Flexible Product Platforms

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Abstract

The research contributes to the uncertainty management of engineering systems by proposing and demonstrating a way to implement flexible platform strategy to respond to future uncertainties. In today's competitive market, where market segments are becoming more fragmented, pressure to develop and market diverse sets of products is increasing. To meet such market needs and reduce production cost at the same time, product platform strategy has been implemented in several different industries. Using a core set of common platform elements and variant-specific unique elements, a family of products can be produced to satisfy various market segments. However, the growing cost of platform development and undesired side effects of the strategy (e.g. performance tradeoff, cannibalization) is forcing companies to design their platforms with flexibility, so they can accommodate product variants, differentiate these variants, and be economically flexible to respond to specified future uncertainties. This thesis introduces a design process to architect flexible product platforms. The proposed process is demonstrated in two automotive application case studies. In the first case study, a vehicle floor pan is designed to satisfy two different length requirements, while being economically robust to future specification change and component demand. The second case study investigates a vehicle platform, where the flexible body in white (BIW) platform is designed for a family of three vehicle variants through identification of critical elements subset. Results showed that the flexible BIW platform is less profitable than the inflexible BIW platform, but when the degree of future uncertainty increases, the flexible design eventually becomes more profitable. This research provides additional examples that yet again confirms the general proposition "flexibility gains value as the degree of uncertainty increases."

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I like to dedicate this thesis to my father and mother, who were always there for me and loved me.

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Nomenclature

Abbreviations

BIW	Body In White
CI	Coupling Index
CPI	Change Propagation Index
DP	Design Parameter
DSM	Design Structure Matrix
FR	Functional Requirement
GBM	Geometric Brownian Motion
GVI	Generational Variety Index
QFD	Quality Function Deployment
RSM	Response Surface Model
SAE	Society of Automotive Engineers

Symbols

$\mathcal{M}$	Set of Market Segments
$\mathcal{M}_{\text{veh}}$	Set of Vehicle Market Segments
$\mathcal{P}$	Set of Product Variants
$\mathcal{P}_{\text{veh}}$	Set of Vehicle Variants
$\mathcal{U}$	Set of Uncertainties
$\mathcal{U}_{\text{comp}}$	Component Related Uncertainties
$\mathcal{U}_{\text{veh}}$	Vehicle Family Related Uncertainties
$\mathcal{V}_{\text{comp}}$	Set of Component Design Alternatives
$\mathbf{J}_A$	Product Attribute Vector

$\mathbf{J}_C$	Component Cost Vector
$\mathbf{J}_Z$	Component Performance Vector
$\mathbf{J}_{\mathcal{U}}$	Uncertainty Related Product Attributes Vector
$\mathbf{J}_{\mathcal{U}_{\text{veh}}}$	Uncertainty Related Vehicle Attributes Vector
$\mathbf{X}_A$	Design Variable Vector
$\mathbf{X}_{\text{comp}}$	Design Variables for a Platform Component
$\mathbf{X}_{IE}$	Design Variable Vector for Front Ingress/Egress
$\mathbf{X}_L$	Design Variables for a Long Floor Pan
$\mathbf{X}_{RM}$	Design Variable Vector for Passenger Roominess
$\mathbf{X}_S$	Design Variables for a Short Floor Pan
$\mathbf{X}_{\mathcal{U}}$	Uncertainty Related Attributes Design Vector
$\mathbf{X}_{\mathcal{U}_{\text{veh}}}$	Uncertainty Related Vehicle Attributes Design Vector
AC_{50-70}	50 to 70 mph Acceleration Time
C_{total}	Total Variable Cost
CF	Cash Flow
D	Demand
D_h	Historical Demand
D_o	Initial Demand
$D_{\mathcal{P}}$	Demand of Vehicle Family
D_T	Total Market Demand for Market Segment Set $\mathcal{M}$
ΔE	Binary Number (0,1) Indicating Element's Change
$E[D]$	Expected Demand
$E[NPC]$	Expected Net Present Cost
$E[NPV]$	Expected Net Present Value
FE	Fuel Economy
$H5$	SgRP -Front to Ground
$H11$	Entrance Height - Front
$H30$	SgRP - Front to Heel
$H31$	SgRP - Second to Heel
$H50$	Upper Body Opening to Ground - Front

$H61$	Effective Head Room - Front
$H63$	Effective Head Room - Second
$H112$	Rocker Panel - Front to Ground
$H115$	Step Height - Front
$H122$	Wind Shield Slope Angle
IE	Ease of Front Ingress / Ingress
K	Total Investment Cost for Component Design Alternative
K_{init}	Initial Investment Cost
K_{line}	Line Investment Cost
K_{ref}	Refurbishing Cost
K_{switch}	Switch Related Investment Cost
K_{tool}	Tooling Investment Cost
L	Floor Pan Length
$L18$	Entrance Foot Clearance - Front
$L48$	Knee Clearance - Second
M	Individual Market Segment
NPC	Net Present Cost
NPV	Net Present Value
P	Price of Product Variant
P_w	Weighted Average Price of a Vehicle Variant
R	Total Product Variant Revenue
R_T	Total Product Family Revenue
RM	Customer Perceived Vehicle Roominess
$S_{\mathcal{P}}$	Styling of Vehicle Family
$S97$	Downward Vision Angle
T	Number of Time Periods
TC	Total Cost
T_f	Number of Future Time Periods
T_h	Number of Historical Time Periods
$W5$	Hip Room - Front

$W20$	SgRP - Front Y Coordinate
$W27$	Head Clearance Diagonal - Driver
c	Unit Cost of Component Variant
c_a	Unit Assembly Cost of Component Variant
c_f	Unit Fabrication Cost of Component Variant
c_{veh}	Unit Cost of Vehicle
m	Mass of the Floor Pan
ms	Market Share
n_c	Number of Component Variants
n_{in}	Number of Elements Sending Changes into i^{th} Element
n_m	Number of Market Segments
n_{out}	Number of Elements Receiving Changes from i^{th} Element
n_p	Number of Product Variants
n_{trim}	Number of Vehicle Trim Levels
n_u	Number of Uncertainties
n_v	Number of Design Alternatives
n_x	Number of Design Variables
p	Individual Product Variant
r	Discount Rate
u	Individual Uncertainty
u_{comp}	Individual Uncertainty for Component
v_{comp}	Individual Platform Component Design Alternative
w	Number of Floor Pan Welding Connections
x	Individual Design Variable
α	Demand Trend
ε	Random Number With N(0,1)
σ_v	Demand Volatility

Chapter 1

Introduction

1.1 Prologue: Analogy of Flexibility

1.1.1 The Roman Empire

After the civil war ended in 31 B.C., the Roman Empire underwent a structural reform under the leadership of Augustus Caesar. Roman legions, over 300,000 in regular and reserve troops, were posted in the outer provinces, strategically and far away from each other to minimize the chance of rebellion against the Imperial throne. These provinces were under direct Imperial control, while the inner provinces, where no armies were present, were controlled by the Senate. By instituting this political and military administrative system, Augustus succeeded in achieving political stability, which became the foundation of *Pax Romana*, a period of peace and prosperity.

However, the instituted system based on preclusive security strategy was not without its own weakness. If any foreign invaders breached its outer defenses, there were no military forces to stop them inside. So, it would take a long time to respond to the threat. But at the time of Augustus' reign, the Roman Empire dominated the Mediterranean region and northwestern Europe with no competition. Therefore, this system worked well, despite its weakness to outside disturbances, such as foreign invasions.

During the 3rd century A.D., Emperor Diocletian addressed this weakness by creat-

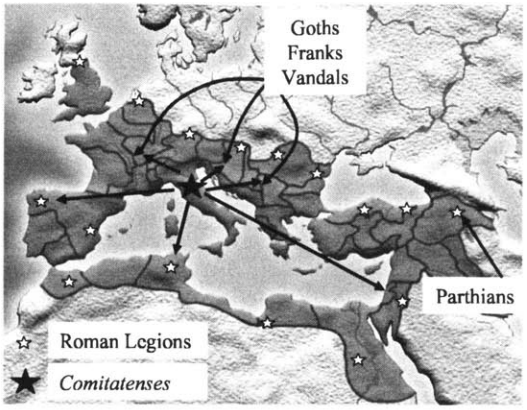


Figure 1-1: Roman Military Strategy (3rd Century)

ing *comitatenses*, a central mobile army, which could respond to foreign invasions more rapidly (shown in Figure 1-1). This was accomplished by stripping 100,000 troops from border provinces and placing the mobile army on a strategic location within the empire. Thus, two distinct types of armies were developed. In the provinces, stationed along the borders, were the frontier armies made up of resident soldiers (*limitanei*) and commanded by a leader (*dux*). A larger, better trained, and more mobile field army (*comitatenses*) was under the command of masters of infantry and cavalry (*magistri peditum, equitum*) [77]. The Roman Empire thus acquired flexibility to respond to foreign threats. However, this reform resulted in significant strength reduction in border legions, making the entire frontier more prone to foreign invasion. Additionally, there was only one complete mobile army unit, so when the war broke out in two fronts, they were ill prepared to engage in both fronts.

