameter, number of speed settings, and the length of the power cord with the battery option weighing more than the cord options. For the mount type, the flat base is reasoned to be the heaviest followed by the wall-mount and the clip since it must support the fan without any type of attachment. To obtain an overall weight that is reasonable for desk fans, a base weight of 1.1lb is used. Finally, after the mapping scheme shown in Table 5.9 is developed, the price mapping scheme is subjectively determined based off of the estimated total costs in Table 5.6. This scheme is shown in Table 5.10 below:

TABLE 5.10: DESK FAN ATTRIBUTE PRICE SCHEME

		Base Price: $5.00						
		Attributes						
		Blade Diameter	Mount Type	Number of Speed Settings	Horizontal Adjustment Range	Vertical Adjustment Range	Power Supply	Color
Levels	1	$1	$3	$1	$5	$9	$2	$3
	2	$2	$5	$2	$5	$9	$3	$3
	3	$3	$6	$3	$4	$5	$4	$3
	4	$4		$6	$5	$10	$17	$3
	5	$5		$7				$5

Similar to the noise level and weight schemes, the price scheme is subjectively developed, but it considers the redesign costs for each customization option from Step 3. For the purposes of this thesis, the prices are assumed to be a multiple of the total redesign cost. As mentioned in Chapter 4, these costs and the price sensitivity of consumers should be considered if the proposed approach is used in an industry setting. Notice that the base price of $30 is obtained and, for any given configuration, the price stays within the tested levels.

With all the dependent attributes mapped to the independent attributes, the current market scenario is defined, and Equation 4.4 is used to calculate the MSP values. The current market scenario is assumed to be the base product (shown in Figure 5.1) and the None, or walk-away, option. To use Equation 4.4, the part-worths from Step 4.3 for each respondent are used. For the dependent attributes, linear interpolation is used to obtain the part-worth values. Notice that all three schemes do not allow a value outside of the range of the tested levels to be obtained for the dependent attributes. Hence, interpolation, and not extrapolation, is always used to obtain part-worth values. This restriction is important because extrapolating part-worth values is error prone and not nearly as reliable as interpolating [65]. The MSP values for the base product and the None option under the current market scenario are 59.05% and 40.95%, respectively.

Step 4.5 - Evaluate potential market scenarios from offering customization options

To complete Step 4, each customization option is analyzed as a new product offering, the MSP values are calculated using Equation 4.4, and these results are presented in the below table:

TABLE 5.11: DESK FAN MSP VALUES FOR MARKET SCENARIOS

Market Scenario	Option Product MSP (%)	Base Product(s) MSP(%)	Competitor Product(s) MSP (%)	% Change in Competitor Product(s)	% Change in Base Product(s)
Current	0	59.05	40.95	N/A	N/A
4" blade	65.61	10.91	23.48	-42.65	-81.53
6" blade	67.04	7.26	25.70	-37.24	-87.71
8" blade	64.53	10.15	25.32	-38.16	-82.81
12" blade	22.90	38.98	38.12	-6.91	-33.99
Clip	18.71	44.38	36.91	-9.86	-24.85
Wall-mount	8.00	52.86	39.14	-4.41	-10.49
1 speed setting	11.53	48.56	39.91	-2.53	-17.77
2 speed settings	13.89	46.75	39.36	-3.87	-20.83
4 speed setting	15.84	47.23	36.93	-9.80	-20.02
5 speed settings	12.59	48.52	38.89	-5.03	-17.83
0° HAR	11.44	48.70	39.86	-2.65	-17.53
60° HAR	44.20	21.15	34.65	-15.39	-64.18
150° HAR	29.68	36.18	34.15	-16.61	-38.73
0° VAR	9.82	50.37	39.81	-2.78	-14.70
30° VAR	6.79	53.39	39.82	-2.76	-9.59
90° VAR	31.15	34.66	34.18	-16.52	-41.30
3ft power cord	32.89	28.78	38.33	-6.39	-51.26
10ft power cord	33.77	29.80	36.43	-11.02	-49.54
Battery-powered	1.82	57.34	40.84	-0.27	-2.90
Red desk fan	34.52	30.15	35.33	-13.73	-48.94
Blue desk fan	33.15	31.91	34.95	-14.66	-45.97
White desk fan	21.39	40.35	38.26	-6.57	-31.68
Custom-color desk fan	25.15	36.74	38.11	-6.94	-37.79

In Table 5.11, HAR and VAR stand for horizontal adjustment range and vertical adjustment range, respectively. As discussed in Chapter 4, the ideal customization option is one that has zero percent change in the base product's MSP and a large negative percent change in the competition's MSP (which is the None option for this case study). A poor customization option is one that has a large negative percent change in the base product's MSP (cannibalization of the base product's sales by the customization option) and zero percent change in the None option's MSP. The option with the largest negative percent change in the None option's MSP is the 4" blade at -42.65%, while the option with the smallest negative percent change in the None option's MSP is the battery-powered option at -0.27%. From these two options, the 4" blade option is the more desirable one from a marketing standpoint because the None option loses more MSP. The option with the least negative percent change in the base product's MSP is battery-powered lid opening mechanism at -2.90%, while the option with the largest negative percent change in the base product's MSP is the 6" blade option at -87.71%. From these two options, the battery-powered option is the more desirable one from a marketing standpoint because the base product loses less MSP. Though percent change in the base product's MSP indicates cannibalization, the percent change in the None option's MSP is deemed more important because it indicates the total gain in MSP for the firm. Therefore, the 4" blade option, which has the greatest negative percent change in the None option's MSP, is considered the best option from a marketing perspective.

5.3.5: Step 5 - Consider tradeoffs between results from Steps 3 & 4

Finally, the last step of the approach is to create a tradeoff plot using the results from Steps 3 and 4 in order to make a better decision about which customization option to pursue for further development. The tradeoff plot is shown below:

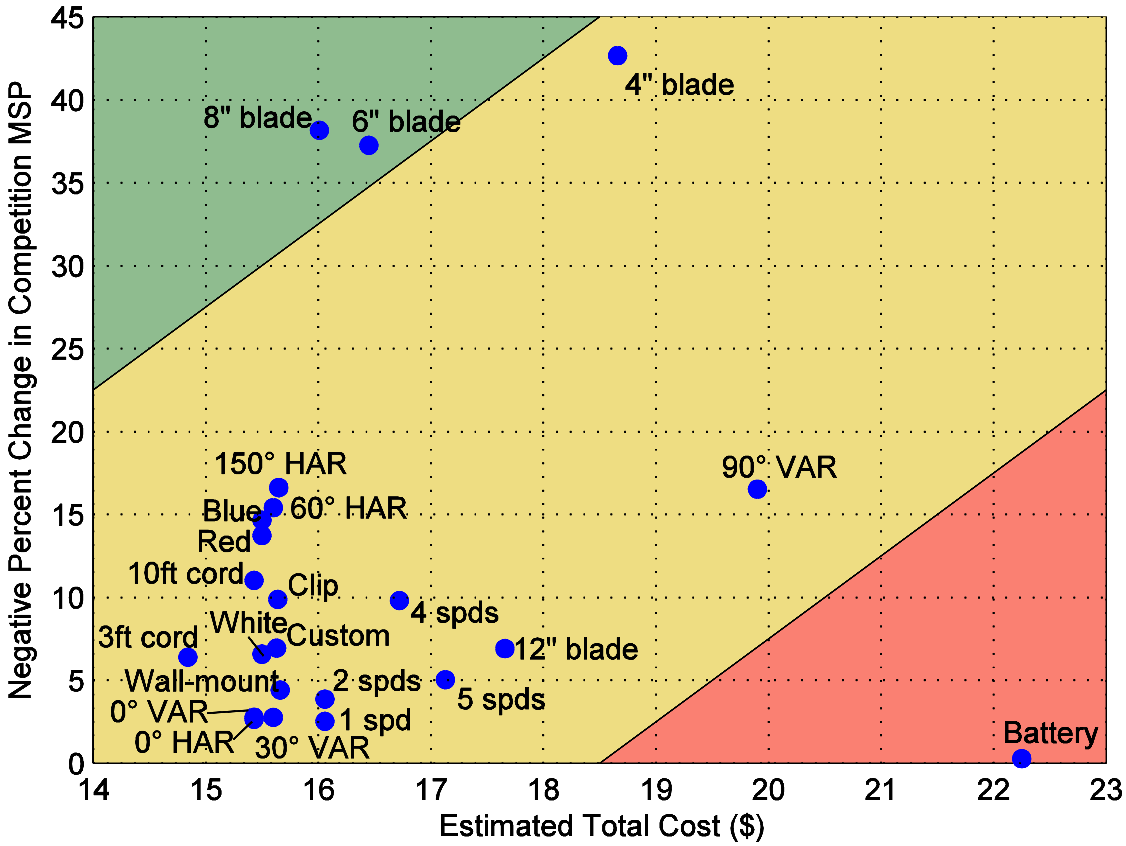


FIGURE 5.11: DESK FAN TRADEOFF PLOT

Before examining Figure 5.11, recall that the 3ft power cord option was selected as the best option from an engineering effort standpoint, while the 4" blade option was chosen as the best option from a market desirability perspective. By considering both the marketing and engineering domains in Figure 5.11, it is clear that the neither the 3ft power cord option nor the 4" blade option is the best customization option. While the 3ft cord option has the lowest estimated total cost, it also has one of the lowest negative percent changes in the competition MSP. In other words, its market desirability is not high. As for the 4" blade option, its cost is one of the highest out of all the options even though it has the highest market desirability. Therefore, from this case study, it is clear that both marketing and engineering tools should be used for customization option assessment and selection.

Instead of considering the information gained from one tool to determine which customization option to offer, information from both marketing and engineering tools can be considered in the fever chart shown in Figure 5.11 to make such a decision. In this figure, many customization options exist in the yellow region, while a few exist in the red and green regions. The battery option exists in the red region, and it should be not selected for further development because its costs are high, while its market desirability is very low. In contrast to this region, the yellow region contains a lot of customization options. Most of these options exist in the $15 and $17 cost range (as shown in Figure 5.9) and in the 5% to 20% range for increase in firm MSP. Though these costs are low and the market desirability values are decent, it is advised that these options are not pursued because of the 8" and 6" blade options that exist in the green region. For a slight increase in cost, there is a large increase in MSP gained by the firm. A conservative redesign team would likely select the 8" blade option because it has a high negative percent change in the competition MSP for an average total cost. A slightly less conservative redesign team may be willing to pay even more for the 4" blade in order to receive the increase in MSP. For the redesign team faced with the information presented in Figure 5.11, the decision to pursue the 4", 6", or 8" blade customization option into the detailed design phase will depend upon their willingness to pay extra in order to receive a boost in MSP.

Before beginning the gas grill case study, notice that the three options considered the 'best' (the 4", 6", and 8" blade options) are not related to potential Subsystems 2 or 4. The options related to these subsystems (clip, wall-mount, and all the HAR and VAR options) are relatively cheap with the exception of 90° VAR, but they are not nearly as desirable to consumers as the options related to Subsystem 6. Therefore, potential subsystems from Step 1 are not necessarily the best candidates for redesign just because they can be changed at low cost.

5.4: Gas Grill

The second case study problem focuses on the Master Forge 2-burner gas grill, as shown in the figure below:

FIGURE 5.12: 2-BURNER GAS GRILL

The relevant characteristics of this gas grill are [155]:

- 2 gas burners that use liquid propane (LP) and are ignited with an electronic ignition button
- 2 cast-iron cooking grates with a warming rack attached to the grill's lid for a total cooking area of 455 in^2
- Cabinet storage underneath the grill that holds one LP tank
- 2 foldable side tables with no tool hooks or side burners
- An analog thermometer on the grill lid with no grill lights or grill cover
- Painted steel construction with black finish, 4 casters & 44in tall
- Price: $240

5.4.1: Step 1 - Identify potential subsystems for redesign based on average changes

The first step of the proposed approach is to identify the potential subsystems from a change analysis. The sub-steps for the gas grill are shown below:

<u>Step 1.1 - Break product down into subsystems</u>

The first sub-step of this step is to break down the product into subsystems. To complete this sub-step, the instruction manual of the Master Forge grill is used to identify the following six subsystems based on function and location: grill body, control system, fuel transport system, side tables, cart system, and cooking zone. These subsystems are identified in Figure 5.13 below [155]:

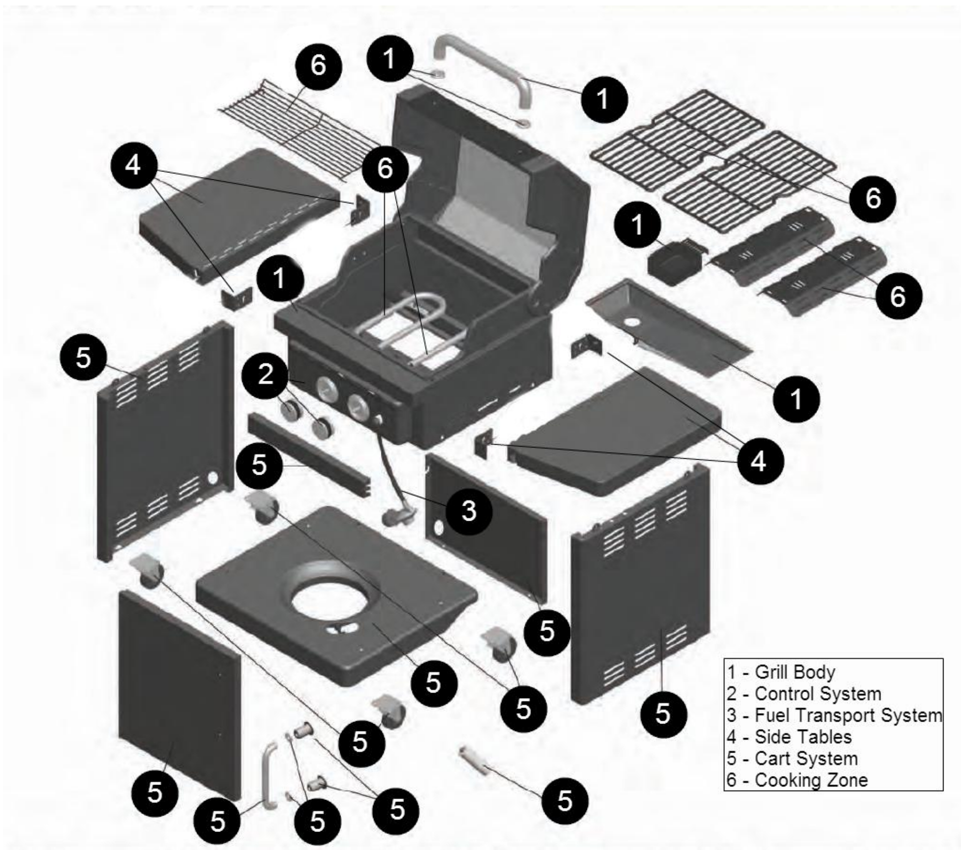


FIGURE 5.13: GAS GRILL BREAKDOWN

Before moving to Step 1.2, these six subsystems are further explained. As shown in Figure 5.13, the grill body subsystem (Subsystem 1) contains the firebox, the lid, and the grease drip pan and cup. The control subsystem (Subsystem 2) contains the controls for each burner, the electronic ignition button, and the housing for these controls. This subsystem is connected to the grill body. The fuel transport system (Subsystem 3) contains the fuel line from the LP tank to the control system that goes through the firebox (or Subsystem 1). Note that the LP tank is not included in this subsystem breakdown. Subsystem 4 contains the side tables and their connections with the grill body (or Subsystem 1). The cart system (Subsystem 5) contains everything underneath the grill body. Lastly, the cooking zone (Subsystem 6) is defined as an area inside the grill body in which the amount of heat reaching the food can be controlled through (a) the amount of fuel burned and/or (b) the height above the burning fuel. Therefore Subsystem 6 contains the 2 main burners, the cooking grates, the warming rack, and the heat tents.