The Roman Empire acqiored flexibility to respond to uncertain foreign military threat, but the newly implemented flexible strategy weakened its border defenses significantly, increasing chances of uncertain invasion. According to the Byzantine historian Zosimus [11], this military reform contributed significantly to the decline of the Roman Empire. This lesson - which is at the core of this thesis - is that flexibility is desirable when a system of any kind is faced with exogenous uncertainty, but must be implemented carefully to minimize undesirable side effects.

1.1.2 The Automotive Industry

Today's automotive market is a fiercely competitive market where many global motor companies are competing for market shares. In the 50's, the market was dominated by the American Big Three (GM, Ford, and Chrysler), capturing 95 percent of total U.S. market share in 1955. Three companies produced their vehicles on mass production strategy based assembly lines. This was evident, since six models accounted for 80% of all cars sold in 1955 [86]. It was easy to "defend" their market shares with small number of vehicle models back then.

Since then, the automotive market evolved significantly. Customers started to demand variety in vehicle models. Several Asian and European competitors started to gain market shares in the United States. Market segments started to become more fragmented, creating a need (or opportunity) for more diverse, yet low-volume vehicles. In 2004, Mark Chernoby, Vice President at DaimlerChrysler Corp. stated "twenty years ago we didn't have as much competition, the market wasn't as fragmented, and you could enjoy high volume....we can no longer expect to enjoy these huge half-million-per-model sales volume any more [13]." The traditional mass production strategy could not keep up with market trend, since switch costs for changing to a new product is very high.

To reduce this inefficiency in cost and to respond to the need of customers, automotive manufacturers implemented *product platform strategy*. By sharing key elements among various products in the product family, firms were able to develop new products quickly, at reduced cost. One of the key concepts of product families is the distinction between common and unique elements, where common elements are used in all product variants while unique elements are specific to a single variant. In some ways, a product platform may be viewed as a central reserve (similar to *comitatenses*) or infrastructure from which multiple product variants can be derived, as seen on Figure 1-2.

However, in recent years potential drawbacks of the product platform strategy have become apparent. By sharing too many elements among different vehicles, vari-

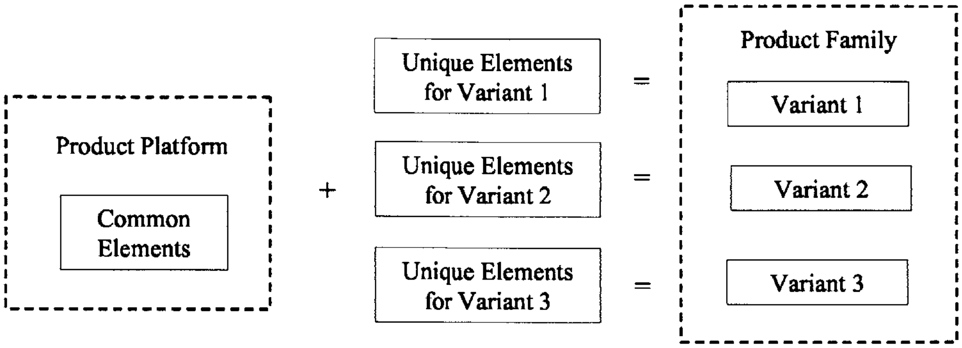


Figure 1-2: Product Platform and Family

ants were not differentiated sufficiently from each other, losing their unique brand identity. An example of this is the Chrysler **K** platform, which at one point, was the base platform for virtually every car the company developed [13]. In addition, sharing elements between high end vehicles and low end vehicles resulted in cannibalization of sales of high-end vehicles by low-end vehicle variants [16]. Finally, due to the high cost of platform development, the firms that own the platform were reluctant to accept new product innovations that couldn't be implemented into already existing platforms. What was needed is a product platform strategy that is indeed an effective strategy to reduce development time and cost, while remaining flexible enough to support multiple vehicle variants from a single platform.

One of the main drivers for such strategy improvement arises from the general increase in the number of models to satisfy a wider range of customer markets which, in turn, is becoming more and more fragmented due to more demand for customization. At the same time, motor companies are under severe pressure to keep costs down to be competitive in a highly competitive market, with a very low profit margin. As results, companies are trying to reduce the number of vehicle platforms, since each platform costs upwards of a billion dollars to create and sustain. Figure 1-3 shows a projection of the number of vehicle variants per platform for major automotive manufacturers. What each company defined as its vehicle platform may differ.

Note that for each company, the expected average vehicle models per platform generally increases in the future. This trend implies that each vehicle platform must

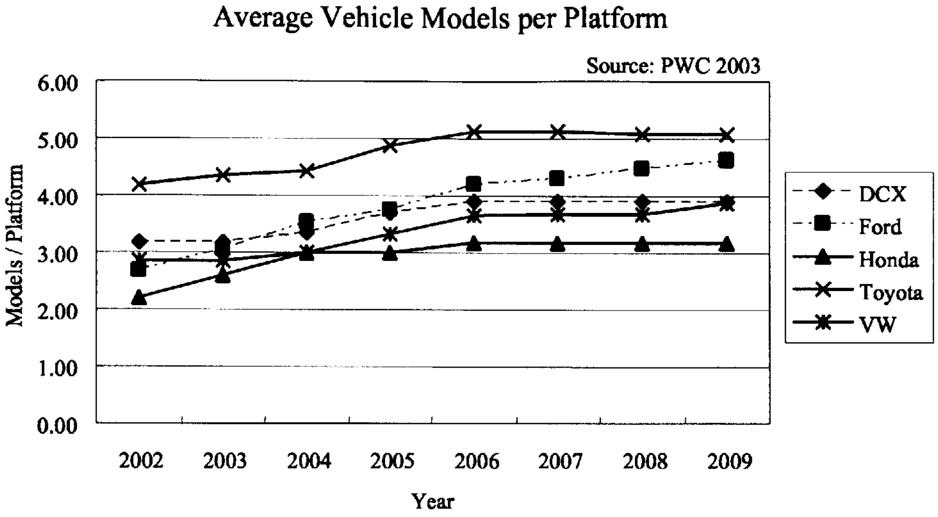


Figure 1-3: Projected Number of Vehicle Models / Platform for Automakers

accommodate a greater number of vehicle variants, thus requiring a wider platform bandwidth in terms of product attributes and system-level design variable values.

From the discussion above, it is clear how the incorporation of flexibility into the vehicle platform can help companies achieve objectives for the number of desired product variants per platform, and create a distinct variety for each product in terms of performance and brand distinction, while reducing costs and development time.

This raises a key research issue: how can we identify critical areas within a product platform to incorporate flexibility for maximizing product distinctiveness and element commonality, while minimizing switching cost, so that one may respond to changing customer needs, policy decisions and emerging technologies?

1.2 Research Background

In the late 1980's, the mass customization paradigm [18, 62] emerged. Mass customization focuses on serving the need of individual customers through high product variety, while achieving economies of scale through high volume production using flexible manufacturing processes. The rise of paradigm was a result of the emergence of global markets, which created new market segments based on age, gender, ethnicity and lifestyle, resulting in a product variety increase and with development time decrease [69].

Manufacturers were forced to seek more efficient and flexible product design and manufacturing strategies to satisfy regional policies and regulations, demand for more product variety, rising costs for raw materials, labor costs, manufacturing resources, and faster evolution of new technologies. Two of the most successfully implemented strategies were the lean manufacturing strategy [86] and the product platform strategy [9, 51]. The lean manufacturing strategy attempts to reduce manufacturing costs by decreasing or totally eliminating inefficiencies in the supply chain, as well as in fabrication and assembly processes. The product platform strategy attempts to save costs by sharing core elements among different products in the product family. A significant amount of scientific research results have been published in the field of lean manufacturing and platform strategy, but there still are many opportunities for further research. In this thesis, major emphasis is placed on the product platform strategy, especially on the question of how to incorporate flexibility in product platforms. A major contribution of the thesis is the introduction of a *flexible product platform design process*, taking into account exogenous uncertainties, and a concept of *flexible elements*, which lie in-between common and unique elements.