<u>Step 1.2 - Create subsystem dependency DSM</u>

With the gas grill decomposed into its subsystems, the subsystem dependency DSM is created. This matrix is shown below:

TABLE 5.12: GAS GRILL SUBSYSTEM DEPENDENCY DSM

		Initiating Subsystems					
		1	2	3	4	5	6
Affected Subsystems	1		X	X	X	X	X
	2	X		X			X
	3		X				
	4	X				X	
	5	X					
	6	X	X				

Step 1.3 - Create direct likelihood and impact DSMs

The values in the direct likelihood and impact DSMs are determined from a group of engineering students with the guidance of the scales presented in Table 4.2. These values for the gas grill are shown in the below tables:

TABLE 5.13: GAS GRILL DIRECT LIKELIHOOD DSM

		Initiating Subsystems					
		1	2	3	4	5	6
Affected Subsystems	1		0.5	0.2	0.5	0.3	0.9
	2	0.2		0.6			0.7
	3		0.4				
	4	0.3				0.1	
	5	0.5					
	6	0.7	0.6				

TABLE 5.14: GAS GRILL DIRECT IMPACT DSM

		Initiating Subsystems					
		1	2	3	4	5	6
Affected Subsystems	1		0.3	0.1	0.5	0.5	0.6
	2	0.2		0.6			0.5
	3		0.4				
	4	0.3				0.3	
	5	0.5					
	6	0.7	0.6				

Step 1.4 - Calculate combined likelihood, impact, and risk DSMs

Once Tables 5.12 through 5.14 are defined, Step 1.4 is completed by using the CAM software with the settings described in Chapter 4. The combined likelihood, impact, and risk DSMs are shown in Figure 5.14 below:

Combined Likelihood		Initiating Subsystems					
		1	2	3	4	5	6
Affected Subsystems	1		0.79	0.57	0.5	0.34	0.94
	2	0.59		0.65	0.3	0.2	0.75
	3	0.26	0.4		0.13	0.09	0.33
	4	0.34	0.34	0.25		0.18	0.39
	5	0.5	0.47	0.34	0.25		0.56
	6	0.74	0.75	0.53	0.37	0.25	

Combined Impact		Initiating Subsystems					
		1	2	3	4	5	6
Affected Subsystems	1		0.55	0.47	0.5	0.51	0.63
	2	0.46		0.61	0.46	0.47	0.5
	3	0.41	0.4		0.41	0.42	0.41
	4	0.31	0.33	0.34		0.31	0.33
	5	0.5	0.54	0.55	0.5		0.54
	6	0.72	0.71	0.73	0.72	0.72	

Combined Risk		Initiating Subsystems					
		1	2	3	4	5	6
Affected Subsystems	1		0.43	0.27	0.25	0.17	0.59
	2	0.27		0.40	0.14	0.09	0.38
	3	0.11	0.16		0.05	0.04	0.14
	4	0.11	0.11	0.09		0.06	0.13
	5	0.25	0.25	0.19	0.13		0.30
	6	0.53	0.53	0.39	0.27	0.18	

FIGURE 5.14: GAS GRILL COMBINED LIKELIHOOD, IMPACT, & RISK DSMS

Step 1.5 - Determine potential subsystem(s)

After these combined matrices are determined, the potential subsystems for the gas grill are determined using the definition outlined in Chapter 4. As with the desk fan, the average rework cost of each subsystem is estimated using the same procedure (see Section 5.3.1). These cost estimates are shown below:

TABLE 5.15: GAS GRILL SUBSYSTEM AVERAGE REWORK COST ESTIMATES

Subsystem #	Percentage (%)	fix_j	$rework_j$
1	33	\$39.60	\$26.40
2	14	\$16.80	\$11.20
3	5	\$6.00	\$4.00
4	10	\$12.00	\$8.00
5	22	\$26.40	\$17.60
6	16	\$19.20	\$12.80

From Table 5.15, the subsystems with low average redesign costs are good potentials for redesign based solely on their easiness to change. Using an arbitrary cutoff amount of \$15.20 (halfway between the minimum and maximum average rework costs), Subsystems 2-4 and 6 could be potential subsystems for redesign depending upon their risk for change propagation (the highlighted cells in Table 5.15).

To determine a subsystem's risk for change propagation, risk portfolio and case risk plots can be created. The scaled risk portfolio plot for the gas grill is presented below:

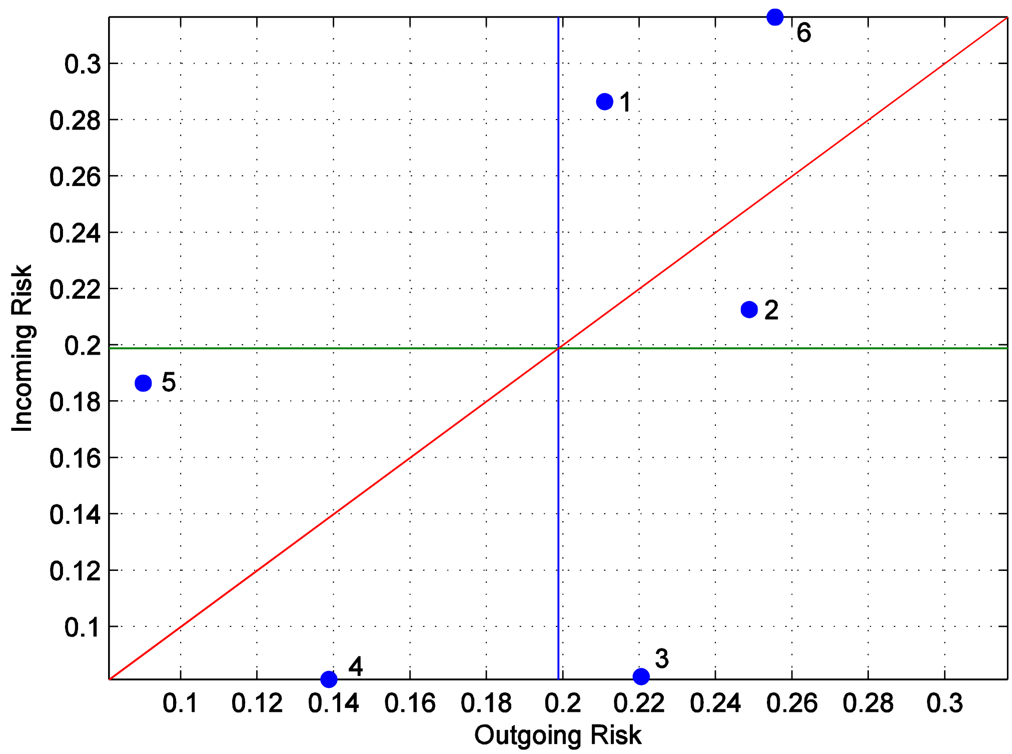


FIGURE 5.15: GAS GRILL RISK PORTFOLIO - SCALED

In analyzing Figure 5.15, subsystems close to the bottom left corner are desired, and thus Subsystems 4 and 5 are considered potential subsystems for redesign. In contrast, Subsystems 1, 2, and 6 are closer to the top right corner, indicating that these systems are high risk. Subsystem 3 is a change multiplier, similar to Subsystem 7 for the desk fan, and is therefore not considered a candidate for redesign.

As with the desk fan case study, case risk plots are created to further explore change propagation throughout the base product and identify potential subsystems. The case risk plots for each subsystem are combined into two figures with three subsystems per figure:

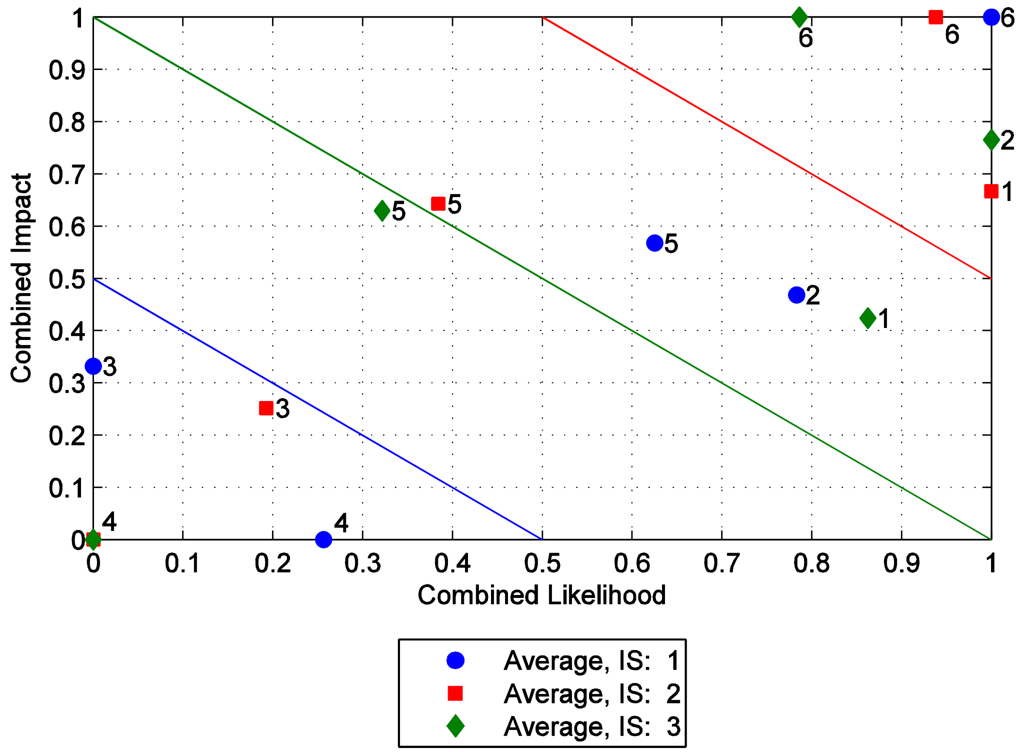


FIGURE 5.16: GAS GRILL AVERAGE CASE RISK PLOT - SCALED, IS=1-3

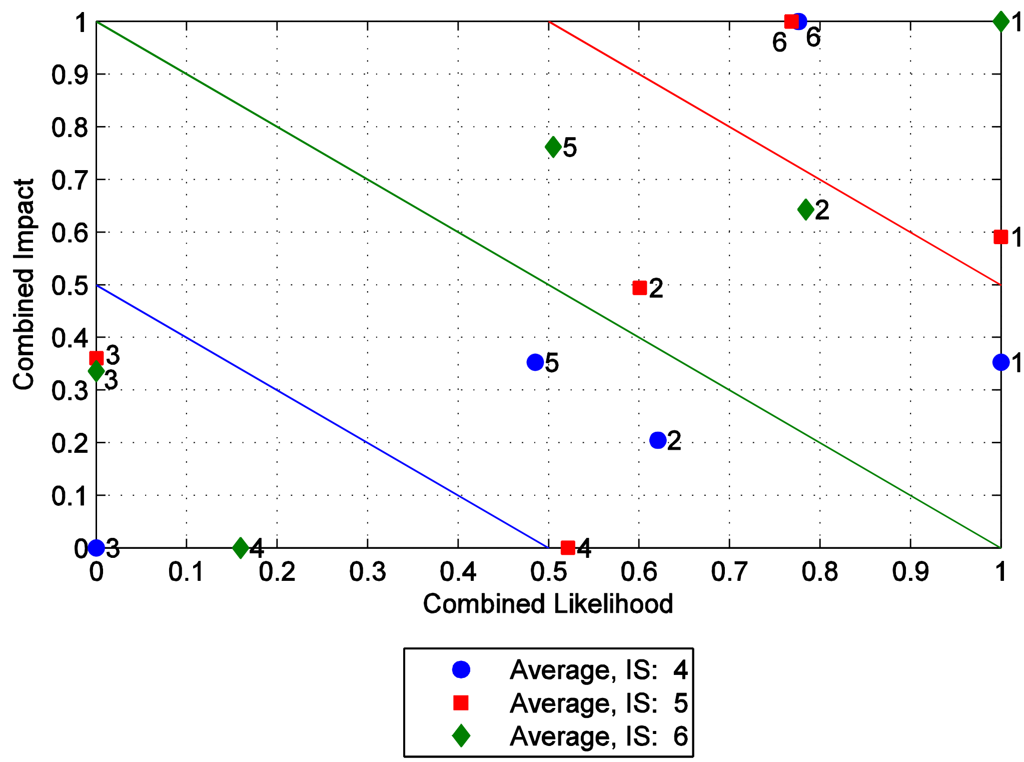


FIGURE 5.17: GAS GRILL AVERAGE CASE RISK PLOT - SCALED, IS=4-6

From Figure 5.16, Subsystems 1-3 have the majority of their affected subsystems at medium to high risk (above the green or red lines). Out of three initiating subsystems who have affected subsystems above the red line, Subsystems 2 and 3 have the highest number of affected subsystems. Therefore, all three of these subsystems are considered poor candidates for customization option development. In comparison to Figure 5.17, Subsystem 4 only has one affected subsystem at the high risk level with the remaining subsystems below the red line and most of them below the green line. Subsystems 5 and 6 have most of their affected subsystems above the green line, with Subsystem 5 having more affected subsystems above the red line. From this figure, Subsystem 4 is considered a potential subsystem, while Subsystems 5 and 6 are poor candidates due to their high risk.

By considering the observations from Table 5.15 and the above figures, the potential subsystems for redesign are identified. Table 5.15 suggests Subsystems 2-4 and 6, while the figures shown above suggest Subsystem 4. Therefore, Subsystem 4 is considered a potential subsystem for customization option development as it is easy to change with a low risk of change propagation on average.

5.4.2: Step 2 - Develop conceptual-level customization options

The second step of the proposed approach outlined in Chapter 4 is to develop conceptual-level customization options. The sub-steps for the gas grill are presented below.

Step 2.1 - Identify consumer suggestions for the base product

Unlike the desk fan case study, marketing data was available for the gas grill. In particular, marketing data from two previous surveys about grills in general was available. In these surveys, respondents were asked to comment upon what they liked and disliked about the current grill(s) they owned. These studies were fielded using college students and young business professionals. Therefore, the responses from these surveys are deemed appropriate for use in this case study. From this data, the following consumer suggestions are determined:

- Add side burner
- Add grill light
- Change under-grill storage configuration
- Add grill cover
- Add customization options

Before moving onto Step 2.2, these suggestions are further discussed. First, a few respondents suggested adding or removing the side burner to or from their current grill. For the grill shown in Figure 5.12, 'add side burner' is adopted as a consumer suggestion for Subsystem 4. Second, several respondents suggested adding a grill light to their current grill, and this suggestion is adopted as a consumer suggestion for the case study grill.

In addition to these two suggestions, responses indicated that consumers wanted different configurations for the under-grill storage. One respondent owned a gas grill whose LP tank was centered in the middle of the cart system (similar to the case study grill), and this individual suggested that the tank be moved to the left or right in order "to provide more usable space underneath [the] grill." Therefore, 'change under-grill storage configuration' is adopted as a consumer suggestion. Moreover, some respondents suggested changing their grill color, thus this suggestion is added to the list.

In comparison to the first four consumer suggestions, the last two consumer suggestions are unique. A few respondents suggested adding a grill cover to their current grill, and hence this suggestion is adopted. Customization options developed for this suggestion are considered accessory items in accordance with the customization definition defined in Chapter 4. Such options do not require a change in any subsystem because it can be accomplished without any subsystem-level changes to the base product. Therefore, the redesign effort (estimated in Step 3.6) is based solely on the effort required to design and produce the cover.

Finally, the last suggestion is very broad and can apply to any subsystem(s). One respondent commented that grill manufacturers should "provide options for add-ons such as take one side [table] off to add on a warmer [or burner] or other feature." Therefore, 'add customization options' is noted in Table 5.16 to encourage the redesign team to develop customization options in Step 2.5.

Step 2.2 - Map consumer suggestions to one or more subsystems

From these suggestions, the first three suggestions are related to subsystem-level changes to the base gas grill. Therefore, these suggestions are mapped to one or more subsystems for Step 2.2. This mapping is shown below:

TABLE 5.16: GAS GRILL CONSUMER SUGGESTIONS TO SUBSYSTEMS MAPPING

		Subsystems					
		1	2	3	4	5	6
Consumer Suggestions	Add side burner				X		
	Add grill light	X					
	Change under-grill storage configuration					X	

As can be seen in Table 5.16, each consumer suggestion is mapped to only one subsystem. The 'add grill light' suggestions is linked to the grill body (Subsystem 1) and not the cooking zone (Subsystem 6) because adding a light in direct contact with the flame was deemed to be a questionable design decision. With these options mapped to subsystems, Step 2.3 is begun for the gas grill.

Step 2.3 - Select consumer suggestions that are mapped to potential subsystem(s)

From Table 5.16, the only consumer suggestion that maps to potential Subsystem 4 is the 'add side burner' suggestion (highlighted yellow). Therefore, this suggestion is selected.

Step 2.4 - Develop conceptual-level customization options from selected suggestion(s)

Brainstorming is used to develop customization options for the 'add side burner' suggestion. The following options are developed at the level of detail present in the third entry of Figure 4.2:

- Change side table specifications from no side burner or tool hooks to:
    - 2 tool hooks per side table
    - 4 tool hooks per side table
    - 1 side burner and no tool hooks
    - 1 side burner and 2 tool hooks per side table
    - 1 side burner and 4 tool hooks per side table

Step 2.5 - If desired, develop additional customization options

To complete Step 2, optional Step 2.5 is implemented, and other customization options are created based off of the remaining consumer suggestions and concept generation techniques. Students from the spring 2013 MAE 495 - Product Design Management course were used to develop additional customization options. Groups of 3-5 students were created (a total of 38 students divided into 9 groups) and asked to develop customization options for the case study grill. Specifically, each group was given the grill's instruction manual and asked to use concept generation techniques to develop as many customization options as possible. In all, 196 different customization options were developed using mind-maps, brainstorming, and the gallery method. From these options, a few are selected and modified, where necessary, to exist at the necessary level of detail. Options are selected to satisfy the consumer suggestions identified in Step 2.1. These options are listed below:

- Change lid opening mechanism from manual to:
    - Spring-assisted
    - Hydraulic-assisted
    - Motorized
- Change total grill height from 46in to:
    - 44in
    - 48in
    - 42in
    - 40in
    - Adjustable from 40in to 48in
- Change grill color from black to:
    - Brown
    - Red

- Green
- Blue
- No paint (bare metal)

- Change grill cover from absent to:
  - Black cover
  - Brown cover
  - Tan cover
  - Green cover
  - Black cover with a sport's team logo
- Change under-grill cabinet storage configuration from one LP tank to:
  - 2 LP tanks (one as a back-up tank)
  - 1 LP tank plus three fixed shelves
  - 1 LP tank plus three, vertically adjustable shelves
  - 1 LP tank plus a trash can
  - 1 LP tank plus a small, insulated cooler
- Change cooking zone specifications from 2 main burners and a warming rack (3 zones) to:
  - 2 main burners and 2 warming racks (4 zones)
  - 3 main burners and a warming rack (4 zones)
  - 2 main burners and 3 warming racks (5 zones)
  - 3 main burners and 2 warming racks (5 zones)
  - 4 main burners and a warming rack (5 zones)
- Change grill accessories from analog thermometer and no grill light to:
  - Analog thermometer and a grill light on the lid handle
  - Analog thermometer and a grill light inside the lid

- Digital thermometer and no grill light
- Digital thermometer and a grill light on the lid handle
- Digital thermometer and a grill light inside the lid

From this list of customization options, all the consumer suggestions listed in Table 5.16 are addressed. Additionally, all of these options are related to one subsystem (with the exception of grill color and cover), and these mappings are formerly presented in the next section.

5.4.3: Step 3 - Conduct change analysis for the options

The third step of the proposed approach is to conduct a change analysis for the customization options. The sub-steps for the gas grill are shown below.