Flexibility is defined as "the property of a system that is capable of undergoing classes of changes with relative ease [3]." This property is embedded in many engineering systems and products to account for any unforeseen future changes in the operating environment, customer needs, and technological advances. One such example is the Black & Decker power tool family. They created various product variants by using common set of motors which have same diameter, but different lengths. The common motor casing, to accommodate motors with different length, had built in "degree of freedom" in terms of interior motor space [51].

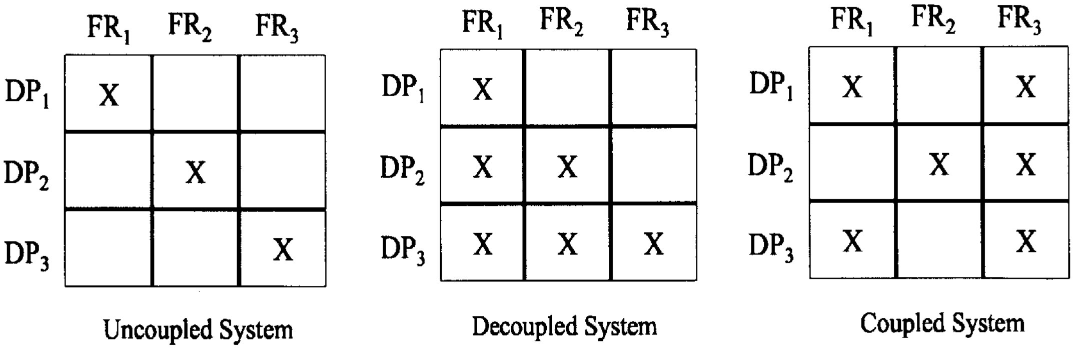
With continuous fragmentation of product market segments and diversifying customer needs, incorporating the right amount of flexibility in engineering, product development and manufacturing has become a key strategic initiative for many product manufacturers. The product platform is no exception. One of the original purposes of the product platform was to create a flexible infrastructure for a family of products. But the big question is how to identify places to embed flexibility? How much flexibility is needed? How much will the flexibility cost? What is the future benefit of flexibility? This thesis attempts to address the aforementioned questions by formulating a design process for flexible product platforms that can be applied to systems of increasing complexity.

1.3 Thesis Problem Formulation

In this section, the relevance of the thesis research is demonstrated through a simple example. Then the objectives of the research are stated, followed by the limitation of research scope.

1.3.1 Axiomatic Design Generic Example

Figure 1-4 shows FRDP (Functional Requirement - Design Parameter) representation of three different systems. The first system is uncoupled, meaning that only one DP is associated with each FR. The second system is decoupled, meaning that if DP is changed in sequence, it can "guarantee the independence of FR [80]." Third system is a coupled system, where change in a single DP affects multiple FRs.



	FR_1	FR_2	FR_3
DP_1	X		
DP_2		X	
DP_3			X

Uncoupled System

	FR_1	FR_2	FR_3
DP_1	X		
DP_2	X	X	
DP_3	X	X	X

Decoupled System

	FR_1	FR_2	FR_3
DP_1	X		X
DP_2		X	X
DP_3	X		X

Coupled System

Figure 1-4: Three Systems in FRDP Form

Let's assume that, in the future, FR$_1$ will change, and the system architect wishes to incorporate flexibility in the system to absorb the change. If flexibility is incorporated in DP_1 for uncoupled and decoupled systems, other DPs and FRs will not be affected by change in FR_1. However, it is no longer the case with the coupled system. DP_1 and DP_3 are candidate DPs for the coupled system.

If uncertainty increases, and FR_1 and FR_2 are both uncertain, then the issue of incorporating flexibility becomes more challenging. For uncoupled system, DP_1 and DP_2 can be independently changed to accommodate future uncertainties in FRs. For the decoupled system, the flexibility can be incorporated into DP_2 to accommodate changes in both FRs, or DP_3 can be flexible as well. In the coupled system, it is not clear where to embed the flexibility.

Finally, if all three FRs are uncertain, situation becomes even more difficult. For the uncoupled system, the flexibility can be incorporated in all DPs to suit changes in FRs. For the decoupled system, the flexibility can be incorporated into DP_3 in a way that it will not affect other DPs, but other DPs must be investigated as well. For the coupled system, on the other hand, it becomes very difficult to identify where the flexibility should be incorporated.

In the last case, where all FRs are uncertain, the uncoupled system required flexibility in all three DPs. However, adding flexibility to each DP is relatively simple, since flexible design for each DP can be tailored to the corresponding FR. In the decoupled system, it is not the case. Flexibility in DP_3 (if it is chosen as key DP) must be incorporated in such a way to meet the requirement in all three FRs, thus making it difficult to come up with a satisfying design. For the coupled system, it becomes even more difficult. One way to find critical DPs, assuming all FRs are differentiable by all DPs, is to find the first derivatives for all FRs and DPs. The Jacobian matrix of coupled system is shown in Equation (1.1).

$$\frac{\partial \mathrm{FR}}{\partial \mathrm{DP}} = \begin{bmatrix} \frac{\partial \mathrm{FR}_1}{\partial \mathrm{DP}_1} & 0 & \frac{\partial \mathrm{FR}_1}{\partial \mathrm{DP}_3} \\ 0 & \frac{\partial \mathrm{FR}_2}{\partial \mathrm{DP}_2} & \frac{\partial \mathrm{FR}_2}{\partial \mathrm{DP}_3} \\ \frac{\partial \mathrm{FR}_3}{\partial \mathrm{DP}_1} & 0 & \frac{\partial \mathrm{FR}_3}{\partial \mathrm{DP}_3} \end{bmatrix} \tag{1.1}$$

Observing sensitivities of each FR with respect to corresponding DPs can reveal the priorities of DPs which can be candidates for incorporating flexibility. Much research has been accomplished to identify sensitive DPs. However, once these DPs are identified, how can they be made flexible so they can respond to uncertainties in a specific FR without affecting other FRs? This can be accomplished only through investigation of the physical system itself, and redesign of related elements that affects that particular DP. Additional challenge comes from the fact that for each DP, there might be several physical elements which need to be redesigned to achieve such flexibility. After such redesign, the new flexible system then must be economically evaluated, under several different uncertainty scenarios, to see if the incorporated flexibility has value. This research gap awaits to be explored.

Most large complex engineering systems today (including product platforms) are coupled systems, where a single DP may affect several FRs. When certain FR's trend becomes uncertain in the future, it is very difficult to change the system to meet the goal of that FR, largely due to such coupling and economic impact of making such changes. If a critical subset (if it exists) of the system can be identified and made flexible, the system can be flexible to changes induced by future uncertainties with relative ease, compared to a system that has no flexibility. To address this issue, especially for product platforms, this thesis proposes a design process, stated in the next section.

1.3.2 Thesis Objective

The main objectives of the thesis is to formulate and demonstrate a new processes to design flexible product platforms. The proposed process is shown in Figure 1-5. Detailed formulation of the process is presented in Chapter 3.

The process starts with identification of product family, uncertainty, uncertainty related attributes, and relevant system-level design variables. Then the product family's system-level design variable bandwidths are determined through revenue optimization. Established design variables are mapped to platform elements, and through the change propagation analysis, critical elements are identified. Identified elements are designed with incorporated flexibility to satisfy required design variable band-

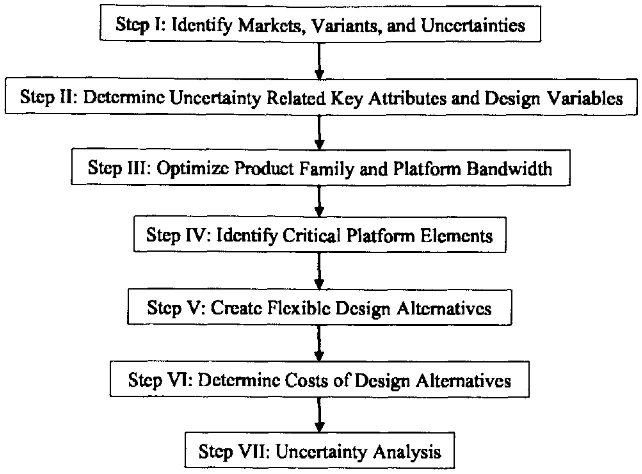


Figure 1-5: Flexible Product Platform Design Process

width and to respond to uncertain changes in the future. Costs for incorporating such flexibility for the platform is calculated. Finally, the value of the flexibility is determined through the uncertainty analysis, and the final decision to implement the flexible design is made. It is hoped that this thesis will contribute to the advancement of the field of engineering systems by introducing a framework to design flexible product platforms, a complex engineering system, and demonstrating the process through industry-based case studies.