Step 3.1 - Select customization options for analysis

As with the desk fan example, customization options related to the subsystem identified in Step 1.5 (Subsystem 4) and non-potential subsystems are selected for analysis.

Step 3.2 - Map customization options to base product's subsystems

For Step 3.2, the mappings between the customization options and the subsystems of the grill shown in Figure 5.12 are shown in the table below:

TABLE 5.17: MAPPING CUSTOMIZATION OPTIONS TO GRILL SUBSYSTEMS

Customization Options	Subsystem #
2 THs/table	4
4 THs/table	4
1 SB, 0 THs	4
1 SB, 2 THs/table	4
1 SB, 4 THs/table	4
Spring-assisted lid opening	1
Hydraulic-assisted lid opening	1
Motorized lid opening	1
46in height	5
48in height	5
42in height	5
40in height	5
Adjustable height	5
Brown gas grill	1, 2, 4, 5
Red gas grill	1, 2, 4, 5
Green gas grill	1, 2, 4, 5
Blue gas grill	1, 2, 4, 5
Bare metal gas grill	1, 2, 4, 5
Black grill cover	N/A
Brown grill cover	N/A
Tan grill cover	N/A
Green grill cover	N/A
Black grill cover with sport's team logo	N/A
2 LP tanks	5
LP tank plus 3 fixed shelves	5
LP tank plus 3 adjustable shelves	5
LP tank plus trash can	5
LP tank plus small, insulated cooler	5
2 MBs, 2 WRs	6
3 MBs, 1 WR	6
2 MBs, 3 WRs	6
3 MBs, 2 WRs	6
4 MBs, 1 WR	6
Analog thermometer, lid handle grill light	1
Analog thermometer, inside lid grill light	1
Digital thermometer, no grill light	1
Digital thermometer, lid handle grill light	1
Digital thermometer, inside lid grill light	1

In Table 5.17, SB, TH, MB, and WR are acronyms for side burner, tool hook, main burner, and warming rack, respectively. From this table, all the customization options, excluding the grill color and cover options, are mapped to one subsystem. Notice that the height options are mapped to Subsystem 4 (the Cart System) because these options are anthropological and attempt to allow the consumer to grill comfortably at a height appropriate for him/her. Since each option is linked to one initiating subsystem, the CPM can be used to evaluate these customization options.

The grill color options are considered emotion-focused system-level changes, so the CPM method is not needed. Notice these options that are mapped to Subsystems 1, 2, 4, and 5. Subsystems 3 and 6 are considered not affected by the color options because Subsystem 3 is hidden inside Subsystem 5, and Subsystem 6 is in direct contact with flames and intense heat. The grill cover options do not propagate change because they are not mapped to any subsystem; a subsystem does not initiate a change to enable these customization options.

Step 3.3 - Determine direct likelihood and impact values for the options

With the mapping shown above, the direct likelihood and impact values for each customization option are determined to fulfill Step 3.3. As discussed in Section 4.5.3, related customization options are compared to each other and the relationships between values of affected subsystems are compared to help determine these values. These tables, along with a brief discussion of the thought process used to obtain them, are presented in Appendix C. An important observation from this sub-step is that a change dependency, not originally present from Step 1.3, is added for the customization options that added a side burner.

Step 3.4 - Replace these values with the ones created in Step 1

Once the direct likelihood and impact values are determined for each customization option, the old values from Step 1 are replaced with these values. The columns associated with the initiating subsystems are replaced in each matrix, as shown in Figure 4.13.

Step 3.5 - Calculate the combined likelihood, impact, and risk DSMs

After replacing the old direct likelihood and impact values with the ones determined in Step 3.2, the CAM software with the CPM toolbox is used to calculate the likelihood, impact, and risk DSMs for each customization option. These values are presented in Appendix D, and the $\boldsymbol{r_k(i \rightarrow j)}$ values are the values shown in the risk DSMs.

Step 3.6 - Compute total redesign effort for the customization options

The last sub-step of Step 3 is to compute the total redesign effort for the customization options. To complete this step, the $\boldsymbol{fix_j}$ and $\boldsymbol{rework_j}$ values from Table 5.15 are used, and the $\boldsymbol{rework_{k,i}}$ and $\boldsymbol{E_{k,i \rightarrow j}}$ values are estimated. The $\boldsymbol{rework_{k,i}}$ values are estimated using the same procedure discussed for the desk fan (the impact values for the initiating subsystems are shown in Appendix C), and these values are presented in Table 5.18. The same procedure described for estimating $\boldsymbol{E_{k,i \rightarrow j}}$ is used for the gas grill, and, similar to the desk fan, the values for $\boldsymbol{E_{k,i \rightarrow j}}$ are all 1, except for the 2 MBs, 3 WRs option and the 4 MBs, 1 WR option. For the 2 MBs, 3 WRs option, $\boldsymbol{E_{2MBs/3WRs,6 \rightarrow 1}}$ is 2 because Subsystem 1 is expected to add two interfaces to accommodate the two additional warming racks. For the 4 MBs, 1 WR option, $\boldsymbol{E_{4MBs/1WR,6\rightarrow1}}$ is 3 because Subsystem 1 is expected to change shape and add 2 interfaces to accommodate the extra burner. Also for this option, $\boldsymbol{E_{4MBs/1WR,6\rightarrow2}}$ is 2 because Subsystem 2 is expected to add 2 interfaces to allow the two burners to be controlled. With all the parameters estimated, Equation 4.2 is used to estimate the total cost for each customization option induced by a subsystem-level change.

To estimate the total cost for the emotional system-level changes (i.e.: the color options), the same procedure used for the desk fan is adopted. However, unlike the desk fan, not all the manufacturing and material costs for all subsystems are considered (see Table 5.17). Lastly, to estimate the total cost for the accessory changes (i.e.: the grill covers), a grill cover produced by Master Forge for $25 is found. A 100% markup is assumed so cost is estimated at $12.50, and this value is added onto the total cost of the base grill ($120). The black cover with the logo option is assumed to be 25% more to account for the copyright royalties.

With all these estimates complete, the total costs for all the customization options are shown in the below table:

TABLE 5.18: GAS GRILL ESTIMATED TOTAL COSTS

Customization Options	$rework_{k,i}$	$ETC_{k,i}$
2 THs/table	$0.90	$120.90
4 THs/table	$1.80	$121.80
1 SB, 0 THs	$5.20	$166.08
1 SB, 2 THs/table	$6.10	$166.98
1 SB, 4 THs/table	$6.60	$167.48
Spring-assisted lid opening	$4.64	$124.64
Hydraulic-assisted lid opening	$6.96	$126.96
Motorized lid opening	$11.60	$137.60
46in height	$2.00	$122.00
48in height	$2.24	$122.24
42in height	$1.52	$121.52
40in height	$1.28	$121.28
Adjustable height	$10.64	$136.92
Brown gas grill	N/A	$123.16
Red gas grill	N/A	$123.16
Green gas grill	N/A	$123.16
Blue gas grill	N/A	$123.16
Bare metal gas grill	N/A	$116.84
Black grill cover	N/A	$132.50
Brown grill cover	N/A	$132.50
Tan grill cover	N/A	$132.50
Green grill cover	N/A	$132.50
Black grill cover with sport's team logo	N/A	$135.63
2 LP tanks	$6.16	$146.96
LP tank plus 3 fixed shelves	$5.22	$138.35
LP tank plus 3 adjustable shelves	$7.96	$141.09
LP tank plus trash can	$3.89	$141.64
LP tank plus small, insulated cooler	$7.91	$148.71
2 MBs, 2 WRs	$2.68	$136.42
3 MBs, 1 WR	$5.06	$145.97
2 MBs, 3 WRs	$4.72	$156.94
3 MBs, 2 WRs	$7.10	$156.54
4 MBs, 1 WR	$8.20	$186.68
Analog thermometer, lid handle grill light	$2.07	$122.07
Analog thermometer, inside lid grill light	$6.78	$126.78
Digital thermometer, no grill light	$1.82	$121.82
Digital thermometer, lid handle grill light	$3.89	$123.89
Digital thermometer, inside lid grill light	$8.60	$128.60

Given the assumptions about the estimated cost data, the estimated total costs in Table 5.18 are analyzed, and a customization option is chosen based on engineering effort (recall that the only one customization option is offered at a time). To visualize the range of the cost values, a scatter plot is created:

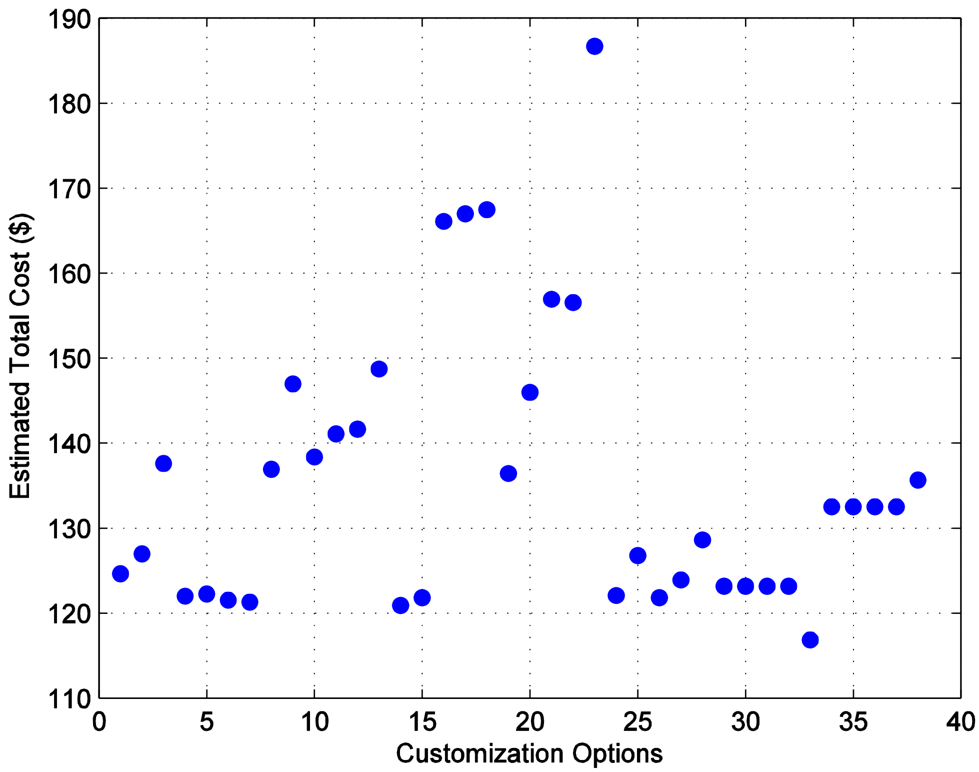


FIGURE 5.18: GAS GRILL ETC SCATTER PLOT

Unlike the desk fan, the estimated total costs are more scattered, yet it is clear that most customization options are within the $120 to $140 range. On average, the redesign team should expect to pay $135.63 for a customization option ($15.63 greater than the cost of the base gas grill). If a redesign team is considering the best option from each grouping, the following options would be considered, listed in order from least expensive to most expensive:

- Bare metal, or no paint, at $116.84
- 2 tool hooks per table at $120.90
- 40in total grill height at $121.28
- Digital thermometer with no grill light at $121.82
- Spring-assisted lid opening mechanism at $124.64
- Any grill cover, except the logo one, at $132.50 each
- 2 main burners plus 2 warming racks at $136.42
- LP tank plus 3, fixed shelves at $138.35

From this list, it is clear that the best customization option to pursue, based solely on engineering effort, is the no paint option at $116.84 (less than the cost of the base gas grill). The next best customization option is the 2 THs/table option at $120.90 (just $0.90 higher than the base product's cost). The worst option to pursue is the 4 MBs, 1 WR option at $186.68. Though these conclusions are drawn about which customization option to pursue, the marketing domain must be considered, as is done in Step 4 below.

5.4.4: Step 4 - Gather and evaluate consumer preferences for the options

The fourth step of the proposed approach is to gather and evaluate consumer preferences for the developed customization options. The sub-steps for the gas grill are presented below.

Step 4.1 - Create discrete choice conjoint survey attributes and levels from options

The customization options listed above are left in their respective groupings, and attributes and levels are developed with Sawtooth's recommendations in mind. These attributes and levels are displayed in the below table:

TABLE 5.19: GAS GRILL ATTRIBUTES & LEVELS

Levels		Lid Opening	Total Height	Color	Cover	Storage Configuration	Side Table	Cooking Zone	Accessory Details	Price ($)
	1	Manual	44in	Black	Absent	LP tank only	0 SBs, 0 THs	2 MBs, 1 WR	A	Base-$20
	2	Spring-assisted	46in	Brown	Black	2 LP tanks	2 THs/table	2 MBs, 2 WRs	A,h	Base
	3	Hydraulic-assisted	48in	Red	Brown	LP tank + 3 fixed shelves	4 THs/table	3 MBs, 1 WR	A,i	Base+$30
	4	Motorized	42in	Green	Tan	LP tank + 3 vertically adjustable shelves	1 SB, 0 THs	2 MBs, 3 WRs	D	Base+$60
	5		40in	Blue	Green	LP + trash can	1 SB, 2 THs/table	3 MBs, 2 WRs	D,h	Base+$90
	6		Adjustable (40in to 48in)	No paint	Black with sport's team logo	LP + small insulated cooler	1 SB, 4 THs/table	4 MBs, 1 WR	D,i	Base+$120
	7									Base+$150

In Table 5.19, the acronyms SB, TH, MB, WR, A, A,h, A,i, D, D,h, and D,i stand for side burner, tool hook, main burner, warming rack, analog thermometer with no grill light, analog thermometer with lid handle grill light, analog thermometer with inside lid grill light, digital thermometer with no grill light, digital thermometer with lid handle grill light, and digital thermometer with inside lid grill light, respectively. Notice that the base product's specifications are present in this table (specifically, all the first levels of each attribute correspond to the base product). These levels are needed to complete Steps 4.4 and 4.5. Similar to the desk fan, a price attribute is added to the discrete choice conjoint survey to obtain consumer preference information on price. However, in contrast to the desk fan, the price attribute is set-up differently. Instead of explicitly stating the total price of the customized grill, the price is represented in relation to dollars taken away or added to the base price of the grill shown in Figure 5.12. The price can increase or decrease from the base price depending upon the customization option selected.

Step 4.2 - Determine discrete choice survey design, including additional questions

Not only is the price attribute set-up differently for this case study, but also the entire discrete choice conjoint survey design is set-up differently. For the new survey configuration, respondents first select their base grill from a set of three grills in a product family, and then they are taken to one of three discrete choice conjoint surveys based on their selection of the base grill. With the Chapter 2 product review in mind, it is clear that this set-up better represents the process of purchasing a customized product. Consider a consumer buying a Dell computer. First, he/she selects a product from a group of products (a product family), and then he/she chooses the options for the selected product. However, this thesis only uses the results from the discrete choice survey whose baseline product matches the foundational product for this case study.

For the survey design, three product profiles are presented per task, a Balanced Overlap design scheme is adopted, a Dual-Response None option is used, and a total of twelve tasks are asked including two holdout tasks. The Dual-Response None option is used instead of the traditional None option for two reasons. First, it better represents actual purchase scenarios [65]. Second, consumer preference information is not lost when the None option is selected, as it could with the traditional None option. This second point is considered important because, due to the set-up of the survey (select base product first and then answer task questions), it is expected that responses will be spread over the three surveys, and the number of responses could be lower than required from Equation 4.3. If responses are low for a survey and the None option is selected often, consumer preference information could be lost with the traditional None option, but more information would be preserved with the Dual-Response None option. Hence, the Dual-Response None option is used for this case study. A screen shot of a task question for the gas grill conjoint survey is shown below:

Grill Customization Conjoint Survey

Base Grill

Brand	Master Forge
Fuel Source	Liquid Propane (LP)
Cooking Area & Cooking Grate	455 in^2 area (~22 burgers) with cast-iron grates
Number of Primary Cooking Zones	3
Grill Finish & Mobility	Painted steel with 4 wheels
Side Tables, Side Burners & Tool Hooks	2 side tables with no burners or tool hooks
Under-Grill Storage Configuration	Cabinet storage with LP tank only
Grill Footprint Shape	Square
Grill Lid Opening Mechanism	Manual
Total Grill Height with Lid Closed	44 in
Accessories	Electronic ignition, analog thermometer, no grill cover
Grill Color	Black
Base Price	$240

From this set of customization options, which would you most likely purchase for the base grill shown above?
Choose by clicking one of the buttons below:

Grill Lid Opening Mechanism	Motorized	Hydraulic-assisted	Spring-assisted
Total Grill Height with Lid Closed	Adjustable from 40 in to 48 in	Decrease 4 in (total of 40 in)	Increase 4 in (total of 48 in)
Grill Color	Brown	Red	Blue
Grill Cover	Green grill cover	Green grill cover	Tan grill cover
Under-Grill Cabinet Storage Configuration	2 LP tanks (one back-up tank)	LP tank plus small insulated cooler	Standard configuration (LP tank only)
Side Table Specifications	One side burner, 2 tool hooks per table	No side burner, 4 tool hooks per table	One side burner, 4 tool hooks per table
Cooking Zone Specifications	5 zones - 3 main burners plus 2 warming racks	4 zones - 2 main burners plus 2 warming racks	5 zones - 2 main burners plus 3 warming racks
Accessory Details	Analog thermometer, grill light inside lid	Digital thermometer, no grill light	Analog thermometer, grill light on lid handle
New Price	Base - $20	Base - $20	Base + $150
	○	○	○

Given what you know about the market, would you really buy the customized grill you chose above?

- Yes
- No

Next

FIGURE 5.19: GAS GRILL TASK QUESTION EXAMPLE

As shown in Figure 5.19, the base grill's characteristics are shown as a reminder to the respondent so they can compare the base grill with the customized grills. In contrast to the desk fan survey, the attributes dealing with color are made unambiguous by including color blocks.

Step 4.3 - Field discrete choice conjoint survey, gather data, & create preference model

After the survey was created and posted on the web, it was distributed via social media sites, grill and outdoor cooking forums, and e-mails to obtain as many responses as possible. From this distribution, a total of 112 respondents were obtained between all three surveys. Only 29 respondents were obtained for the survey matching the baseline product used in this case study. Although the number of respondents for this survey is below the minimum number predicted by Equation 4.3, it is deemed acceptable for the purposes of this thesis, whose main goal is to demonstrate the proposed approach. If the proposed approach is used in an industry setting, then more responses should be obtained in order to create a more reliable consumer preference model.

With the respondent data downloaded from the website, individual part-worth values are computed. Sawtooth Software's CBC/HB software is used with a majority of the default software settings implemented. The number of iterations before using results and both skip factors are altered from their default values. Specifically, the number of iterations before using results is set to 20,000 instead of 10,000 and both skip factors are set to 100. Also, similar to the desk fan, the price levels are constrained such that the lowest price is always favorable. Once the individual-level part-worths are obtained, current and potential market scenarios are evaluated with respect to market share of preference.

Step 4.4 - Evaluate current market scenario

Similar to the desk fan, the current market scenario is assumed to be the base product (shown in Figure 5.12) and the None, or walk-away, option. Then, a scheme is developed to map the independent attributes to the dependent price attribute. Similar to the desk fan case study, the pricing scheme for the grill is subjectively developed, but it considers the redesign costs for each customization option from Step 3. For the purposes of this thesis, the prices are assumed to be a multiple of the total redesign cost. As mentioned in Chapter 4, these costs and the price sensitivity of consumers should be considered if the proposed approach is used in an industry setting. Notice that the base price of $240 is obtained, and, for any given configuration, the price stays within the tested levels. The price scheme for the case study grill is shown in the below table:

TABLE 5.20: GAS GRILL ATTRIBUTE CHANGE IN BASE PRICE SCHEME

		Attributes							
		Lid Opening	Total Height	Color	Cover	Storage Configuration	Side Table	Cooking Zone	Accessory Details
Levels	1	+$0	+$0	+$0	+$0	+$0	+$0	+$0	+$0
	2	+$5	+$2	+$0	+$25	+$20	+$1	+$5	+$2
	3	+$10	+$4	+$0	+$25	+$10	+$2	+$10	+$6
	4	+$15	-$2	+$0	+$25	+$15	+$30	+$10	+$2
	5		-$4	+$0	+$25	+$10	+$31	+$15	+$4
	6		+$15	-$10	+$30	+$30	+$32	+$20	+$8
	7								

With the price scheme shown in Table 5.20, Equation 4.4 is used to calculate the market share of preference (MSP) values for the base grill and the None option, and these values are determined to be 48.09% and 51.91%, respectively.

Step 4.5 - Evaluate potential market scenarios from offering customization options

To complete Step 4, each customization option is analyzed as a new product offering, the MSP values are calculated using Equation 4.4, and these results are presented in the below table:

TABLE 5.21: GAS GRILL MSP VALUES FOR MARKET SCENARIOS

Market Scenario	Option Product MSP (%)	Base Product(s) MSP(%)	Competitor Product(s) MSP (%)	% Change in Competitor Product(s)	% Change in Base Product(s)
Current	0	48.09	51.91	N/A	N/A
2 THs/table	22.00	28.82	49.19	-5.24	-40.09
4 THs/table	34.75	19.30	45.94	-11.48	-59.87
1SB, no THs	26.50	23.92	49.58	-4.48	-50.26
1 SB, 2 THs/table	6.69	42.49	50.82	-2.09	-11.66
1 SB, 4 THs/table	11.13	40.31	48.55	-6.45	-16.18
Spring-assisted lid opening	11.32	39.37	49.31	-5.00	-18.14
Hydraulic-assisted lid opening	5.06	43.07	51.87	-0.06	-10.45
Motorized lid opening	6.33	44.16	49.51	-4.62	-8.19
46in height	6.37	41.87	51.75	-0.29	-12.93
48in height	9.48	40.05	50.47	-2.77	-16.72
42in height	22.85	29.51	47.64	-8.21	-38.64
40in height	4.08	44.39	51.53	-0.73	-7.70
Adjustable height	10.40	39.25	50.34	-3.01	-18.39
Brown gas grill	24.69	25.94	49.37	-4.88	-46.07
Red gas grill	38.57	12.41	49.02	-5.57	-74.19
Green gas grill	29.83	21.43	48.74	-6.10	-55.44
Blue gas grill	33.41	16.82	49.77	-4.11	-65.03
Bare metal gas grill	0.50	47.60	51.90	-0.01	-1.02
Black grill cover	25.83	26.24	47.92	-7.67	-45.44
Brown grill cover	9.84	40.96	49.20	-5.20	-14.83
Tan grill cover	5.43	44.40	50.17	-3.34	-7.67
Green grill cover	3.68	45.83	50.49	-2.73	-4.71
Black grill cover with sport's team logo	6.87	44.23	48.91	-5.78	-8.04

TABLE 5.21 CONTINUED

2 LP tanks	15.06	34.48	50.46	-2.78	-28.32
LP tank plus 3 fixed shelves	28.29	27.12	44.60	-14.08	-43.62
LP tank plus 3 adjustable shelves	25.70	26.50	47.80	-7.91	-44.90
LP tank plus trash can	33.46	26.23	40.31	-22.34	-45.46
LP tank plus small, insulated cooler	20.57	30.35	49.08	-5.45	-36.90
2 MBs, 2 WRs	17.33	35.48	47.19	-9.08	-26.22
3 MBs, 1 WR	20.58	32.57	46.85	-9.74	-32.27
2 MBs, 3 WRs	13.68	38.77	47.55	-8.39	-19.39
3 MBs, 2 WRs	0.52	47.87	51.61	-0.56	-0.47
4 MBs, 1 WR	7.47	41.76	50.77	-2.18	-13.18
Analog thermometer, lid handle grill light	12.83	36.57	50.61	-2.50	-23.97
Analog thermometer, inside lid grill light	9.20	40.67	50.13	-3.42	-15.44
Digital thermometer, no grill light	15.10	36.07	48.83	-5.92	-25.01
Digital thermometer, lid handle grill light	16.97	33.66	49.37	-4.89	-30.02
Digital thermometer, inside lid grill light	11.35	38.28	50.37	-2.96	-20.41

Using the percent change values in Table 5.21, the best customization option based on consumer desirability is determined. As discussed in Chapter 4, the ideal customization option is one that has zero percent change in the base product's MSP and a large negative percent change in the competition's MSP (which is the None option for this case study, just as it was for the desk fan case study). A poor customization option is one that has a large negative percent change in the base product's MSP (cannibalization of the base product's sales by the customization option), and zero change in the None option's MSP. The option with the largest negative percent change in the None option's MSP is the LP tank plus trash can option at -22.34%, while the option with the smallest negative percent change in the None option's MSP is bare metal (or no paint) option at -0.01% (so the option takes its MSP from the base product). From these two options, the LP tank plus trash can option is the more desirable one from a marketing standpoint because the None option loses more MSP. The option with the least negative percent change in the base product's MSP is the 3 MBs, 2 WRs option at -0.47%, while the option with the largest negative percent change in the base product's MSP is the red gas grill at -74.19%. From these two options, the 3 MBs, 2 WRs option is the more desirable one from a marketing standpoint because the base product loses less MSP. Though percent change in the base product's MSP indicates cannibalization, the percent change in the None option's MSP is deemed more important because it indicates the total gain in MSP for the firm. Therefore, the LP tank plus trash can option, which has the greatest negative percent change in the None option's MSP, is considered the best option from a marketing perspective.

5.4.5: Step 5 - Consider tradeoffs between results from Steps 3 & 4

Finally, the last step of the approach is to create a tradeoff plot using the results from Steps 3 and 4 in order to make a better decision about which customization option to pursue for further development. The tradeoff plot is shown below:

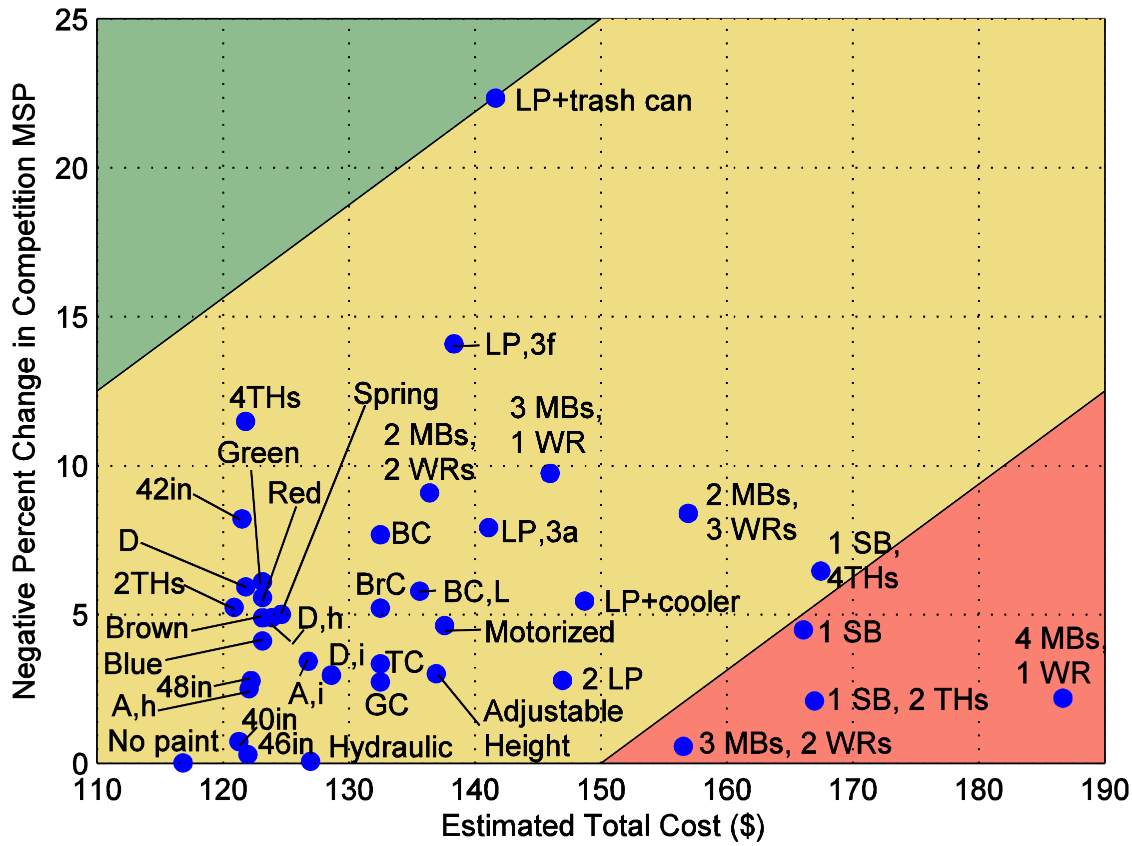


FIGURE 5.20: GAS GRILL TRADEOFF PLOT

In Figure 5.20, D stands for digital thermometer, A,h stands for analog thermometer with handle grill light, D,h stands for digital thermometer with handle grill light, A,i stands for analog thermometer with grill light inside lid, D,i stands for digital thermometer with grill light inside lid, BC stands for black grill cover, BC,L stands for black grill cover with sport's team logo, BrC stands for brown grill cover, TC stands for tan grill cover, GC stands for green grill cover, LP,3f stands for LP tank plus 3 fixed shelves, and LP,3a stands for LP tank plus 3 vertically-adjustable shelves.

From Step 3.6, the no paint (or bare metal) customization option was identified as the best option based on engineering effort, and, from Step 4.5, the LP tank plus trash can was chosen as the best option based on marketing desire. By looking at Figure 5.20, it is clear that the no paint (or bare metal) option is certainly not the best option because it has practically zero increase in MSP for the firm. However, for some redesign teams, the LP plus trash can option can be considered the best option shown in Figure 5.20. Clearly, this option is the best, by far, with regard to market desirability, but it also total cost that is just outside the $120 to $140 window identified in Figure 5.18. Therefore, this option may be considered a good option for further development in the detailed design phase. Other options that may be good options include the 4 THs/table option and the LP plus 3 fixed shelves option. Options to avoid, based on Figure 5.20, include options that add a side burner or main burner. The final decision regarding which option to pursue is at the discretion of the redesign team and their evaluation of the tradeoffs presented above.

As with the desk fan, notice that only one of the options identified as a candidate for further development during the redesign process is associated with potential Subsystem 4 identified in Step 1. Again, potential subsystems from Step 1 are not necessarily the best candidates for redesign. In contrast to the desk fan example, notice that the options related to potential Subsystem 4 are, on average, more expensive than many of the other subsystems. An explanation is given in the following section.

5.5: Assessing Approach Validity

In this section, the approach proposed in Chapter 4 and implemented above is partially validated. The approach could not be completely validated due to the inability to make comparison to a historical change case. This validation is left for future work. For this section, the approach is analyzed in two ways:

- For each case study, the estimated total costs from Step 3.6 are averaged for each initiating subsystem to explore the costs associated with potential subsystems induced by customization options.
- For each case study, a new tradeoff plot is created using the combined risk values from Step 1.4. By comparing the new chart with the one produced in Step 5, the affect and validity of the proposed modification to the CPM is examined.

5.5.1: Potential Subsystem Average Cost Analysis

The estimated total costs are averaged for the initiating subsystems of the desk fan by using the values presented in Table 5.6. These average costs are shown in the below table:

TABLE 5.22: AVERAGE COSTS FOR DESK FAN INITIATING SUBSYSTEMS

Initiating Subsystem	Average Cost
Subsystem 2	$15.65
Subsystem 3	$16.49
Subsystem 4	$16.27
Subsystem 6	$17.19
Subsystem 8	$17.51

In Table 5.22, Subsystems 2 and 4 have the lowest average cost and were also identified as potential subsystems in Step 1.5. Also, the relationship between Subsystems 2 and 4 is maintained in the average cost data shown above. From Table 5.4 and Figure 5.4, Subsystem 2 costs less to change and had a lower risk for change propagation than Subsystem 4. Overall, this data supports the idea that a potential subsystem is, on average, easy to change with low risk for change propagation to other subsystems.

However, when the gas grill case study is observed, a different result is obtained. The average costs for the grill's initiating subsystems are shown below:

TABLE 5.23: AVERAGE COSTS FOR GAS GRILL INITIATING SUBSYSTEMS

Initiating Subsystem	Average Cost
Subsystem 1	$146.47
Subsystem 4	$148.65
Subsystem 5	$134.07
Subsystem 6	$156.61

Subsystem 4 was the potential subsystem identified in Step 1.5, yet in Table 5.23 it has the second highest average cost. At first glance, it is expected that the potential subsystem would have the lowest average cost, as was the case for the desk fan. However, the identification of potential subsystems in Step 1.5 is based on average changes. If non-average changes occur for a subsystem, then the classification of potential subsystem may be lost. Recall for Step 3.3 that an additional change relationship had to be added for the side burner customization options that was not present from the average change analysis done in Step 1. This type of change was not considered an average change when Step 1 was done, thus explaining the higher cost of Subsystem 4. The takeaway from this discussion is that potential subsystems are a good starting point for customization option development, but, depending on the type of change induced, they may or may not be a low cost subsystem.