1.3.3 Limitation of Thesis Scope

The thesis focuses on the development of a design process framework for flexible product platforms. Its contribution is to establish a systematic process to create a flexible platform that can be changed with relatively smaller increase in cost than the inflexible platform, when required by exogenous uncertainties. Carrying pre-identified uncertainties through the entire process, flexible design alternatives are defined, including their initial investment costs, and switch costs for making changes. The main emphasis of this research is to identify and incorporate flexibility in the critical elements of the product platform, and demonstrate the value of flexibility under future uncertainties. Figure 1-6 graphically shows the boundary of the thesis research.

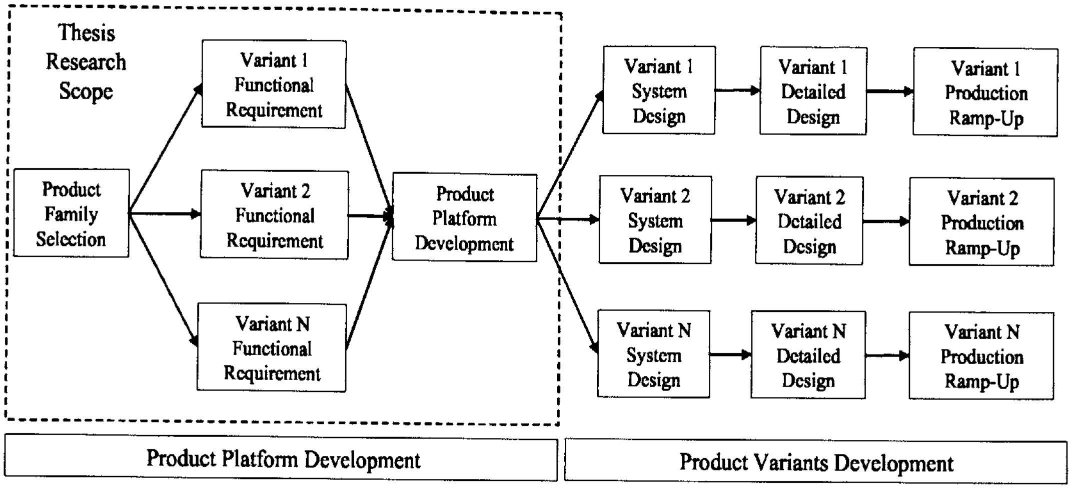


Figure 1-6: Thesis Research Scope

The design process focuses on the early-stage conceptual product platform development strategy. It deals with a new platform development, where a set of specific uncertainties must be known beforehand, and the architecture of the product platform must also be known. The number of desired product variants in the product family is known as well.

Certain steps in the platform design process, namely Step IV (identify critical platform elements) and Step V (generate flexible design alternative), shown in Figure 1-5, require engineering expertise. This is not an automated "push button" process. Additionally, due to the nature of design, there are many non-unique solutions that can satisfy given criteria.

1.4 Literature Review

A brief overview of relevant literature is presented. The main focus of this thesis is the flexible product platform design process development. However, there are many related fields that contribute to this research, directly and indirectly. Listed and discussed here are literature that are closely related to the product platform design research. They include conjoint analysis, attribute-to-design parameter mapping, system decomposition, optimization theory and algorithms, product design, system architecture, product platform concepts and methodologies, flexibility in engineering design and manufacturing, and uncertainty and decision analysis.

Conjoint analysis [1, 14, 32, 33, 82] is the most widely used technique to identify and quantify customer needs on a measurable scale. Using conjoint analysis, firms can 1) identify critical product attributes that affect customers' perceived product values; 2) estimate the likely success of a new product in a competitive environment as a function of its critical attributes; and 3) efficiently design and position products within market segments to maximize net return.

Mapping identified customer needs to designable engineering metrics is accomplished by implementing several techniques. A widely used method to accomplish this task is Quality Function Deployment (QFD) [4, 36], which employs a needs-metric matrix for mapping customer needs to identify and quantify proper design variables. Another popular method is principal component analysis [22], which can identify the most influential design variables when several data points are available. Once engineering design variables and governing equations for customer preferred attributes are established, they must be decomposed to minimize feedback. Numerous articles are published in the area of **system decomposition**, where complex relationships of design variables are graphically expressed and decomposed for modular design or feedback free design. One widely used concept is the Design Structure Matrix (DSM), first proposed by Steward [78] and later refined and applied to industrial products and processes by Eppinger et. al. [24].

The field of **optimization** is well researched. Arora [6] provides a good overview of basic mathematical theories and applications of gradient-based single objective optimization. However, many system and engineering problems need to be optimized for multiple objectives. As result, the field of **multiobjective optimization** emerged, where multiple objectives are optimized, instead of a single objective. See Sawaragi et. al. [70]. Recently, recognizing the importance of system design involving multiple disciplines, **multidisciplinary design optimization** has gained significant importance. In addition, a number of new optimization algorithms have been developed. The current trend of optimization algorithm development is shifting from traditional gradient-based algorithms to more heuristic algorithms, based on natural phenomenons. Examples of the most widely used heuristic algorithms are genetic algorithm [28] and simulated annealing [43].

Product design and development is a key research field that has continuously received great attention. There are many publications in the areas of product design processes [60, 61, 80, 83] and product design paradigms, such as design for assembly [7, 84, 85], design for manufacturing [8], and design for variety [49], of all which are parts of Design for X methodologies. In addition, the field of **system architecture** is gaining more attention as products themselves become more complex. Maier and Rechtin [47] published a book that presents a basic heuristic framework for system architecting. Crawley [17] is currently expanding the theory on system architecture as well.

A product design and development strategy, which is the core of this thesis, is the **product platform strategy** [65], the term coined by Meyer and Lehnerd [51]. The strategy focuses on sharing core elements (components, interfaces, processes) among different variants of a product family, achieving reductions in development cost and time, while diversifying a number of product variants. According to Simpson [75], a product platform strategy is mostly implemented in modular and scalable product families. Examples of platform applications in modular families include Sony Walkman [68], ink jet and laser jet printers [25], modular component-based structures [63], and automotive components [83]. Examples of scalable platform applications include aircraft engines [66], airplanes [67] and automobiles [9, 57]. Numerous articles on product platform strategy have been published. Topics include platform design methodology [21, 30, 54, 58, 73, 76], platform-related metrics and definitions [44, 49, 52, 59, 87] as well as economic evaluation [27, 31, 45, 46]. It is surprising that almost no literature exists on the question of how product platforms can assist in responding to uncertainty through incorporation of flexibility. The discussion is usually dominated by the tradeoff between commonality (re-use) and distinctiveness, for a known set of variant functional requirements.

In summary, this thesis will focus on product platform design to incorporate flexibility [13, 79] in critical platform elements, including components, interfaces and manufacturing processes. **Manufacturing flexibility** is a mature research area. Classic papers by Sethi and Sethi [74] and Brown et. al. [10] outline different classifications of flexible manufacturing systems. Additionally, a publication by Fine and Freund [26] developed generic formulation of flexibility evaluation method and applied it to optimize flexible manufacturing investment for profit.

The prime motivation for embedding flexibility in product platform elements themselves is to exploit opportunities arising from future uncertainties, such as unmet or shifting customer needs, product demands, government regulations and technology innovations. Once alternatives for embedding flexibility in product platforms have been identified, their future value must be estimated and subjected to a decision-making process. A widely accepted method in industry and academia is **decision analysis** [15]. The recent rise of **real options theory** [71, 81] introduced new views on future risk assessment and exploitation.

1.5 Research Gap Analysis

1.5.1 Platform Design Related Literature

In this section, literature closely related to the proposed research are described in detail. Once these published design processes are presented, a research gap analysis is done to identify gaps in the field of product platform design, and how the newly proposed process can fill the gap. Several publications are available in the area of product platform design. In this section, five papers are closely reviewed in detail. They are papers published by Simpson et. al. [76], Martin and Ishii [49], Li and Azarm [46], and Gonzalez-Zugasti et. al. [30, 31].

Simpson et. al. [76] proposed the Product Platform Concept Exploration Method. In the paper, the authors state that it is a "formal method that facilitates the synthesis and exploration of a common product platform concept that can be scaled into an appropriate family of products." The method applies to scalable product platforms and families, and consists of five steps; 1) market segmentation grid creation, 2) factor and range classification, 3) meta-model creation an validation, 4) product platform specifications aggregation, and 5) product platform and family development. The method is demonstrated through a universal motor case study, where a family of ten motors are designed by varying the stack length. The compromise Decision Support Problem formulation [53] is used for the optimization problem formulation. This work presents a systematic way to determine the product platforms and families.