5.5.2: Tradeoff Plot Analysis

In this section, a new tradeoff plot is created by using the combined risk values obtained during Step 1.4 instead of the combined risk values obtained during Step 3.5. The $\boldsymbol{fix_j}$, $\boldsymbol{rework_j}$, $\boldsymbol{rework_{k,i}}$, and $\boldsymbol{E_{k,i\rightarrow j}}$ values obtained in Step 3.6 are kept the same. Also, it is noted that by changing the combined risk values, only the estimated redesign costs will change for the customization options induced by a subsystem-level change; the prices were kept the same. To make the analysis easier, only subsystem-level options are plotted. The tradeoff plots for the desk fan are shown below:

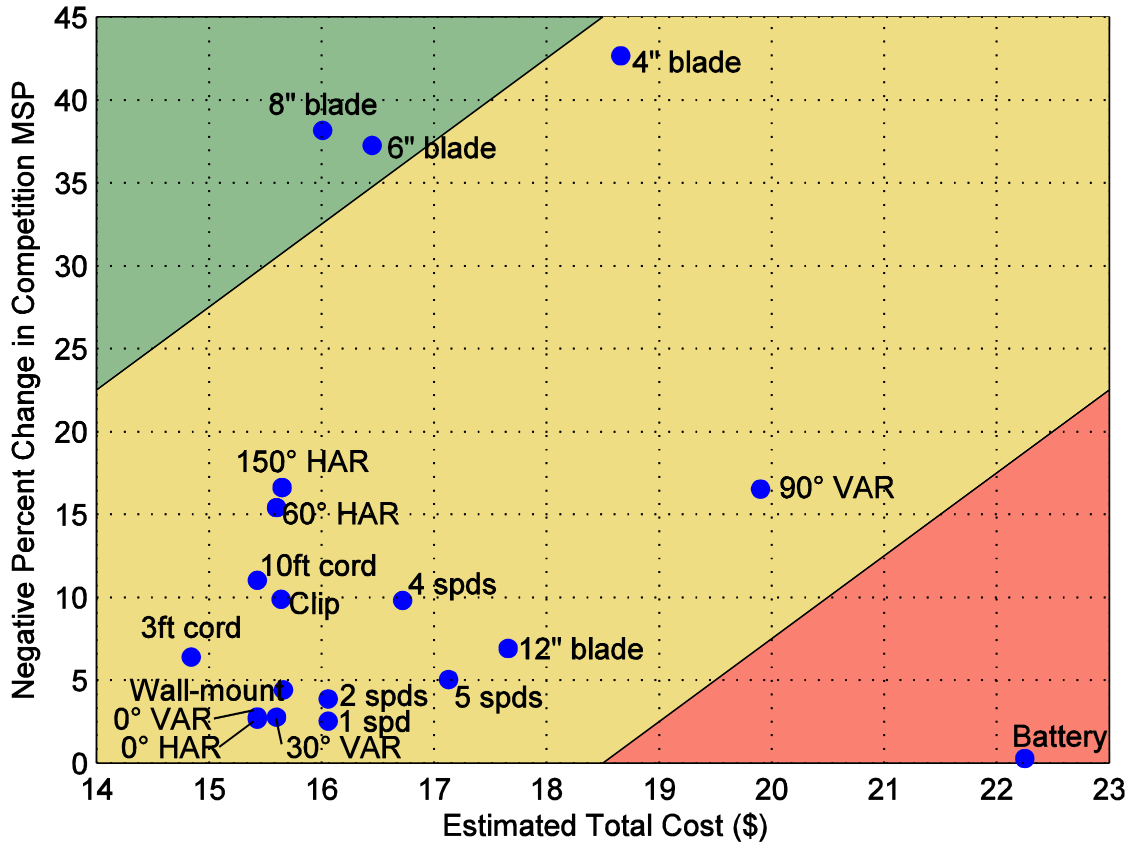


FIGURE 5.21: DESK FAN TRADEOFF PLOT, STEP 3.5 RISKS

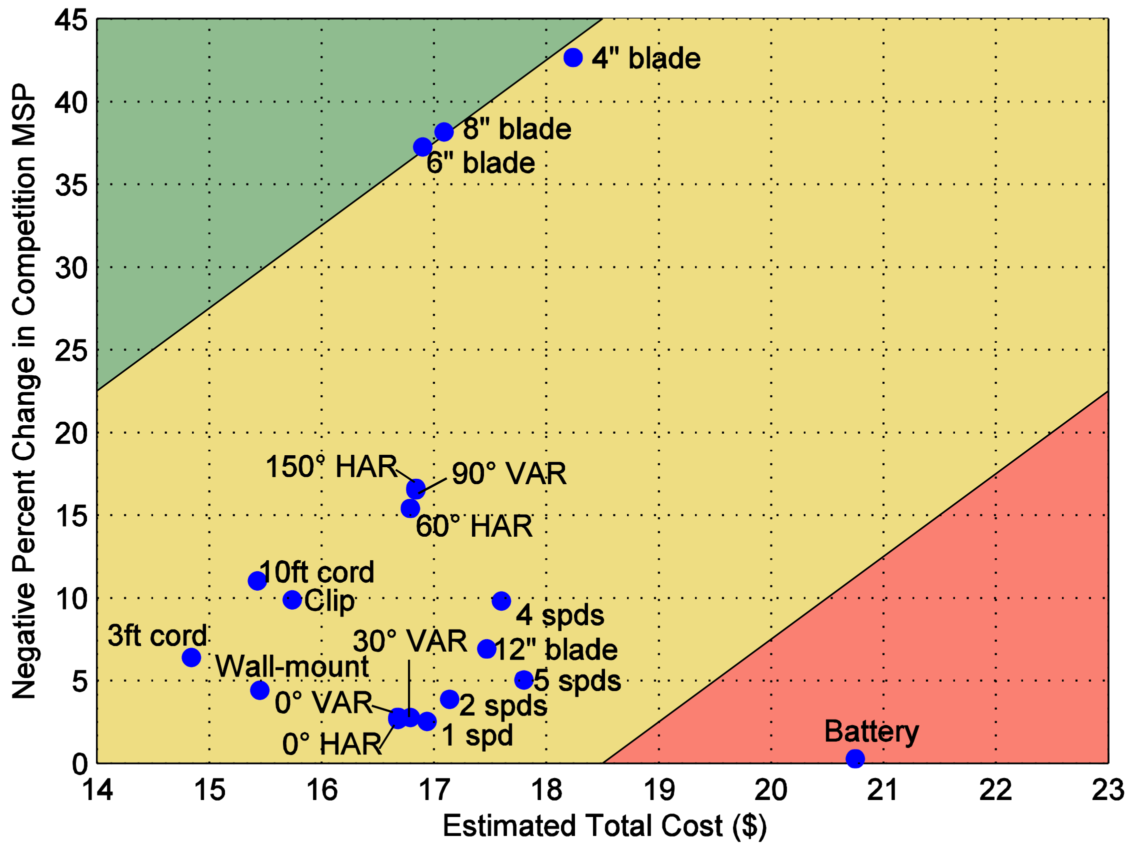


FIGURE 5.22: DESK FAN TRADEOFF PLOT, STEP 1.4 RISKS

By examining Figures 5.21 and 5.22, the affect of the proposed modification to the CPM is examined. From the estimated total costs using the combined risk values from Step 3.5, the cost of 2 options are unchanged (the 3ft and 10ft options), 4 options are less expensive, and 10 options are more expensive. For most of these changes, the options stay within their respective color regime; the 6" and 8" blade options get closer to the border between the green and yellow regions. To further analyze the differences between these two tradeoff plots, the average and standard deviation values are calculated and shown below:

TABLE 5.24: DESK FAN ESTIMATED TOTAL COST COMPARISON

	Step 3.5	Step 1.4
Average ETC	$16.64	$16.95
Standard Deviation ETC	$1.85	$1.25

From Table 5.24, the average estimated total cost (ETC) increases from $16.64 to $16.95, and the standard deviation decreases from $1.85 to $1.25 when the combined risk values from Step 1.4 are used. Therefore, these risk values move the estimated total cost for each option closer to the average value. Now, the tradeoff plots for the gas grill are shown:

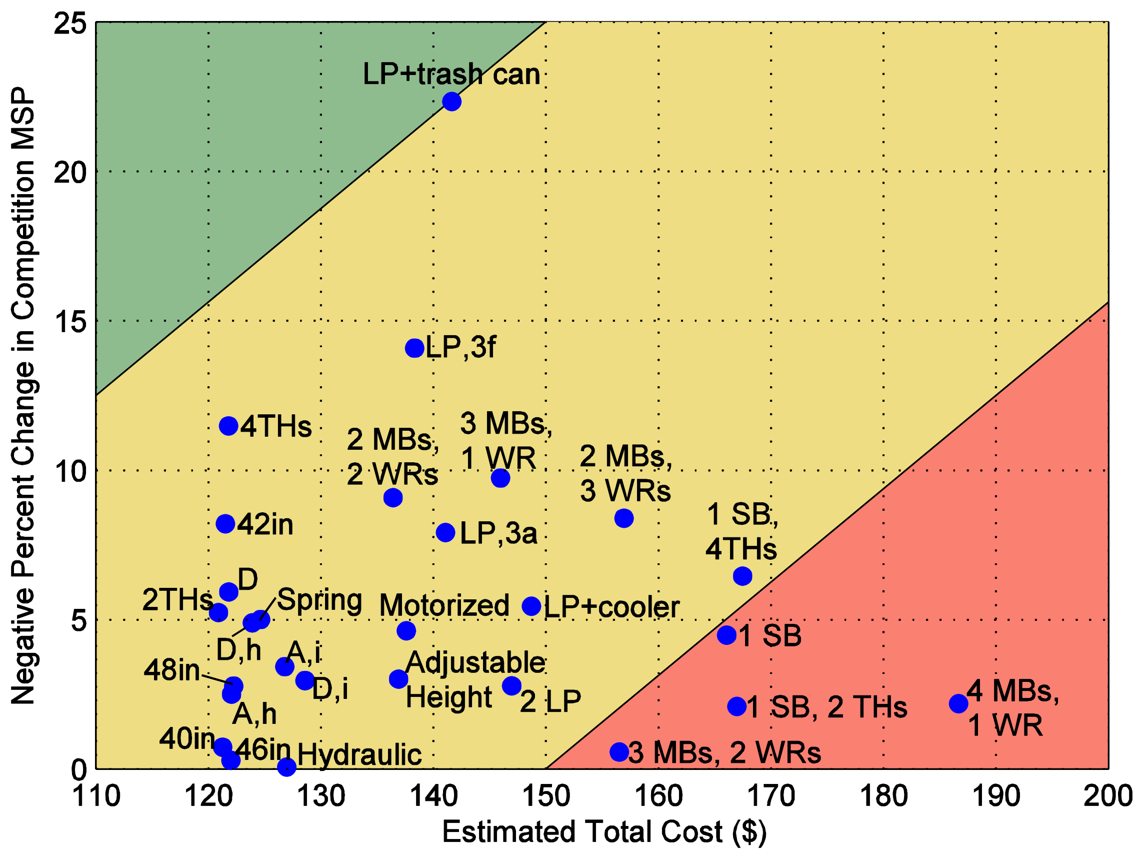


FIGURE 5.23: GAS GRILL TRADEOFF PLOT, STEP 3.5 RISKS

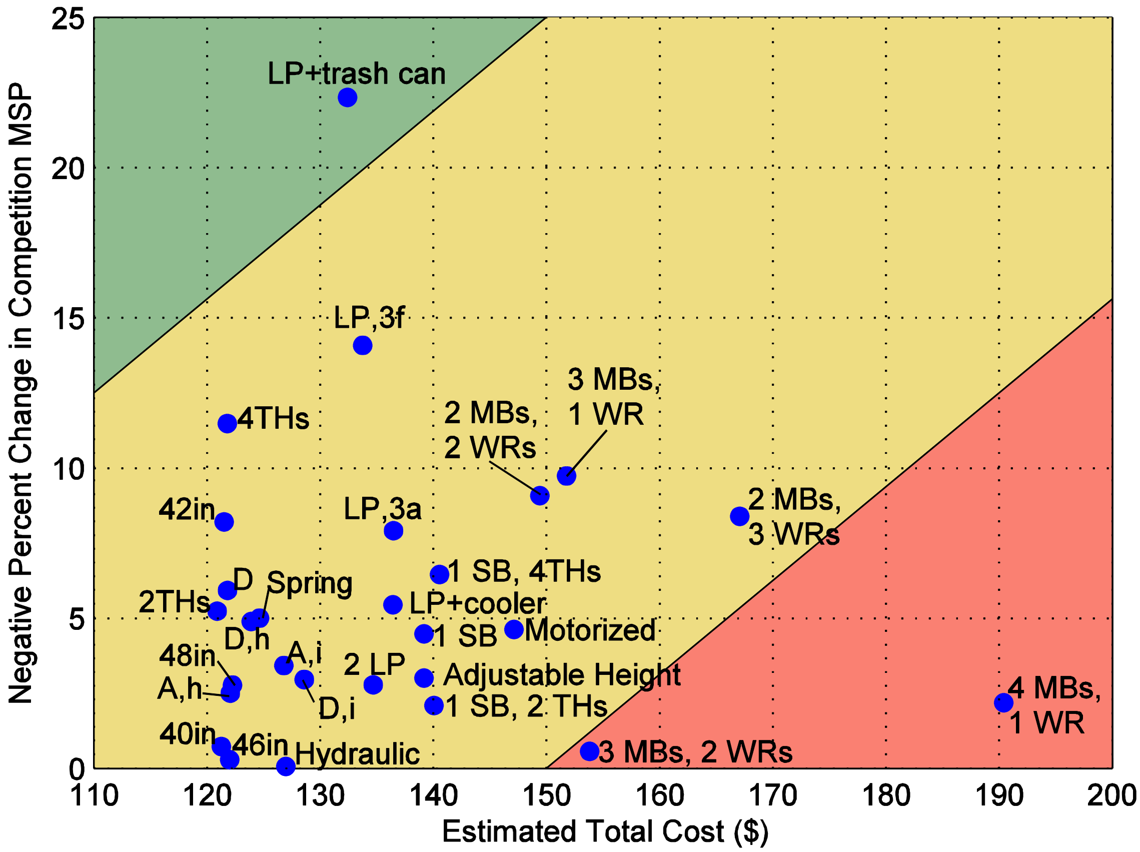


FIGURE 5.24: GAS GRILL TRADEOFF PLOT, STEP 1.4 RISKS

From Figures 5.23 and 5.24, the estimated total cost remains unchanged for 13 options (the ones with no change propagation, see Appendix D), increases for 6 options, and decreases for 9 options. Unlike the desk fan, some options transition between the three colored regions when the combined risks from Step 1.4 are used. The LP tank plus trash can option shifts completely into the green region, while the side burner and side burner with 4 THs/table options move into the yellow region. To further analyze the differences between these two tradeoff plots, the average and standard deviation values are calculated and shown below:

TABLE 5.25: GAS GRILL ESTIMATED TOTAL COST COMPARISON

	Step 3.5	Step 1.4
Average ETC	$138.53	$135.60
Standard Deviation ETC	$17.94	$16.10

From Table 5.25, the average estimated total cost decreases from $138.53 to $135.60, and the standard deviation decreases from $17.94 to $16.10. Therefore, the combined risk values from Step 1.4 move the ETC for each option closer to the average value.

By considering both case studies, it is clear that the combined risk values in Step 1.4 group together the costs of the customization options. For the desk fan case study, these movements had little influence on the locations of the options with respect to the three color regions. However, for the gas grill case study, the movements had a large influence; two options (the side burner options) that were in the red region shifted far into the yellow region (close to the average ETC value), and it is argued that such movements are dangerous. The side burner options are big changes to the base product, and the ETC values should reflect the magnitude of these changes. Otherwise, a poor decision may be made to select a customization option that costs much more than predicted. Therefore, it is argued that the proposed approach is used to estimate the total cost of customization options induced by changing a subsystem, especially those in which the subsystem changes are non-average.

5.6: Summary

In this chapter, the customization option assessment approach proposed in Chapter 4 was applied to an electromechanical and mechanical product. Specifically, the approach was successfully applied to a desk fan and a gas grill to assess several customization options. For both case studies, it was shown that considerations of the marketing and engineering domain are required to make a good decision about which customization option to pursue for further development. Additionally, it was shown that the potential subsystems in Step 1 are merely a guide to start developing customization options. The options developed from changing such subsystems should not automatically be pursued because they are not always the lowest cost options nor are they the most desirable from consumers. Finally, in the last section of this chapter, a supporting argument is made for the approach by comparing the estimated total cost values when the combined risk values from Step 1.4 are used instead of those developed in Step 3.5. This section showed that the combined risk values from Step 1.4 aggregate the costs closer to the average, which could result in lower costs for risky customization options. With Chapter 5 concluded, a summary of this thesis and future work is suggested in the last chapter.

CHAPTER 6: CONCLUSIONS & FUTURE WORK

6.1: Introduction

In Chapter 1, a product development strategy was proposed that suggested products evolve over time from being produced with craft production to mass production, and most recently towards mass customization. This product development strategy, which was anecdotally supported with the review of seven products in Chapter 2, states that firms following mass customization are striving towards Davis' definition by offering product variety with product platforms and customization options. In Chapter 3, numerous academic research was presented to show the product development tools available to firms striving towards mass customization. On the marketing side, methods for gathering and modeling consumer preferences were presented with a focus on discrete choice conjoint analysis and hierarchical Bayes estimation due to their popularity and ability to estimate individual consumer preferences. On the engineering side, several methods for creating product variety with platforms and managing product changes were presented. At the end of Chapter 3, limitations of the current research were identified. In particular, no bottom-up method exists for creating product variety through customization options that considers the ramifications of both the marketing and engineering domains. To address this limitation, Chapter 4 proposed a five step method for assessing and selecting customization options during the early stages of redesign by using a modified version of an existing change prediction tool and a popular consumer preference modeling tool. Then, in Chapter 5, the approach was successfully applied to two products, a desk fan and a gas grill. The results from these case studies suggest that the proposed approach can be used to assess and select customization options during the early stages of redesign.

In this chapter, the two research questions presented in Chapter 1 are revisited, and the answers from the proposed approach are explicitly stated. After addressing these questions, lessons learned from answering each question is presented. Then, suggestions for future work are discussed, and the chapter concludes with final remarks.

6.2: Research Question 1

The first research question is concerned with the engineering aspect of offering customization options. In particular, the research question is:

RQ 1: How can an existing engineering change tool be modified to analyze changes on an existing product induced by customization options?

For the reasons discussed in Chapter 4, the Change Prediction Method (CPM) was selected as the existing engineering tool, and it was modified to analyze customization options in Steps 3.3 to 3.5. In Step 1, the CPM was used as described by Clarkson et al. [139] to determine the risk for change propagation based on average changes or an average redesign process. At the end of this step, direct and combined likelihood and impact DSMs were obtained. For the modification in Step 3.3, direct likelihood and impact values were estimated based on specific changes to a subsystem due to a customization option and not average changes. Then, in Step 3.4, the columns in the Step 1 direct likelihood and impact

DSMs for the initiating subsystem were replaced with the new values. By replacing the old values in Step 1 with the new values in Step 3.4, the change propagation from the customization option (or the specific change to the initiating subsystem) can be understood when the CPM algorithm is applied in Step 3.5.

During the implementation of these modifications in two case studies, a few lessons were learned. By considering a specific subsystem change, the direct likelihood and impact values were easier to determine in Step 3.3 than when average changes were considered. Also, change relationships can be added or removed more easily because the change is specific. However, a downside is that this process is very labor intensive. For one customization option, direct likelihood and impact values have to be determined for the entire product based on average changes, and then direct likelihood and impact values have to be determined for the customization option. It is easy to see that this process becomes very labor intensive as more and more customization options are considered.

Concerning lessons learned from Steps 3.4 and 3.5, the estimated total cost comparison done in Section 5.5.2 showed the benefit of using risks based on specific changes as opposed to average changes. By using combined risk values from average changes considered in Step 1.4, the total cost of customization options are grouped more towards the average cost, which may cause high risk options to be shown as less risky. With the combined risk values from Step 3.5, a greater variety of costs is obtained, and thus the cost of customization options can be considered more accurately. Therefore, it is argued that the proposed modification to the CPM be used for assessing customization options.

6.3: Research Question 2

The second research question is concerned with combining the engineering aspect of offering customization options with the marketing perspective. In particular, the research question is:

RQ 2: How can existing marketing and engineering tools be used to guide design decisions regarding customization option development during the early stages of redesign?

In answering this research question, an existing marketing tool had to be identified. Discrete choice conjoint analysis with hierarchical Bayes estimation was chosen because it allows consumer preferences to be quantitatively estimated on an individual-respondent level. With this tool, the percent change in market shares of preference were calculated for the competition and plotted against the estimated total cost obtained from answering RQ 1 for each option. With such a tradeoff plot, engineers can consider both the marketing and engineering ramifications and select an appropriate customization option for further development in the detailed design phase.

The main lesson learned in answering this research question is that it is advantageous to consider both domains when making a decision about which customization option to offer. In the desk fan case study, the 3ft power cord option was selected as the best option with respect to engineering effort, while the 4" blade option was selected as the best option from a marketing standpoint. However, neither of these options was chosen as the overall best customization option because these options did not perform well in their counterpart domain; the 8" blade option was chosen because it performed well in both domains. In the gas grill case study, the best option with respect to marketing (the LP tank plus trash can) was selected as the best overall option because it had a relatively low estimated total cost. Overall, both the marketing and engineering domains should be considered in selecting which customization option to pursue, and the proposed approach presented in Chapter 4 allows such an assessment to be performed.

6.4: Additional Lessons Learned

Additional lessons were learned about customization options in relation to both engineering effort and marketing desirability. These lessons were learned by considering the customization options of both case studies by analyzing the options based on the type of customization mentioned by Ferguson et al. [10]. As a reminder, these types are functional (or performance), anthropological (or fit and comfort), and emotional (or style). Each customization option is classified according to these three categories, and then average estimated total costs (ETC) and average negative percent changes in the competition MSP are calculated to determine if any trends exist. The results from this analysis are presented below.

For the desk fan, functionality is defined as any attribute that controls the directionality, amount, or speed of the airflow produced by the fan. Therefore, all the options related to fan blade diameter, mount type, number of speed settings, horizontal adjustment ranges, vertical adjustment ranges, and power supply are considered functional customization options. The color customization options, however, are classified under the emotional category. The average cost and market desirability values for each grouping are shown below:

TABLE 6.1: DESK FAN CUSTOMIZATION TYPE ANALYSIS

Customization Options	Average ETC	Average Negative % Change in Competition MSP
Functional	$16.64	12.36%
Anthropological	N/A	N/A
Emotional	$15.53	10.47%

As expected, Table 6.1 shows that functional customization options for the desk fan are more expensive on average than emotional customization options. The market desirability of functional options is also higher than emotional options.

For the gas grill, functionality is defined as any attribute related to cooking food over an open flame, whether that be measuring and controlling the amount of heat reaching the food or storing equipment used to cook the food. With this definition, the customization options relating to under-grill storage, side table specifications, cooking zone specifications, and accessories are classified as functional. Even though the grill cover's function is to protect the grill, the customization options relating to grill cover are classified under the emotional category since they relate to the grill cover's color. In addition to the grill cover options, the grill color options are considered emotional customization options. Finally, the grid lid opening and the total grill height options are classified under the anthropological category since they both consider a consumer's ability to apply a force and his/her height, respectively. The average cost and market desirability values for each grouping are shown below:

TABLE 6.2: GAS GRILL CUSTOMIZATION TYPE ANALYSIS

Customization Options	Average ETC	Average Negative % Change in Competition MSP
Functional	$143.29	0.56%
Anthropological	$126.64	3.09%
Emotional	$127.51	4.54%

Similar to the desk fan, Table 6.2 shows that functional customization options are the most expensive on average, while emotional customization options are the least expensive on average with anthropological customization options in the middle. Unlike the desk fan, functional options have the lowest market desirability on average (though the best option selected for the gas grill was a functional one), while emotional customization options have the highest market desirability on average with anthropological options again in the middle.

Based on the results from both case studies, it is concluded that functional customization options are the most expensive, while emotional options are the least expensive. Concerning market desirability, the most desirable type of customization option depends upon the product and options offered. However, based on the Step 5 results for both case studies, functional customization options appear to be the most desirable.

6.5: Suggested Future Work

Though the approach presented in this thesis addresses a current research gap, further research is required for customization option assessment and selection. First, in this thesis, the proposed approach was only partially validated. In the future, this method should be applied several times to different products in which historical change data is available. With such a study, the predicted risks and estimated total costs can be compared with the actual values, and the approach can be more fully validated.

In addition to this future research, further work is required in considering multiple customization options being offered at a time. First, Equation 4.1 should be validated with more case studies, and a similar equation should be developed and validated for impact. Once such modifications are made to the CPM, the proposed approach should be tested with multiple customization options. Challenges in testing this approach will arise in dealing with the combinatorial nature of the marketing problem and the laborious task of direct likelihood and impact values for each option. A method that easily determines all feasible combinations of customization options is needed for the marketing problem, and a more automated way of determining the likelihood and impact values (perhaps a method that is based on the type of change) is needed to reduce the amount of time required to implement the proposed approach.

Finally, the last suggested future work deals with estimating consumer preferences. Recall for the grill case study that three discrete choice conjoint surveys were used as a way to better represent the actual purchase process of products with customization options. The downside to this method is that part-worth values cannot be compared between surveys. For example, the marketing ramifications of offering a customization option on a low end product that is already present on a high end product cannot be evaluated. In other words, the cannibalization of products within a product family due to offering customization options cannot be analyzed to obtain MSP values with the method implemented for the gas grill case study. Therefore, a hierarchal discrete choice conjoint survey is suggested. In this survey, part-worth data would be available for members of the product family and for customization options specific to each family member. The scope of the survey could even be expanded so that product family configurations can be considered in addition customization options. With such a method, a product platforming and customization option approach could be developed to determine the product platform(s), product variant configurations, and customization options offered with each variant.

6.6: Concluding Remarks

In this thesis, the need for a bottom-up method to assess and select customization options with the consideration of the marketing and engineering ramifications was identified. Then, an approach was proposed to address this research gap by combining a modified, existing change propagation tool with a popular marketing tool. Through the case studies, the approach was partially verified and shows promise for allowing engineers to assess and select customization options during the early stages of redesign. Though the proposed approach does address a research gap, further research is required to enable firms pursuing mass customization to reach the point where consumers get "exactly what they want when they want it" [3].

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APPENDICES

Appendix A: Direct Likelihood and Impact Values for Desk Fan

This section contains the direct likelihood and impact values for each customization option, as well as a brief discussion on the thought process used to obtain them, related to the desk fan case study. This appendix is divided into subsections by customization option groupings, starting with fan blade diameter and ending with power supply.

A.1: Fan Blade Diameter

The direct likelihood and impact values for the customization options relating to fan blade diameter are shown in the below tables:

TABLE A.1: FAN BLADE DIAMETER DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	4" Blade	6" Blade	8" Blade	12" Blade
	Initiating Subsystem	6	6	6	6
Affected Subsystems	1 - Stand				
	2 - Base				
	3 - Speed Control System				
	4 - Angular Adjustment System				
	5 - Head Assembly Casing				
	6 - Fan Blades				
	7 - Grill Assembly	0.8	0.5	0.2	1
	8 - Power Supply				
	9 - Motor	0.8	0.5	0.2	0.8

TABLE A.2: FAN BLADE DIAMETER DIRECT IMPACT VALUES

Direct Impact	Options	4" Blade	6" Blade	8" Blade	12" Blade
	Initiating Subsystem	6	6	6	6
Affected Subsystems	1 - Stand				
	2 - Base				
	3 - Speed Control System				
	4 - Angular Adjustment System				
	5 - Head Assembly Casing				
	6 - Fan Blades				
	7 - Grill Assembly	0.4	0.3	0.2	0.2
	8 - Power Supply				
	9 - Motor	0.7	0.6	0.6	0.6

In determining the values for Tables A.1 and A.2, it is assumed that the redesign team would maintain proportions of the desk fan, thus the likelihood and impact values increase as the fan blade diameter changes more. The 12" blade option has high likelihood values because the physical constraints of the fan require some subsystems to change.

For Step 3.6, the impact on Subsystem 6 is estimated to be 0.8 for each option since it is assumed that the entire fan blade has to be redesigned regardless of the change in diameter.

A.2: Mount Type

The direct likelihood and impact values for the customization options relating to mount type are shown in the below tables:

TABLE A.3: MOUNT TYPE DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	Clip	Wall-mount
	Initiating Subsystem	2	2
Affected Subsystems	1 - Stand	0.2	0.4
	2 - Base		
	3 - Speed Control System		
	4 - Angular Adjustment System		
	5 - Head Assembly Casing		
	6 - Fan Blades		
	7 - Grill Assembly		
	8 - Power Supply		
	9 - Motor		

TABLE A.4: MOUNT TYPE DIRECT IMPACT VALUES

Direct Impact	Options	Clip	Wall-mount
	Initiating Subsystem	2	2
Affected Subsystems	1 - Stand	0.2	0.4
	2 - Base		
	3 - Speed Control System		
	4 - Angular Adjustment System		
	5 - Head Assembly Casing		
	6 - Fan Blades		
	7 - Grill Assembly		
	8 - Power Supply		
	9 - Motor		

For Tables A.3 and A.4, the wall-mount option is assumed to have higher likelihood and impact values as a result of changes made to position the fan so that it blows air appropriately when mounted to a vertical wall.

For Step 3.6, the impact value of Subsystem 2 for the clip option is 0.9, while it is 0.3 for the wall-mount option. The high value for the clip option accounts for the large geometry change from a flat base to a clip, while the smaller change for the wall-mount option accounts for the relatively small change of adding something to the flat base to enable it to attach to a wall.

A.3: Number of Speed Settings

The direct likelihood and impact values for the customization options relating to the number of speed settings are shown in the below tables:

TABLE A.5: NUMBER OF SPEED SETTINGS DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	1	2	4	5
	Initiating Subsystem	3	3	3	3
Affected Subsystems	1 - Stand				
	2 - Base				
	3 - Speed Control System				
	4 - Angular Adjustment System				
	5 - Head Assembly Casing	0.2	0.1	0.2	0.3
	6 - Fan Blades				
	7 - Grill Assembly				
	8 - Power Supply	0.1	0.1	0.1	0.1
	9 - Motor	0.2	0.2	0.2	0.2

TABLE A.6: NUMBER OF SPEED SETTINGS DIRECT IMPACT VALUES

Direct Impact	Options	1	2	4	5
	Initiating Subsystem	3	3	3	3
Affected Subsystems	1 - Stand				
	2 - Base				
	3 - Speed Control System				
	4 - Angular Adjustment System				
	5 - Head Assembly Casing	0.2	0.2	0.2	0.2
	6 - Fan Blades				
	7 - Grill Assembly				
	8 - Power Supply	0.1	0.1	0.1	0.1
	9 - Motor	0.6	0.6	0.6	0.6

For Tables A.5 and A.6, all the values are determined by assuming that the number of speed settings does not affect the motor's low or top speeds; it simply adds more intervals in between these extremes. The likelihood and impact values for Subsystems 8 and 9, and the impact values for Subsystem 5, are assumed to be the same for each option since no difference is perceived. However, for Subsystem 5, it is assumed that adding settings has a higher likelihood for change propagation than removing settings. However, when the number of settings is 1, the likelihood is slightly higher because the speed control becomes an on/off switch.

For Step 3.6, the impact on Subsystem 3 for removing settings is 0.2, but it is slightly higher, 0.3, for adding settings.

A.4: Horizontal Adjustment Range

The direct likelihood and impact values for the customization options relating to the horizontal adjustment range are shown in the below tables:

TABLE A.7: HORIZONTAL ADJUSTMENT RANGE DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	0°	60°	150°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.2	0.3	0.3
	2 - Base			
	3 - Speed Control System			
	4 - Angular Adjustment System			
	5 - Head Assembly Casing	0.1	0.1	0.1
	6 - Fan Blades			
	7 - Grill Assembly	0	0	0
	8 - Power Supply			
	9 - Motor			

TABLE A.8: HORIZONTAL ADJUSMENT RANGE DIRECT IMPACT VALUES

Direct Impact	Options	0°	60°	150°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.2	0.1	0.1
	2 - Base			
	3 - Speed Control System			
	4 - Angular Adjustment System			
	5 - Head Assembly Casing	0.1	0.1	0.1
	6 - Fan Blades			
	7 - Grill Assembly	0	0	0
	8 - Power Supply			
	9 - Motor			

For Tables A.7 and A.8, the side-to-side motion of the fan does not affect Subsystem 7 (there is no interference between Subsystem 7 and Subsystem 1), so the likelihood and impact values are zero. It is reasoned that Subsystem 1 is affected slightly more than Subsystem 5 since it supports Subsystem 4. However, in general, the likelihood and impact values are reasoned to be very small, with the 0° option having a slightly higher impact on Subsystem 1 because Subsystem 4 could be completely removed and Subsystem 1 would have to interface directly with Subsystem 5.

For Step 3.6, the impact on Subsystem 4 is determined to be 0.3, 0.2, and 0.2 for the 0°, 60°, and 150° options, respectively. The 0° option is slightly higher because the difference from the base product (90°) is greater than the difference associated with the other two customization options.

A.5: Vertical Adjustment Range

The direct likelihood and impact values for the customization options relating to the vertical adjustment range are shown in the below tables:

TABLE A.9: VERTICAL ADJUSTMENT RANGE DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	0°	30°	90°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.2	0.3	0.8
	2 - Base			
	3 - Speed Control System			
	4 - Angular Adjustment System			
	5 - Head Assembly Casing	0.1	0.1	0.8
	6 - Fan Blades			
	7 - Grill Assembly	0	0	0.8
	8 - Power Supply			
	9 - Motor			

TABLE A.10: VERTICAL ADJUSTMENT RANGE DIRECT IMPACT VALUES

Direct Impact	Options	0°	30°	90°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.2	0.1	0.7
	2 - Base			
	3 - Speed Control System			
	4 - Angular Adjustment System			
	5 - Head Assembly Casing	0.1	0.1	0.4
	6 - Fan Blades			
	7 - Grill Assembly	0	0	0.3
	8 - Power Supply			
	9 - Motor			

For Tables A.9 and A.10, the base fan shown in Figure 5.1 is assumed to have a full range of motion (+/- 30° for a total of 60° vertical adjustment range). Therefore, at -30°, Subsystem 7 touches Subsystem 1. For the 0° and 30° options, the likelihood and impact value for all affected subsystems are considered to be the same as the 0° and 60° options for the horizontal adjustment range since these changes are perceived to be similar. However, for the 90° option, the likelihood and impact values much higher because Subsystem 7 interferes with Subsystem 1, and the full range of motion (+/- 45°) cannot be obtained. Since this interference problem can be resolved by changing any of the affected subsystems, the likelihood values are the same.

For Step 3.6, the impact on Subsystem 4 is 0.3, 0.2, and 0.2 for the 0°, 30°, and 90° options, respectively. The reasoning is the same as for the horizontal adjustment range options.

A.6: Power Supply

The direct likelihood and impact values for the customization options relating to the power supply are shown in the below tables:

TABLE A.11 POWER SUPPLY DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	3ft	10ft	Battery
	Initiating Subsystem	8	8	8
Affected Subsystems	1 - Stand			
	2 - Base			
	3 - Speed Control System	0	0	0.9
	4 - Angular Adjustment System			
	5 - Head Assembly Casing	0	0	1
	6 - Fan Blades			
	7 - Grill Assembly			
	8 - Power Supply			
	9 - Motor	0	0	0.6

TABLE A.12: POWER SUPPLY DIRECT IMPACT VALUES

Direct Impact	Options	3ft	10ft	Battery
	Initiating Subsystem	8	8	8
Affected Subsystems	1 - Stand			
	2 - Base			
	3 - Speed Control System	0	0	0.8
	4 - Angular Adjustment System			
	5 - Head Assembly Casing	0	0	0.6
	6 - Fan Blades			
	7 - Grill Assembly			
	8 - Power Supply			
	9 - Motor	0	0	0.7

For Tables A.11 and A.12, no change propagation is perceived for the 3ft and 10ft cord options, thus the affected subsystems from Step 1.3 have values of zero for direct likelihood and impact. However, the battery option has very high likelihood and impact values because the change is very big. The likelihood for Subsystem 5 is 1 because the battery is assumed to be attached to this subsystem in some fashion. The likelihood and impact values are high for Subsystems 3 and 9 because it is assumed that the current is changing from AC to DC.

For Step 3.6, the impact values for Subsystem 8 are very small (0.1) for the 3ft and 10ft cord options, while it is quite high (0.8) for the battery option because the change is much more drastic.

Appendix B: Combined Likelihood, Impact, and Risk Values for Desk Fan

The combined likelihood, impact, and risk values for the customization options related to the desk fan case study are presented in this appendix. As with Appendix A, this appendix is broken into subsections based on customization option groupings, starting with fan blade diameter and ending with power supply. For the initiating subsystem for each customization option, the combined likelihood value is 1, the combined impact value is the one presented in Appendix A, and the combined risk is the product of the two.