Martin and Ishii proposed another platform design method, called Design for Variety method, to develop modularized product platform [49]. The authors used Generational Variety Index (GVI) and Coupling Index (CI) [48] to design platform architectures that can be easily changed in the future. In the paper, GVI is defined as an "indicator of the amount of redesign required for a component to meet the future market requirements." The CI "indicates the strength of coupling between the components in a product. The stronger the coupling between components, the more likely a change in one will require a change in other." The method is demonstrated through a water cooler example, where GVI and CI for seven major components are calculated. Then, for components with high GVI and CI, flexible designs were generated to reduce GVI and CI, thus lowering future redesign (switch) cost. The results presented by authors indicate that the product platform designed using DFV method had significantly lower switch cost when it is required to change in the future from external drivers or internal drivers.

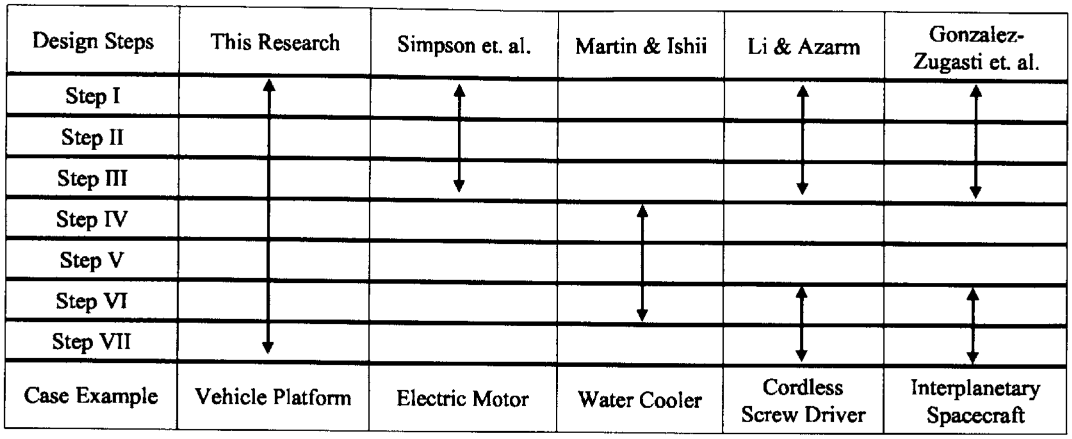
Li and Azarm [46] developed a design process for product line (family) design under uncertainty and competition. The design process is divided into the design alternative generation stage and the design evaluation stage. During the design alternative generation stage, each design alternative is optimized through multiobjective optimization. In the design evaluation stage, each design alternative is evaluated using Multi-Objective Genetic Algorithm [56], due to the combinatoric nature of the formulated optimization problem. In the end, the best product line (family) is chosen using the selection rule, which takes into account designer's utility of the product line balance. The proposed design process is demonstrated through a case study, where a cordless screw driver family is designed. Of three major components (motor, gear, battery), the motor was designated as the platform component *a priori*. Through optimization of the other components, authors identified best designs for several different uncertainty scenarios.

Finally, Gonzalez-Zugasti et. al. introduced a quantitative method to architect product platforms [30], and a framework to assess value of product platform based family using the real options approach [31]. In the first paper [30], the proposed method was implemented to an interplanetary spacecraft family, where three candidate platform designs based on telecommunications technology (X-band, Ka-band, optical) were optimized for mass, cost, and launch margin, given the pre-determined set of future NASA missions. In the second paper [31], the interplanetary spacecraft family was evaluated under uncertain future mission requirements and platform development investments, using the real options approach.

1.5.2 Research Gap

In the previous section, five publications closely related to the proposed research were discussed in detail. They do cover several areas of product platform design. Then the question is, how does the newly proposed process differ from previously published design processes? Figure 1-7 shows side-by-side comparison of the proposed design process with published design processes.

First, of all previously published methods, none of them deals with complete end-to-end design process, where the uncertainty is mapped to product attributes, design variables, components, flexible designs, then to relevant costs for economic evaluation. Second, in most processes, the notion of "flexible elements" and its evaluation is not apparent. In the methods proposed by Li and Azarm, and by Gonzalez-Zugasti et. al., the focus of the process was to identify common and unique elements for maximum performance and/or profit, but no mention of flexible elements. In the work published by Martin and Ishii, flexible design alternatives were presented in the case study, but the economic consequence and subsequent uncertainty analysis was not presented. Work by Simpson et. al. deals with scalable ("flexible") universal



Design Steps	This Research	Simpson et. al.	Martin & Ishii	Li & Azarm	Gonzalez-Zugasti et. al.
Step I	↑	↑		↑	↑
Step II	│	│		│	│
Step III	│	↓		↓	↓
Step IV	│		↑		
Step V	│		│		
Step VI	│		↓	↑	↑
Step VII	↓			↓	↓
Case Example	Vehicle Platform	Electric Motor	Water Cooler	Cordless Screw Driver	Interplanetary Spacecraft

Figure 1-7: Comparison of Product Platform Design Methodologies

motor, but only optimizes them for current needs. Finally, most of the previous work deals with very simple examples, thus not capturing the intricacy of true engineering systems design. From the discussion above, it is clear that the newly proposed process will fill the research gap that exists in product platform design process. A graphical representation of research gaps is shown in Figure 1-8.

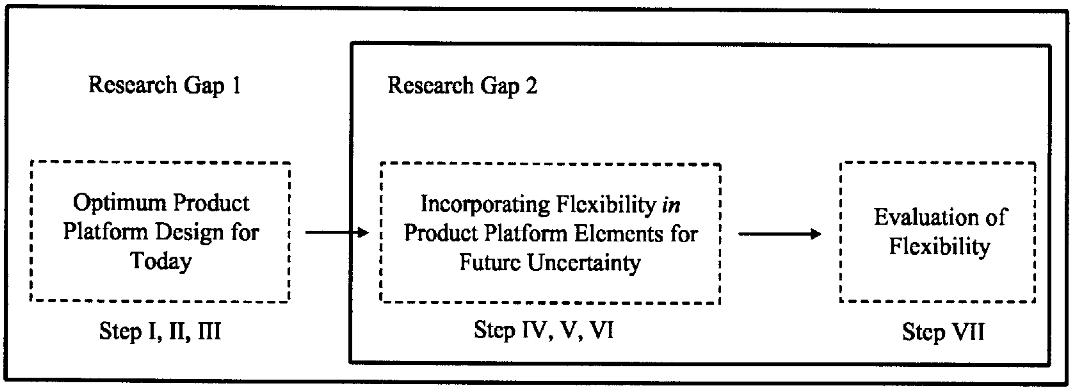


Figure 1-8: Research Gap

The first research gap represents a comprehensive end-to-end design process, and the second research gap represents evaluation of flexible elements under future uncertainty. This thesis proposes a design process that identifies critical elements in the product platform for incorporating flexibility. Once the flexibility is incorporated into identified product platform elements, uncertainty analysis must be performed to estimate how valuable the flexible design is, compare to the inflexible design. The broader objective of this thesis is to fill a gap in the research area of uncertainty management for large complex engineering systems by proposing a framework to incorporate flexibility in complex systems to deal with uncertainties.

1.6 Guide to Thesis

A brief overview of subsequent chapters is presented in this section to guide readers to the structure of this thesis. Short description of each chapter is presented.

In Chapter 2, a general overview of the product platform is presented. This chapter presents definition, classification, deployment strategy, pros and cons, and practical applications of product platforms.

Chapter 3 presents the theoretical framework of the flexible platform design process. The process first defines the boundary of product family and related uncertainties. Then the family is positioned in market segments for maximum revenue. A critical set of platform elements is identified, and is designed with incorporated flexibility. Uncertainty analysis reveals the benefit of the flexibility in the product platform, thus completing the process.

Chapter 4 presents a case study that demonstrates the incorporation of flexibility in a single element. In the case study, an automotive floor pan is flexibly designed to accommodate vehicles of different lengths, while being cost-efficient under future uncertainties in demand and component specification change.

Chapter 5 presents a case study to illustrate the proposed design process in Chapter 3. The case study investigates an automotive vehicle platform, where the Body in White (BIW) assembly structure is designed flexibly to mitigate risks and to profit from opportunities, which arise from future uncertainties. Finally, a thesis contribution and conclusion are summarized in Chapter 6, with discussion of promising future research topics and directions.

Chapter 2

Product Platform Overview

In this chapter, the product platform concept is investigated from a broad perspective. A general overview of the product platform concept is presented, including its definition, classification, deployment strategies, advantages and disadvantages, and its role within the corporate strategy. Practical examples and actual business cases of platform implementations are also presented.