B.1: Fan Blade Diameter

The combined likelihood, impact, and risk values for the customization options relating to the fan blade diameter are shown in the below tables:

TABLE B.1: FAN BLADE DIAMETER COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	4" Blade	6" Blade	8" Blade	12" Blade
	Initiating Subsystem	6	6	6	6
Affected Subsystems	1 - Stand	0.51	0.34	0.14	0.57
	2 - Base	0.46	0.30	0.13	0.52
	3 - Speed Control System	0.75	0.50	0.22	0.77
	4 - Angular Adjustment System	0.65	0.45	0.19	0.71
	5 - Head Assembly Casing	0.81	0.57	0.25	0.84
	6 - Fan Blades	1.00	1.00	1.00	1.00
	7 - Grill Assembly	0.87	0.61	0.27	1.00
	8 - Power Supply	0.66	0.43	0.18	0.68
	9 - Motor	0.85	0.57	0.25	0.86

TABLE B.2: FAN BLADE DIAMETER COMBINED IMPACT VALUES

Combined Impact	Options	4" Blade	6" Blade	8" Blade	12" Blade
	Initiating Subsystem	6	6	6	6
Affected Subsystems	1 - Stand	0.37	0.36	0.34	0.37
	2 - Base	0.30	0.28	0.27	0.30
	3 - Speed Control System	0.77	0.75	0.74	0.78
	4 - Angular Adjustment System	0.40	0.38	0.36	0.41
	5 - Head Assembly Casing	0.62	0.58	0.54	0.62
	6 - Fan Blades	0.80	0.80	0.80	0.80
	7 - Grill Assembly	0.44	0.32	0.23	0.27
	8 - Power Supply	0.60	0.58	0.57	0.61
	9 - Motor	0.75	0.65	0.64	0.69

TABLE B.3: FAN BLADE DIAMETER COMBINED RISK VALUES

Combined Risk	Options	4" Blade	6" Blade	8" Blade	12" Blade
	Initiating Subsystem	6	6	6	6
Affected Subsystems	1 - Stand	0.19	0.12	0.05	0.21
	2 - Base	0.14	0.08	0.04	0.16
	3 - Speed Control System	0.58	0.38	0.16	0.60
	4 - Angular Adjustment System	0.26	0.17	0.07	0.29
	5 - Head Assembly Casing	0.50	0.33	0.14	0.52
	6 - Fan Blades	0.80	0.80	0.80	0.80
	7 - Grill Assembly	0.38	0.20	0.06	0.27
	8 - Power Supply	0.40	0.25	0.10	0.41
	9 - Motor	0.64	0.37	0.16	0.59

B.2: Mount Type

The combined likelihood, impact, and risk values for the customization options relating to the mount type are shown in the below tables:

TABLE B.4: MOUNT TYPE COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	Clip	Wall-mount
	Initiating Subsystem	2	2
Affected Subsystems	1 - Stand	0.20	0.40
	2 - Base	1.00	1.00
	3 - Speed Control System	0.03	0.05
	4 - Angular Adjustment System	0.04	0.08
	5 - Head Assembly Casing	0.03	0.07
	6 - Fan Blades	0.03	0.07
	7 - Grill Assembly	0.05	0.09
	8 - Power Supply	0.02	0.05
	9 - Motor	0.03	0.06

TABLE B.5: MOUNT TYPE COMBINED IMPACT VALUES

Combined Impact	Options	Clip	Wall-mount
	Initiating Subsystem	2	2
Affected Subsystems	1 - Stand	0.20	0.40
	2 - Base	0.90	0.30
	3 - Speed Control System	0.72	0.72
	4 - Angular Adjustment System	0.29	0.29
	5 - Head Assembly Casing	0.51	0.51
	6 - Fan Blades	0.59	0.59
	7 - Grill Assembly	0.21	0.21
	8 - Power Supply	0.59	0.59
	9 - Motor	0.70	0.70

TABLE B.6: MOUNT TYPE COMBINED RISK VALUES

Combined Risk	Options	Clip	Wall-mount
	Initiating Subsystem	2	2
Affected Subsystems	1 - Stand	0.04	0.16
	2 - Base	0.90	0.30
	3 - Speed Control System	0.02	0.04
	4 - Angular Adjustment System	0.01	0.02
	5 - Head Assembly Casing	0.02	0.04
	6 - Fan Blades	0.02	0.04
	7 - Grill Assembly	0.01	0.02
	8 - Power Supply	0.01	0.03
	9 - Motor	0.02	0.04

B.3: Number of Speed Settings

The combined likelihood, impact, and risk values for the customization options relating to the number of speed settings are shown in the below tables:

TABLE B.7: NUMBER OF SPEED SETTINGS COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	1	2	4	5
	Initiating Subsystem	3	3	3	3
Affected Subsystems	1 - Stand	0.18	0.14	0.18	0.21
	2 - Base	0.15	0.12	0.15	0.18
	3 - Speed Control System	1.00	1.00	1.00	1.00
	4 - Angular Adjustment System	0.25	0.20	0.25	0.29
	5 - Head Assembly Casing	0.39	0.31	0.39	0.46
	6 - Fan Blades	0.31	0.27	0.31	0.36
	7 - Grill Assembly	0.27	0.23	0.27	0.32
	8 - Power Supply	0.30	0.26	0.30	0.34
	9 - Motor	0.35	0.30	0.35	0.40

TABLE B.8: NUMBER OF SPEED SETTINGS COMBINED IMPACT VALUES

Combined Impact	Options	1	2	4	5
	Initiating Subsystem	3	3	3	3
Affected Subsystems	1 - Stand	0.37	0.37	0.37	0.37
	2 - Base	0.29	0.29	0.29	0.30
	3 - Speed Control System	0.20	0.20	0.30	0.30
	4 - Angular Adjustment System	0.39	0.39	0.39	0.39
	5 - Head Assembly Casing	0.47	0.54	0.47	0.43
	6 - Fan Blades	0.67	0.67	0.67	0.68
	7 - Grill Assembly	0.28	0.28	0.28	0.28
	8 - Power Supply	0.45	0.42	0.45	0.47
	9 - Motor	0.68	0.66	0.68	0.70

TABLE B.9: NUMBER OF SPEED SETTINGS COMBINED RISK VALUES

Combined Risk	Options	1	2	4	5
	Initiating Subsystem	3	3	3	3
Affected Subsystems	1 - Stand	0.07	0.05	0.07	0.08
	2 - Base	0.04	0.03	0.04	0.05
	3 - Speed Control System	0.20	0.20	0.30	0.30
	4 - Angular Adjustment System	0.10	0.08	0.10	0.11
	5 - Head Assembly Casing	0.18	0.17	0.18	0.20
	6 - Fan Blades	0.21	0.18	0.21	0.24
	7 - Grill Assembly	0.08	0.06	0.08	0.09
	8 - Power Supply	0.14	0.11	0.14	0.16
	9 - Motor	0.24	0.20	0.24	0.28

B.4: Horizontal Adjustment Range

The combined likelihood, impact, and risk values for the customization options relating to the horizontal adjustment range are shown in the below tables:

TABLE B.10: HORIZONTAL ADJUSTMENT RANGE COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	0°	60°	150°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.21	0.31	0.31
	2 - Base	0.11	0.15	0.15
	3 - Speed Control System	0.08	0.10	0.10
	4 - Angular Adjustment System	1.00	1.00	1.00
	5 - Head Assembly Casing	0.12	0.14	0.14
	6 - Fan Blades	0.09	0.10	0.10
	7 - Grill Assembly	0.09	0.11	0.11
	8 - Power Supply	0.07	0.08	0.08
	9 - Motor	0.09	0.10	0.10

TABLE B.11: HORIZONTAL ADJUSTMENT RANGE COMBINED IMPACT VALUES

Combined Impact	Options	0°	60°	150°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.21	0.11	0.11
	2 - Base	0.29	0.30	0.30
	3 - Speed Control System	0.72	0.72	0.72
	4 - Angular Adjustment System	0.30	0.20	0.20
	5 - Head Assembly Casing	0.19	0.23	0.23
	6 - Fan Blades	0.63	0.63	0.63
	7 - Grill Assembly	0.23	0.22	0.22
	8 - Power Supply	0.58	0.58	0.58
	9 - Motor	0.73	0.73	0.73

TABLE B.12: HORIZONTAL ADJUSTMENT RANGE COMBINED RISK VALUES

Combined Risk	Options	0°	60°	150°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.04	0.03	0.03
	2 - Base	0.03	0.05	0.05
	3 - Speed Control System	0.06	0.07	0.07
	4 - Angular Adjustment System	0.30	0.20	0.20
	5 - Head Assembly Casing	0.02	0.03	0.03
	6 - Fan Blades	0.06	0.06	0.06
	7 - Grill Assembly	0.02	0.02	0.02
	8 - Power Supply	0.04	0.05	0.05
	9 - Motor	0.07	0.07	0.07

B.5: Vertical Adjustment Range

The combined likelihood, impact, and risk values for the customization options relating to the vertical adjustment range are shown in the below tables:

TABLE B.13: VERTICAL ADJUSTMENT RANGE COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	0°	30°	90°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.21	0.31	0.86
	2 - Base	0.11	0.15	0.61
	3 - Speed Control System	0.08	0.10	0.75
	4 - Angular Adjustment System	1.00	1.00	1.00
	5 - Head Assembly Casing	0.12	0.14	0.91
	6 - Fan Blades	0.09	0.10	0.79
	7 - Grill Assembly	0.09	0.11	0.90
	8 - Power Supply	0.07	0.08	0.68
	9 - Motor	0.09	0.10	0.78

TABLE B.14: VERTICAL ADJUSTMENT RANGE COMBINED IMPACT VALUES

Combined Impact	Options	0°	30°	90°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.21	0.11	0.70
	2 - Base	0.29	0.30	0.32
	3 - Speed Control System	0.72	0.72	0.80
	4 - Angular Adjustment System	0.30	0.20	0.20
	5 - Head Assembly Casing	0.19	0.23	0.59
	6 - Fan Blades	0.63	0.63	0.71
	7 - Grill Assembly	0.23	0.22	0.38
	8 - Power Supply	0.58	0.58	0.66
	9 - Motor	0.73	0.73	0.80

TABLE B.15: VERTICAL ADJUSTMENT RANGE COMBINED RISK VALUES

Combined Risk	Options	0°	30°	90°
	Initiating Subsystem	4	4	4
Affected Subsystems	1 - Stand	0.04	0.03	0.60
	2 - Base	0.03	0.05	0.20
	3 - Speed Control System	0.06	0.07	0.60
	4 - Angular Adjustment System	0.30	0.20	0.20
	5 - Head Assembly Casing	0.02	0.03	0.54
	6 - Fan Blades	0.06	0.06	0.56
	7 - Grill Assembly	0.02	0.02	0.34
	8 - Power Supply	0.04	0.05	0.45
	9 - Motor	0.07	0.07	0.62

B.6: Power Supply

The combined likelihood, impact, and risk values for the customization options relating to the power supply are shown in the below tables:

TABLE B.16: POWER SUPPLY COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	3ft	10ft	Battery
	Initiating Subsystem	8	8	8
Affected Subsystems	1 - Stand	0	0	0.59
	2 - Base	0	0	0.52
	3 - Speed Control System	0	0	0.97
	4 - Angular Adjustment System	0	0	0.77
	5 - Head Assembly Casing	0	0	1.00
	6 - Fan Blades	0	0	0.87
	7 - Grill Assembly	0	0	0.82
	8 - Power Supply	1.00	1.00	1.00
	9 - Motor	0	0	0.92

TABLE B.17: POWER SUPPLY COMBINED IMPACT VALUES

Combined Impact	Options	3ft	10ft	Battery
	Initiating Subsystem	8	8	8
Affected Subsystems	1 - Stand	0	0	0.41
	2 - Base	0	0	0.33
	3 - Speed Control System	0	0	0.85
	4 - Angular Adjustment System	0	0	0.46
	5 - Head Assembly Casing	0	0	0.78
	6 - Fan Blades	0	0	0.78
	7 - Grill Assembly	0	0	0.35
	8 - Power Supply	0.10	0.10	0.80
	9 - Motor	0	0	0.84

TABLE B.18: POWER SUPPLY COMBINED RISK VALUES

Combined Risk	Options	3ft	10ft	Battery
	Initiating Subsystem	8	8	8
Affected Subsystems	1 - Stand	0	0	0.24
	2 - Base	0	0	0.17
	3 - Speed Control System	0	0	0.82
	4 - Angular Adjustment System	0	0	0.35
	5 - Head Assembly Casing	0	0	0.78
	6 - Fan Blades	0	0	0.68
	7 - Grill Assembly	0	0	0.29
	8 - Power Supply	0.10	0.10	0.80
	9 - Motor	0	0	0.77

Appendix C: Direct Likelihood and Impact Values for Gas Grill

This section contains the direct likelihood and impact values for each customization option, as well as a brief discussion on the thought process used to obtain them, related to the gas grill case study. This appendix is divided into subsections by customization option groupings, starting with side table specifications and ending with grill accessories.

C.1: Side Table Specification

The direct likelihood and impact values for the customization options relating to side table specifications are shown in the below tables:

TABLE C.1: SIDE TABLE SPECIFICATION DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	2 THs/ table	4 THs/ table	1 SB, 0 THs	1 SB, 2 THs/ table	1 SB, 4 THs/ table
	Initiating Subsystem	4	4	4	4	4
Affected Subsystems	1 - Grill Body	0	0	0.8	0.8	0.8
	2 - Control System			1	1	1
	3 - Fuel Transport System					
	4 - Side Table					
	5 - Cart System					
	6 - Cooking Zone					

TABLE C.2: SIDE TABLE SPECIFICATION DIRECT IMPACT VALUES

Direct Impact	Options	2 THs/ table	4 THs/ table	1 SB, 0 THs	1 SB, 2 THs/ table	1 SB, 4 THs/ table
	Initiating Subsystem	4	4	4	4	4
Affected Subsystems	1 - Grill Body	0	0	0.3	0.3	0.3
	2 - Control System			0.7	0.7	0.7
	3 - Fuel Transport System					
	4 - Side Table					
	5 - Cart System					
	6 - Cooking Zone					

In Tables C.1 and C.2, TH stands for tool hook, and SB stands for side burner. The addition of tool hooks to Subsystem 4 is reasoned to not propagate change to Subsystem 1, and thus the likelihood and impact values are zero. However, adding a side burner has high likelihood values for Subsystems 1 and 2. Subsystem 1 has to support the extra weight of Subsystem 4 from adding a burner, and Subsystem 2 has to be able to control the amount of fuel going to the side burner. The likelihood and impact values are the same across customization options because no difference in terms of change propagation is perceived. Unlike the other direct likelihood and impact values, notice from the highlighted cells that an additional change dependency is needed for the last three customization options that did not exist in Step 1.3.

For Step 3.6, the impact values for Subsystem 4 are 0.1, 0.2, 0.8, 0.9, and 0.9 for 2 THs/table, 4 THs/table, 1 SB and 0 THs, 1 SB and 2 THs/table, and 1 SB and 4 THs/table, respectively. The tool hooks are reasoned to have minimal impact on Subsystem 4 in comparison to adding a side burner.

C.2: Grill Lid Opening Mechanism

The direct likelihood and impact values for the customization options relating to grill lid opening mechanism are shown in the below tables:

TABLE C.3: GRILL LID OPENING MECHANISM DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	Spring-assisted	Hydraulic-assisted	Motorized
	Initiating Subsystem	1	1	1
Affected Subsystems	1 - Grill Body			
	2 - Control System	0	0	0.5
	3 - Fuel Transport System			
	4 - Side Table	0	0	0
	5 - Cart System	0	0	0.6
	6 - Cooking Zone	0	0	0

TABLE C.4: GRILL LID OPENING MECHANISM DIRECT IMPACT VALUES

Direct Impact	Options	Spring-assisted	Hydraulic-assisted	Motorized
	Initiating Subsystem	1	1	1
Affected Subsystems	1 - Grill Body			
	2 - Control System	0	0	0.2
	3 - Fuel Transport System			
	4 - Side Table	0	0	0
	5 - Cart System	0	0	0.2
	6 - Cooking Zone	0	0	0

For Tables C.3 and C.4, the spring-assisted and hydraulic-assisted options are not perceived to propagate changes to any subsystems, thus the likelihood and impact values are zero. However, the motorized option could affect Subsystem 2 because the motor has to be controlled by the user through some interface. Subsystem 5 could be affected because the power supply for the motor could be located in Subsystem 5. For both affected subsystems, the impact values are low because the changes to these subsystems are small.

For Step 3.6, the impact on Subsystem 1 is 0.2, 0.3, and 0.5 for the spring-assisted, hydraulic-assisted, and motorized options, respectively. The differences in these values reflect the complexity associated with each option.

C.3: Total Grill Height

The direct likelihood and impact values for the customization options relating to total grill height are shown in the below tables:

TABLE C.5: TOTAL GRILL HEIGHT DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	46in	48in	42in	40in	Adjustable
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0	0	0	0	0.2
	2 - Control System					
	3 - Fuel Transport System					
	4 - Side Table	0	0	0	0	0.2
	5 - Cart System					
	6 - Cooking Zone					

TABLE C.6: TOTAL GRILL HEIGHT DIRECT IMPACT VALUES

Direct Impact	Options	46in	48in	42in	40in	Adjustable
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0	0	0	0	0.3
	2 - Control System					
	3 - Fuel Transport System					
	4 - Side Table	0	0	0	0	0.2
	5 - Cart System					
	6 - Cooking Zone					

In Tables C.5 and C.6, no change propagation is perceived for the first four options since these options can be controlled by simply changing the height of the panels associated with Subsystem 5. However, the last option, adjustable height from 40in to 48in, could affect Subsystems 1 and 4 based on how the height is made adjustable. Therefore, likelihood and impact values exist for these subsystems.

For Step 3.6, the impact values for Subsystem 5 are 0.2, 0.2, 0.2, 0.2, and 0.9 for the 46in, 48in, 42in, 40in, and adjustable options, respectively. The first four options are reasoned to be very small changes to the subsystem, while the last option is reasoned to be a very large change that will require a lot of design work.

C.4: Under-grill Cabinet Storage Configuration

The direct likelihood and impact values for the customization options relating to under-grill cabinet storage configuration are shown in the below tables:

TABLE C.7: STORAGE CONFIGURATION DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	2 LP	LP + 3 shelves	LP + 3 adjustable shelves	LP + trash can	LP + cooler
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0.6	0.4	0.4	0.5	0.6
	2 - Control System					
	3 - Fuel Transport System					
	4 - Side Table	0.6	0.3	0.3	0.5	0.6
	5 - Cart System					
	6 - Cooking Zone					

TABLE C.8: STORAGE CONFIGURATION DIRECT IMPACT VALUES

Direct Impact	Options	2 LP	LP + 3 shelves	LP + 3 adjustable shelves	LP + trash can	LP + cooler
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0.5	0.5	0.5	0.5	0.5
	2 - Control System					
	3 - Fuel Transport System					
	4 - Side Table	0.3	0.3	0.3	0.3	0.3
	5 - Cart System					
	6 - Cooking Zone					

In Tables C.7 and C.8, the likelihood values for Subsystems 1 and 4 are determined based on the perceived changes in length and depth to Subsystem 5. Subsystem 1 is likely affected because it is directly connected to Subsystem 5, while Subsystem 4 is likely affected because such changes could prohibit the side tables from being folded down. The difference in likelihood values are based on the perceived amount of change in length and depth to

Subsystem 5. For example, these dimensions are expected to change more for the 2 LP tank option than for the LP plus shelves option because shelves can be made to wrap around the one LP tank. The impact values shown in Table C.8 are assumed to be similar to the values used in Step 1.3 because similar changes to length and depth were considered in Step 1.3.

For Step 3.6, the impact values for Subsystem 5 are 0.5, 0.4, 0.7, 0.2, and 0.6 for the options shown in Tables C.7 and C.8 from left to right, respectively. The differences in the values are based on the perceived complexity of the options.

C.5: Cooking Zone Specification

The direct likelihood and impact values for the customization options relating to cooking zone specifications are shown in the below tables:

TABLE C.9: COOKING ZONE SPECIFICATION DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	2 MBs, 2 WRs	3 MBs, 1 WR	2 MBs, 3 WRs	3 MBs, 2 WRs	4 MBs, 1 WR
	Initiating Subsystem	6	6	6	6	6
Affected Subsystems	1 - Grill Body	1	0.6	1	1	0.7
	2 - Control System	0	1	0	1	1
	3 - Fuel Transport System					
	4 - Side Table					
	5 - Cart System					
	6 - Cooking Zone					

TABLE C.10: COOKING ZONE SPECIFICATION
DIRECT IMPACT VALUES

Direct Impact	Options	2 MBs, 2 WRs	3 MBs, 1 WR	2 MBs, 3 WRs	3 MBs, 2 WRs	4 MBs, 1 WR
	Initiating Subsystem	6	6	6	6	6
Affected Subsystems	1 - Grill Body	0.3	0.5	0.5	0.6	0.6
	2 - Control System	0	0.3	0	0.3	0.5
	3 - Fuel Transport System					
	4 - Side Table					
	5 - Cart System					
	6 - Cooking Zone					

In Tables C.9 and C.10, additional warming racks (WRs) are assumed to part of Subsystem 1 since the warming rack on the base grill shown in Figure 5.12 is attached to this subsystem. Therefore, for options that just relate to changing the number of warming racks, the likelihood and impact values for Subsystem 2 are zero. When a main burner (MB) is added, likelihood values exist for Subsystems 1 and 2 because Subsystem 1 has to be able to hold another main burner and Subsystem 2 has to control the additional burner. It is assumed that each burner is controllable by a knob present in Subsystem 2. This assumption is made because the base grill has this characteristic; both main burners are controlled by a separate knob in Subsystem 2. Similar to the storage configuration options, the impact values are based on the perceived complexity of the options.

For Step 3.6, the impact values for Subsystem 6 are 0.2, 0.4, 0.3, 0.5, and 0.5 for the options listed in Tables C.9 and C.10 from left to right, respectively. The differences in these values are based on whether a burner or warming rack is added and how many of each is added. Burners are considered to have a greater impact on the subsystem than warming racks because they are more complex than warming racks. Multiple burners or warming racks added are assumed to have larger impacts than when a single burner or warming rack is added because more changes are required to the subsystem.

C.6: Grill Accessories

The direct likelihood and impact values for the customization options relating to grill accessories are shown in the below tables:

TABLE C.11: GRILL ACCESSORIES DIRECT LIKELIHOOD VALUES

Direct Likelihood	Options	Analog, handle light	Analog, inside light	Digital, No light	Digital, handle light	Digital, inside light
	Initiating Subsystem	1	1	1	1	1
Affected Subsystems	1 - Grill Body					
	2 - Control System	0	0	0	0	0
	3 - Fuel Transport System					
	4 - Side Table	0	0	0	0	0
	5 - Cart System	0	0	0	0	0
	6 - Cooking Zone	0	0	0	0	0

TABLE C.12: GRILL ACCESSORIES DIRECT IMPACT VALUES

Direct Impact	Options	Analog, handle light	Analog, inside light	Digital, No light	Digital, handle light	Digital, inside light
	Initiating Subsystem	1	1	1	1	1
Affected Subsystems	1 - Grill Body					
	2 - Control System	0	0	0	0	0
	3 - Fuel Transport System					
	4 - Side Table	0	0	0	0	0
	5 - Cart System	0	0	0	0	0
	6 - Cooking Zone	0	0	0	0	0

In Tables C.11 and C.12, all the likelihood and impact values are zero because no change propagation is perceived. Specifically, it is assumed that a logical designer would not run any wires (to control or power the lights) through the cooking zone.

For Step 3.6, the impact values for Subsystem 1 are 0.1, 0.4, 0.1, 0.2, and 0.5 for the options listed in Tables C.11 and C.12 from left to right, respectively. The handle grill lights and digital thermometer are considered small changes to Subsystem 1. However, the grill lights inside the lid are considered larger, more difficult changes to Subsystem 1 since the light has to be able to withstand the heat.

Appendix D: Combined Likelihood, Impact, and Risk Values for Gas Grill

The combined likelihood, impact, and risk values for the customization options related to the gas grill case study are presented in this appendix. As with Appendix C, this appendix is broken into subsections based on customization option groupings, starting with side table specifications and ending with grill accessories. For the initiating subsystem for each customization option, the combined likelihood value is 1, the combined impact value is the one presented in Appendix C, and the combined risk is the product of the two.

D.1: Side Table Specification

The direct likelihood and impact values for the customization options relating to side table specifications are shown in the below tables:

TABLE D.1: SIDE TABLE SPECIFICATION COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	2 THs/ table	4 THs/ table	1 SB, 0 THs	1 SB, 2 THs/ table	1 SB, 4 THs/ table
	Initiating Subsystem	4	4	4	4	4
Affected Subsystems	1 - Grill Body	0	0	0.96	0.96	0.96
	2 - Control System	0	0	1.00	1.00	1.00
	3 - Fuel Transport System	0	0	0.52	0.52	0.52
	4 - Side Table	1.00	1.00	1.00	1.00	1.00
	5 - Cart System	0	0	0.68	0.68	0.68
	6 - Cooking Zone	0	0	0.90	0.90	0.90

TABLE D.2: SIDE TABLE SPECIFICATION COMBINED IMPACT VALUES

Combined Impact	Options	2 THs/ table	4 THs/ table	1 SB, 0 THs	1 SB, 2 THs/ table	1 SB, 4 THs/ table
	Initiating Subsystem	4	4	4	4	4
Affected Subsystems	1 - Grill Body	0	0	0.59	0.59	0.59
	2 - Control System	0	0	0.77	0.77	0.77
	3 - Fuel Transport System	0	0	0.44	0.44	0.44
	4 - Side Table	0.10	0.20	0.80	0.90	0.90
	5 - Cart System	0	0	0.59	0.59	0.59
	6 - Cooking Zone	0	0	0.81	0.81	0.81

TABLE D.3: SIDE TABLE SPECIFICATION COMBINED RISK VALUES

Combined Risk	Options	2 THs/ table	4 THs/ table	1 SB, 0 THs	1 SB, 2 THs/ table	1 SB, 4 THs/ table
	Initiating Subsystem	4	4	4	4	4
Affected Subsystems	1 - Grill Body	0	0	0.57	0.57	0.57
	2 - Control System	0	0	0.77	0.77	0.77
	3 - Fuel Transport System	0	0	0.23	0.23	0.23
	4 - Side Table	0.10	0.20	0.80	0.90	0.90
	5 - Cart System	0	0	0.40	0.40	0.40
	6 - Cooking Zone	0	0	0.73	0.73	0.73

D.2: Grill Lid Opening Mechanism

The direct likelihood and impact values for the customization options relating to grill lid opening mechanism are shown in the below tables:

TABLE D.4: GRILL LID OPENING MECHANISM COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	Spring-assisted	Hydraulic-assisted	Motorized
	Initiating Subsystem	1	1	1
Affected Subsystems	1 - Grill Body	1.00	1.00	1.00
	2 - Control System	0	0	0.50
	3 - Fuel Transport System	0	0	0.20
	4 - Side Table	0	0	0.06
	5 - Cart System	0	0	0.60
	6 - Cooking Zone	0	0	0.30

TABLE D.5: GRILL LID OPENING MECHANISM COMBINED IMPACT VALUES

Combined Impact	Options	Spring-assisted	Hydraulic-assisted	Motorized
	Initiating Subsystem	1	1	1
Affected Subsystems	1 - Grill Body	0.20	0.30	0.50
	2 - Control System	0	0	0.20
	3 - Fuel Transport System	0	0	0.40
	4 - Side Table	0	0	0.30
	5 - Cart System	0	0	0.20
	6 - Cooking Zone	0	0	0.60

TABLE D.6: GRILL LID OPENING MECHANISM COMBINED RISK VALUES

Combined Risk	Options	Spring-assisted	Hydraulic-assisted	Motorized
	Initiating Subsystem	1	1	1
Affected Subsystems	1 - Grill Body	0.20	0.30	0.50
	2 - Control System	0	0	0.10
	3 - Fuel Transport System	0	0	0.08
	4 - Side Table	0	0	0.02
	5 - Cart System	0	0	0.12
	6 - Cooking Zone	0	0	0.18

D.3: Total Grill Height

The direct likelihood and impact values for the customization options relating to total grill height are shown in the below tables:

TABLE D.7: TOTAL GRILL HEIGHT COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	46in	48in	42in	40in	Adjustable
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0	0	0	0	0.28
	2 - Control System	0	0	0	0	0.17
	3 - Fuel Transport System	0	0	0	0	0.08
	4 - Side Table	0	0	0	0	0.25
	5 - Cart System	1.00	1.00	1.00	1.00	1.00
	6 - Cooking Zone	0	0	0	0	0.21

TABLE D.8: TOTAL GRILL HEIGHT COMBINED IMPACT VALUES

Combined Impact	Options	46in	48in	42in	40in	Adjustable
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0	0	0	0	0.38
	2 - Control System	0	0	0	0	0.48
	3 - Fuel Transport System	0	0	0	0	0.42
	4 - Side Table	0	0	0	0	0.23
	5 - Cart System	0.20	0.20	0.20	0.20	0.90
	6 - Cooking Zone	0	0	0	0	0.73

TABLE D.9: TOTAL GRILL HEIGHT COMBINED RISK VALUES

Combined Risk	Options	46in	48in	42in	40in	Adjustable
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0	0	0	0	0.11
	2 - Control System	0	0	0	0	0.08
	3 - Fuel Transport System	0	0	0	0	0.03
	4 - Side Table	0	0	0	0	0.06
	5 - Cart System	0.20	0.20	0.20	0.20	0.90
	6 - Cooking Zone	0	0	0	0	0.15

D.4: Under-grill Cabinet Storage Configuration

The direct likelihood and impact values for the customization options relating to under-grill cabinet storage configuration are shown in the below tables:

TABLE D.10: STORAGE CONFIGURATION COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	2 LP	LP + 3 shelves	LP + 3 adjustable shelves	LP + trash can	LP + cooler
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0.72	0.49	0.49	0.63	0.72
	2 - Control System	0.47	0.30	0.30	0.40	0.47
	3 - Fuel Transport System	0.22	0.14	0.14	0.19	0.22
	4 - Side Table	0.67	0.38	0.38	0.58	0.67
	5 - Cart System	1.00	1.00	1.00	1.00	1.00
	6 - Cooking Zone	0.56	0.37	0.37	0.48	0.56

TABLE D.11: STORAGE CONFIGURATION COMBINED IMPACT VALUES

Combined Impact	Options	2 LP	LP + 3 shelves	LP + 3 adjustable shelves	LP + trash can	LP + cooler
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0.56	0.53	0.53	0.55	0.56
	2 - Control System	0.50	0.48	0.48	0.49	0.50
	3 - Fuel Transport System	0.43	0.42	0.42	0.43	0.43
	4 - Side Table	0.33	0.32	0.32	0.33	0.33
	5 - Cart System	0.50	0.40	0.70	0.20	0.60
	6 - Cooking Zone	0.75	0.73	0.73	0.74	0.75

TABLE D.12: STORAGE CONFIGURATION COMBINED RISK VALUES

Combined Risk	Options	2 LP	LP + 3 shelves	LP + 3 adjustable shelves	LP + trash can	LP + cooler
	Initiating Subsystem	5	5	5	5	5
Affected Subsystems	1 - Grill Body	0.40	0.26	0.26	0.35	0.40
	2 - Control System	0.24	0.14	0.14	0.20	0.24
	3 - Fuel Transport System	0.09	0.06	0.06	0.08	0.09
	4 - Side Table	0.22	0.12	0.12	0.19	0.22
	5 - Cart System	0.50	0.40	0.70	0.20	0.60
	6 - Cooking Zone	0.42	0.27	0.27	0.36	0.42

D.5: Cooking Zone Specification

The direct likelihood and impact values for the customization options relating to cooking zone specifications are shown in the below tables:

TABLE D.13: COOKING ZONE SPECIFICATION COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	2 MBs, 2 WRs	3 MBs, 1 WR	2 MBs, 3 WRs	3 MBs, 2 WRs	4 MBs, 1 WR
	Initiating Subsystem	6	6	6	6	6
Affected Subsystems	1 - Grill Body	1.00	0.82	1.00	1.00	0.86
	2 - Control System	0.20	1.00	0.20	1.00	1.00
	3 - Fuel Transport System	0.08	0.43	0.08	0.45	0.43
	4 - Side Table	0.34	0.35	0.34	0.46	0.38
	5 - Cart System	0.50	0.50	0.50	0.64	0.53
	6 - Cooking Zone	1.00	1.00	1.00	1.00	1.00

TABLE D.14: COOKING ZONE SPECIFICATION COMBINED IMPACT VALUES

Combined Impact	Options	2 MBs, 2 WRs	3 MBs, 1 WR	2 MBs, 3 WRs	3 MBs, 2 WRs	4 MBs, 1 WR
	Initiating Subsystem	6	6	6	6	6
Affected Subsystems	1 - Grill Body	0.30	0.50	0.50	0.66	0.59
	2 - Control System	0.20	0.32	0.20	0.33	0.51
	3 - Fuel Transport System	0.40	0.41	0.40	0.42	0.41
	4 - Side Table	0.31	0.34	0.31	0.34	0.34
	5 - Cart System	0.50	0.55	0.50	0.56	0.55
	6 - Cooking Zone	0.20	0.40	0.30	0.50	0.50

TABLE D.15: COOKING ZONE SPECIFICATION COMBINED RISK VALUES

Combined Risk	Options	2 MBs, 2 WRs	3 MBs, 1 WR	2 MBs, 3 WRs	3 MBs, 2 WRs	4 MBs, 1 WR
	Initiating Subsystem	6	6	6	6	6
Affected Subsystems	1 - Grill Body	0.30	0.41	0.50	0.66	0.51
	2 - Control System	0.04	0.32	0.04	0.33	0.51
	3 - Fuel Transport System	0.03	0.18	0.03	0.19	0.18
	4 - Side Table	0.11	0.12	0.11	0.16	0.13
	5 - Cart System	0.25	0.28	0.25	0.36	0.29
	6 - Cooking Zone	0.20	0.40	0.30	0.50	0.50

D.6: Grill Accessories

The direct likelihood and impact values for the customization options relating to grill accessories are shown in the below tables:

TABLE D.16: GRILL ACCESSORIES COMBINED LIKELIHOOD VALUES

Combined Likelihood	Options	Analog, handle light	Analog, inside light	Digital, No light	Digital, handle light	Digital, inside light
	Initiating Subsystem	1	1	1	1	1
Affected Subsystems	1 - Grill Body	1.00	1.00	1.00	1.00	1.00
	2 - Control System	0	0	0	0	0
	3 - Fuel Transport System	0	0	0	0	0
	4 - Side Table	0	0	0	0	0
	5 - Cart System	0	0	0	0	0
	6 - Cooking Zone	0	0	0	0	0

TABLE D.17: GRILL ACCESSORIES COMBINED IMPACT VALUES

Combined Impact	Options	Analog, handle light	Analog, inside light	Digital, No light	Digital, handle light	Digital, inside light
	Initiating Subsystem	1	1	1	1	1
Affected Subsystems	1 - Grill Body	0.10	0.40	0.10	0.20	0.50
	2 - Control System	0	0	0	0	0
	3 - Fuel Transport System	0	0	0	0	0
	4 - Side Table	0	0	0	0	0
	5 - Cart System	0	0	0	0	0
	6 - Cooking Zone	0	0	0	0	0

TABLE D.18: GRILL ACCESSORIES COMBINED RISK VALUES

Combined Risk	Options	Analog, handle light	Analog, inside light	Digital, No light	Digital, handle light	Digital, inside light
	Initiating Subsystem	1	1	1	1	1
Affected Subsystems	1 - Grill Body	0.10	0.40	0.10	0.20	0.50
	2 - Control System	0	0	0	0	0
	3 - Fuel Transport System	0	0	0	0	0
	4 - Side Table	0	0	0	0	0
	5 - Cart System	0	0	0	0	0
	6 - Cooking Zone	0	0	0	0	0