2.1 Overview of Product Platform

2.1.1 Definition

Various definitions of the term *product platform* have been offered by academia and industry:

- "A platform is both an object and a process [9]."
- "The collection of the common elements, especially the underlying core technology, implemented across a range of products [50]."
- "The set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched [51]."
- "The collection of assets (i.e., components, processes, knowledge, people and relationships) that are shared by a set of products [65]."

Summarizing from definitions above, product platforms can be defined as *a common infrastructure that serves as a backbone for multiple product variants.* This can include common components, processes, and interfaces that allow end products to achieve unique variety in their product attributes by adding unique elements to product platforms. Unique elements are only found in individual variants, but not in the common platform. Thus, the classical distinction is between unique parts, which are only found in one variant at-a-time, and common parts, which, taken as a whole, form the product platform.

In this thesis, the goal is to extend the definition of product platform to include flexible elements as well. Product platforms can be redefined as follows

An infrastructure (system) that consists of common and flexible elements (components, processes and interfaces), which enables production of distinctive product variants and product families by adding unique elements, without changing common core elements.

Figure 2-1 graphically shows the relationship between the product platform and product family.

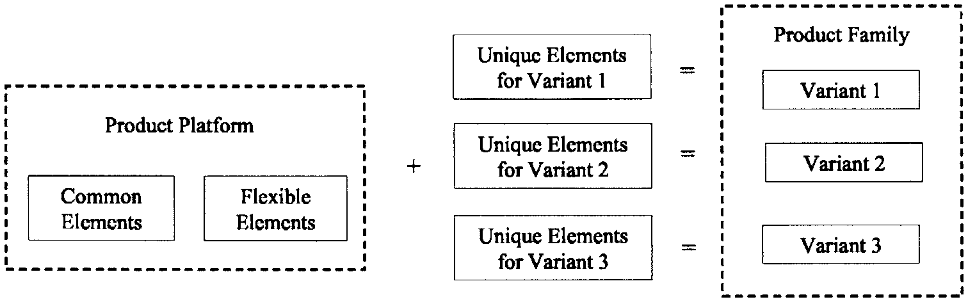


Figure 2-1: Relationship Between Product Platform and Product Family

In the figure, the product platform is a collection of common and flexible elements, when combined with unique elements, becomes a part of product variants, which in turn, are members of the product family. *Flexible elements* in this thesis are defined as *elements that can accommodate each product variant's different requirement through modification at lower additional investments, relative to other unique elements that can achieve the same purpose.* Throughout the thesis, the two terms (product platform and flexible elements) will be used with the definitions declared in this section. Explanation of basic product platform elements (components, processes, interfaces and architecture) are presented below.

- **Components**: This is what most people imagine when the term product platform is mentioned. Many product families share common components across their product variants. Usually, these components are key to achieving the functional requirements of product variants, and contain core technologies, common to all product variants. In some cases, core components vary in size for a variety of purposes (e.g. maintaining common manufacturing processes or differentiated product performance specifications). A perfect example is Black & Decker's scalable motor for its power tool family, where the motor, a platform component, varies in stack length to achieve different power output levels, so it can be used to leverage products in different market segments.

- **Processes**: Several different processes can be part of a product platform. Key processes are the product design process and the manufacturing process. Standardizing the design process is an important aspect of the product platform. Robertson and Ulrich go into detail on this subject, outlining how the high level planning process for product platforms should be managed [65]. By standardizing the design process, the knowledge necessary to design products can be retained more easily. Perhaps more important in some industries than others, enforcing common manufacturing processes can reduce both fixed and variable costs. In 1999, the Mitsubishi Charisma and the Volvo S/V40 were built in the NedCar plant with 80% of the production process and 30% of the components in common [9]. There is much ongoing research to make manufacturing processes share common elements through flexible manufacturing.

- **Interfaces**: To architect a successful product platform, a set of common interfaces must be established to ensure a high degree of modularity in the system, which can lead to wide product variety. One good example of an interface-based product family is the vehicle panel meter family designed by Nippondenso [84]. Panel meters were designed with common interfaces for ease of assembly. This allowed the company to assemble any panel meter variant with virtually no switchover time, enabling them to respond to small order quantities very quickly. The personal computer is another good example of common interface utilization. Finally, when a product family is modular, the importance of common interfaces in the platform and between the platform and the unique components increases sharply.

- **Architecture**: Most importantly, the underlying product architecture for a product family should be the same. For automotive vehicles, one product family can be Body-Frame-Integral architecture based, while another product family can be Body-On-Frame architecture based. For the Sony Walkman product family, the tape player architecture stayed the same while "cosmetic" items around them were changed in order to meet different customer needs. Also, as discussed by Robertson and Ulrich [65], product architecture plays an important role in how product platforms can be deployed to produce multiple product variants. A modular architecture is the preferred choice for platform based products. By combining different modules, the company can achieve product variety with a small number of modular components. For some products, however, modularity - while desirable - is difficult or impossible to achieve. There are indications that products which operate at high power levels, or which are subject to tight light-weighting, aerodynamic and packaging constraints are more likely to feature an integral architecture and platform design. Mass, power and packaging efficiencies are much more important for portable electronic devices and automobiles than they are for static industrial machinery [37].

The final form of the product platform is a collection of common and flexible components, processes, interfaces and architectures that allows the company to offer product families with distinct variants at low cost.

2.1.2 Classification and Deployment Strategies

In general, platforms can be categorized into modular platforms and scalable platforms [29].

- **Modular (Functional) Platforms**: Modular platforms allow creation of functionally different product variants. A good example of such a platform is the Blended Wing Body aircraft from Boeing. Using a common platform, the firm is potentially able to create different product family portfolios, which consist of tanker, commercial airplane, global transport, and bomber portfolios.

- **Scalable Platforms**: Scalable platforms allow the creation of functionally identical products with different capacities. Camera film is a good example. Using the same film casing and the film itself as a platform, products with different numbers of exposures (e.g. 12, 24, 36 exposures) and film qualities (e.g. ASA 100, 200, 400) can be manufactured and offered to suit different consumer needs.

Once the decision to implement the platform is made, the company need to choose the right deployment strategy. Figure 2-2 illustrates various platform strategies which are implemented throughout various industries. In the figure, each cell represents a specific market segment for a particular product. With a single platform, the firm can cover different market segments using different approaches. Some of the most widely practiced platform strategies are *No Leveraging, Vertical Leveraging, Horizontal Leveraging*, and *Beachhead* Strategies [51].

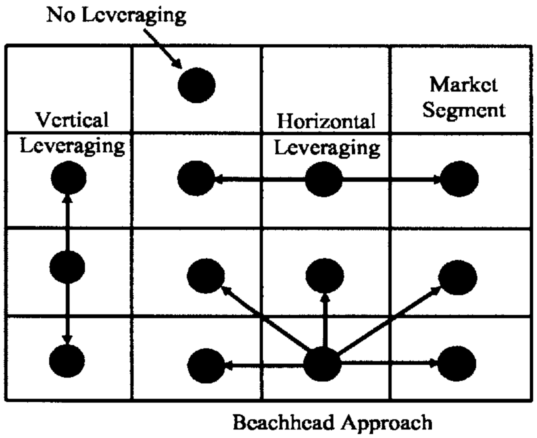


Figure 2-2: Product Platform Deployment Strategies

- **No Leveraging Strategy**: The platform is designed exclusively for a single market segment. There is no other market segments that share this particular platform. This strategy is usually implemented for a high performance product with relatively high development cost limits and limited performance tolerance range.

- **Vertical Leveraging Strategy**: The platform is shared among low-end, mid-range and high-end market segments within the same brand. It is "vertical" in a sense that a single platform is implemented from a low to a high end of the market segment.

- **Horizontal Leveraging Strategy**: The platform is shared across different brands but within the same class of market segment. A good example would be the Volkswagen **A** platform (see Figure 2-6), which covers medium vehicle market segments for Volkswagen, Skoda, Seat and Audi.

- **Beachhead Approach**: This is the most ambitious platform strategy. A single platform is implemented across different market segments horizontally and vertically.

2.1.3 Advantages and Disadvantages

A benefit of the product platform strategy was pointed out by Robertson and Ulrich, who stated that "by sharing components and production processes across a platform of products, companies can develop differentiated products efficiently, increase the flexibility and responsiveness of their manufacturing processes, and take market shares away from competitors that develop only one product at a time [65]." There are many benefits that can be realized by sharing various elements in the product platform.

The most obvious benefit realized is cost savings from economies of scale when common components are used across the product family. These cost savings start with the need to design, test and validate fewer parts and assemblies, which propagates to manufacturing, supply chain and product servicing in the field. In another instance, by acquiring the flexibility to produce an entire product family using a flexible manufacturing process, the company has the ability to produce the "right" product variants at the "right" time, in the "right" quantities. Another advantage is that in some industries, the cost and time saving gained from commonality can be invested in product features that influence consumer purchasing patterns in products whose core functionality has essentially been standardized (e.g. interior design and styling for automobiles).

Interface-based product platforms do not emphasize re-use of parts per se, but specify clear part and module interfaces and common "hard" points. Identified interfaces and points provide more freedom in component and module design, as long as interface standards are strictly followed. Many modular products have this benefit, allowing manufacturers more freedom for product variety. Modern computers are a good example. With standardized interfaces for CPUs, sound cards, video cards and external peripherals, there is great freedom to customize the product to any user's needs.

Design process based product platforms offer yet another unique benefit. By standardizing design processes, firms can retain and store knowledge more efficiently. Additionally, once designers are trained to follow the standard process, they can come up with systematic design solutions faster, potentially reducing development costs and time to market.

Even though there are many advantages of a product platform strategy, system architects must also carefully examine disadvantages of this strategy to create the best platform architecture for their particular needs. One of the foremost drawbacks is the loss of product variant "performance" or distinctiveness due to component sharing. Since common components cannot be customized to optimize each product variant taken one-at-a-time, each variant must sacrifice some of its "performance" for the common good of the product family or firm as a whole. This can result in a potential loss of market share. The second drawback is the phenomenon of cannibalization [16], in which the market share of high end products is usurped by low end products of the same product family. This occurs when consumers are aware of extensive component sharing between high end and low end products in the same family. In Europe during the late 1990's, Volkswagen lost some market share to Skoda, its cheaper Czech brand vehicle, when Volkswagen produced both Volkswagen and Skoda vehicles from the same product platform. German car buyers, usually brand conscious and fiercely loyal to German labels, recognized that buying a Skoda that shared 60% common parts and equivalent quality standards with a Volkswagen could save them more money.

Serious performance flaws and safety problems may be caused unintentionally by sharing a common platform. The Audi TT had to be retrofitted with a rear spoiler from its original version, which was built off the Volkswagen **A** platform. The rear spoiler improved handling and prevented the tail from spinning out at high speeds. The perils of building both front- and rear-wheel-driven vehicles from the same platform are now much better understood than they were in 1999.

Finally, the product platform itself might act as a resistor to new technologies, especially if the current product platform is a big money maker. It is very expensive to develop a new platform and to implement it throughout all manufacturing plants. The added opportunity cost of plant downtime makes developing new platforms financially unattractive. So, ironically, platforms promote innovation in the short-term by facilitating the design and production of a multitude of product variants, but they may well dampen long-term innovation by locking down large investments in standardized design processes, manufacturing tools and supply chain contracts.

2.1.4 Macro-Perspective

The ultimate goal of a product platform strategy is to provide the firm with a core infrastructure (consists of common and flexible elements) that allows production of customized product family variants with a minimum increase in overall product family complexity and development, production, and maintenance cost, while remaining flexible to future changes in technology, customer needs and regulations. By sharing common elements among different product variants, the firm can save money through economies of scale and reduction of development resources. Additionally, sharing common elements saves development time since core technologies or components that are part of the platform do not need to be developed again. As a complex engineering system, product platforms occupy a very important place within the corporate strategy. Figure 2-3 shows a broad view of a generic corporate strategy and the position of the product platform within that strategy.

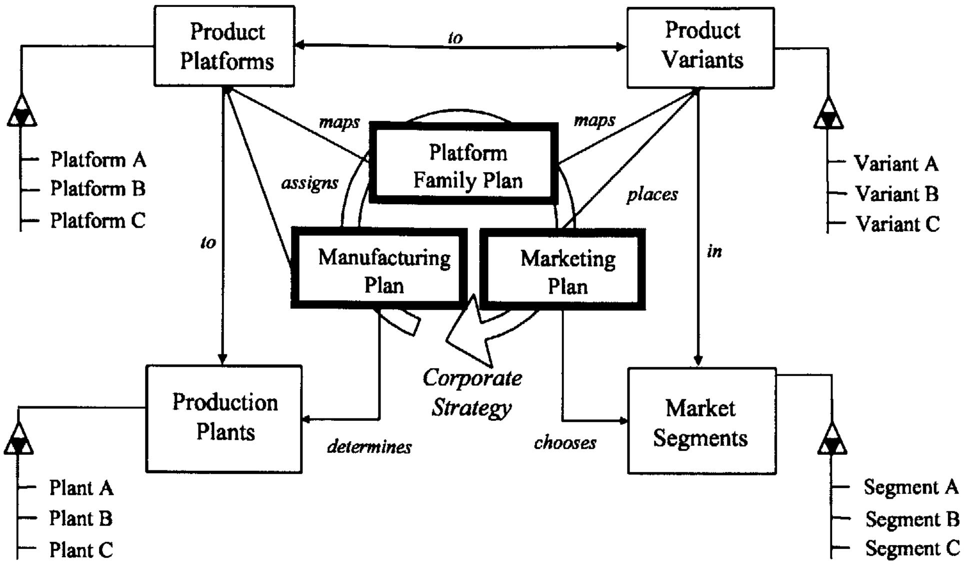


Figure 2-3: Product Platform in Broad Context

The corporate strategy is decomposed into three major plans: marketing plan, platform family plan, and manufacturing plan. All three plans must be executed in harmony to achieve the overall corporate goal: profitability. The marketing plan segments the market(s) and specifies which product variants compete in which segments against which competitors. The platform plan assigns platforms to the variants in one or more product families. The manufacturing plan assigns individual platforms to individual production plants. The three plans are highly interrelated. An example of this interrelationship is through the manufacturing capacity. It is desirable to achieve a high utilization rate for the production plants (target: 85-100% of plant capacity), which requires flowing and balancing actual and expected sales volumes, as shown in the flow of demand from the right side of Figure 2-3 to the left side. This is a difficult undertaking, fraught with uncertainty and significant financial implications.

2.2 Applications of Product Platforms

2.2.1 Examples

There are many different examples of product platform applications, not limited to the manufacturing industry, which are described below.

- **Lego Toys**: Lego building blocks are perhaps one of the best examples for standard interface-based product platforms. Using standard interfaces for each building block, while varying the length, color and shape of each piece, a variety of imaginative shapes can be produced.

- **Cooked Food**: Common manufacturing process-based product platforms are utilized in the food industry (e.g. McDonald's, Subway). For example, the process for making a sandwich is the same - get the bread, spread mayonnaise and mustard, insert sandwich meat, put additional condiments, and assemble them together. The process remains the same, but the assembled components vary (e.g. wheat/rye bread, no mayo or mustard, lettuce, tomato, etc).

- **Credit Card**: A credit card platform is a modular platform, where the basic architecture stays the same, with modular components added or subtracted for product differentiation. Credit cards have a common architecture (or policy) of lending money and getting it back with interest. Product differentiating modular components are credit limits, interest rates, car rental coverage, travel insurance, reward points and buyer protection.

- **USB Key**: A USB key platform has a common architecture, components and processes. Differentiation occurs in the substitution of key memory for different storage capacity and outer casings for aesthetic appeal.

- **MP3 Player**: The product platform for MP3 players is the same as the USB key platform, but with added module options for radio reception and music replay capability. Different platforms can be designed around the data storage architecture (XD, memory stick, flash memory, etc). Differentiation occurs through external appearance, modular options (e.g. radio) and data storage capacity.

- **Swiss Army Knife**: The product platform for a Swiss Army Knife consists of common components, assembly processes, and assembly interfaces. Standardized components (e.g. knife, screw drivers, and other accessories) are assembled using a common interface. By adding and subtracting different components (tweezers, pincers, corkscrew, magnifying glass, screwdrivers, can openers), product differentiation can be achieved.

- **Automobile**: An automobile platform is a complex system comprised of common components (e.g. engine, powertrain, chassis), common processes (e.g. design and manufacturing processes), and common interfaces (e.g. common engine mounting points for V6 and V8 engines) and many more. The details of automobile platforms differ significantly between manufacturers.

- **Power Tools**: The power tool product platform for Black & Decker consists of the motor, motor housing and motor-side interface to the tool attachments. Product differentiation is achieved through variation of motor length (for different power requirements) and tool ends.

2.2.2 Business Case: Black & Decker Power Tools

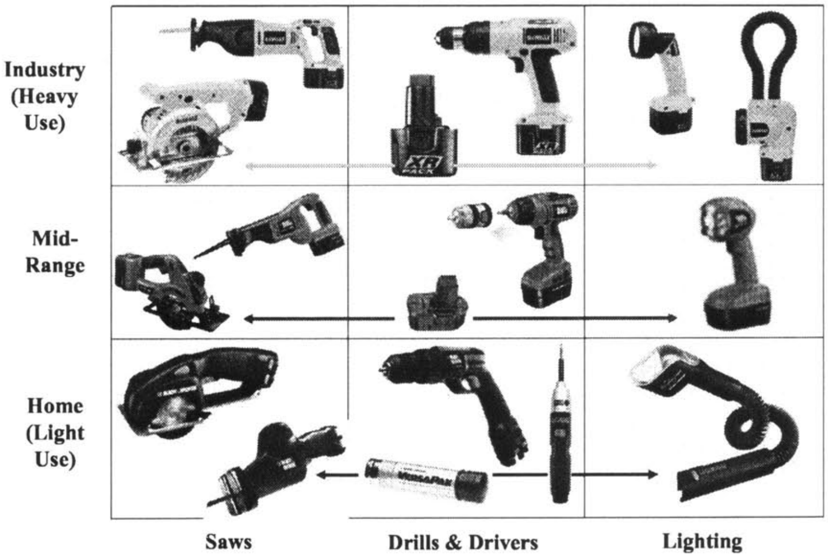


Figure 2-4: Black & Decker Power Tool Family

Black & Decker, a power tool company, was faced with the dilemma of product variety increases and proliferating cost during the 1970's [51]. The proliferation of product variants threatened to become unmanageable. The company decided to create a common product platform, which consisted of an electric motor module and standard interfaces to the motor module. Product differentiation was achieved by varying the motor lengths for different market segments (requiring different power outputs) and business application ends (handle and power tool). By standardizing their core components and processes, they enjoyed immense success, capturing major market share through rapid product differentiation. Figure 2-4 shows various product families offered by Black & Decker, with corresponding market segments.

2.2.3 Business Case: Sony Walkman

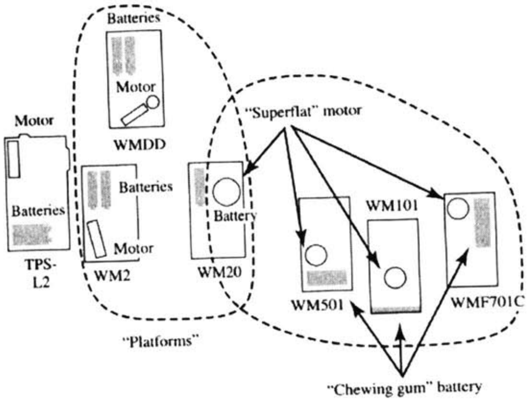
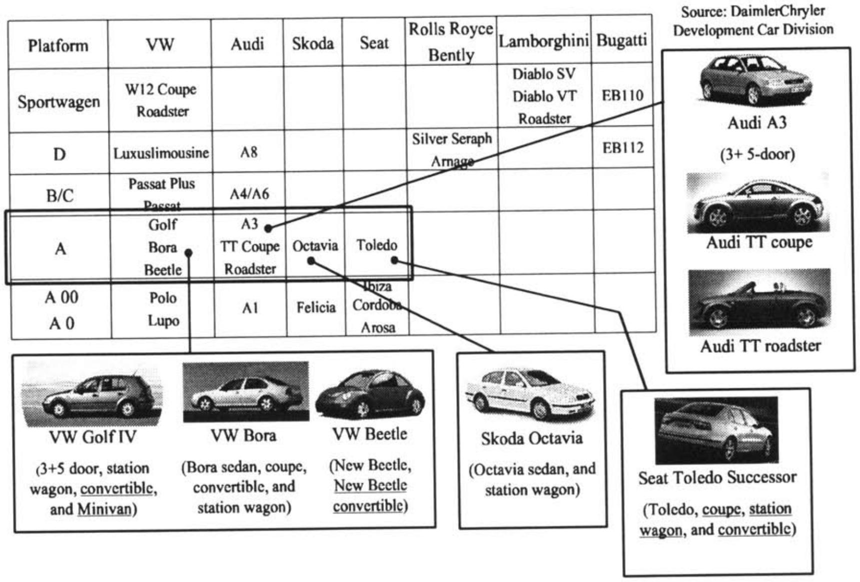


Figure 2-5: Sony Walkman Product Platform

Documented by Sanderson and Uzumeri, Sony enjoyed huge success in its portable Walkman product family [68]. Sony's product platform was its tape player mechanism, which was the core of their product architecture. By differentiating their product family variants through different outer casings (Business Walkman, Sports Walkman, etc) and modular components (e.g. recording mechanism, radio module, etc), they were able to capture the portable music player market quickly and hold a leader position for a long time. Figure 2-5 shows key components of the Sony Walkman platform.

For Sony, the decision to make the tape player mechanism a part of its product platform was a wise business decision, since that particular technology changes very slowly, mainly because it is constrained by several other established standards and government regulations.

2.2.4 Business Case: Volkswagen Vehicle Family



Source: DaimlerChryler Development Car Division

Platform	VW	Audi	Skoda	Seat	Rolls Royce Bently	Lamborghini	Bugatti
Sportwagen	W12 Coupe Roadster					Diablo SV Diablo VT Roadster	EB110
D	Luxuslimousine	A8			Silver Seraph Arnage		EB112
B/C	Passat Plus Passat	A4/A6					
A	Golf Bora Beetle	A3 TT Coupe Roadster	Octavia	Toledo			
A 00 A 0	Polo Lupo	A1	Felicia	Ibiza Cordoba Arosa			

Figure 2-6: Volkswagen **A** Platform and Product Family

In the late 1990's, Volkswagen was recognized as the leading product platform implementer in the automotive industry. Volkswagen defines a product platform as "a unit that has no impact on the vehicle's outer skin and that is a chassis including the inner wheelhouses [9]." Volkswagen's product platform consists of common components, such as front axles, rear axles, front end, rear end, wheels, steering system, brake system, center floor, fuel tanks, exhaust systems, and seat frames. In 1998, Volkswagen owned four out of top ten vehicle platforms (by production volume). Figure 2-6 shows product variants derived from the Volkswagen **A** Platform.

At one time, Volkswagen shared over 65% of its components within its product families, resulting in huge cost savings from economies of scale. However, its common component platform strategy also had some drawbacks. Volkswagen suffered from cannibalization by its platform sharing partner, Skoda, as mentioned earlier. There were issues concerning unforeseen performance drawbacks on the Audi TT. Finally, brand blending from sharing too many components became an issue. In 2002, to address these problems, Ferdinand Piech, then chairman of Volkswagen, switched the company's product platform strategy from a "Four Platform Strategy" to an "Eleven Module Strategy," putting more emphasis on common interfaces and giving more freedom to module designers to achieve more distinctive product variety. Platform managers who had previously overseen platform design and commonality decisions became "module managers."

Indeed, the distinction between a platform strategy and a module-based re-use strategy has become somewhat blurred in recent years. Nevertheless, a platform can also be thought of as the major module (either physical or via common/flexible interface definitions) that is responsible for achieving the product's core functionality.

2.3 Chapter Summary

This chapter reviewed the product platform concept from various perspectives. The definition, classification, deployment strategies, advantages and disadvantages, and the role of product platform within the corporate strategy have been discussed. Several examples of product platform applications were presented, followed by real business cases for product platform implementation.

Product platforms are complex engineering systems that offer efficient solution to today's manufacturers, allowing them to create great variety in their product families, while re-using their developed resources. This strategy has the advantages of potential cost savings and minimizing system complexity, but it also has potential disadvantages ranging from performance tradeoffs, cannibalization and damping of long-term innovation. It is the job of system architects to design platforms to fulfill the needs of various stakeholders. In Chapter 3, a detailed, step-by-step formulation of a newly proposed design processes for flexible product platforms is presented.

Chapter 3

Flexible Product Platform Design Process

3.1 Introduction

This chapter presents a formal mathematical formulation of the flexible product platform design process. The formulation starts with the following hypothesis:

If a critical subset of elements within the product platform is made flexible, it can make the whole platform flexible to a specified set of uncertainties

Given a set of product variants in a product family, the system architect must design a product platform system with flexibility for the company to benefit from (and to protect from) future uncertainties. To do so, the architect must identify a set of critical elements that can make the system flexible to these future uncertainties.

In this chapter, a formulation of a flexible platform design process is presented to support the stated hypothesis. There is much literature that addresses the platform design process. Detailed summary of relevant literature are presented in Chapter 1.

Subsequent sections outline a mathematical formulation for a newly proposed design process. In this process, a new index is introduced. The Change Propagation Index (CPI) measures the degree of change propagation for a single element in the system. The formulation of CPI is presented in this chapter, and will be demonstrated through case studies in Chapter 4 and 5.

3.2 Design Process Framework Overview

The process is designed to be utilized during the early stages of product platform development to establish a system-level platform definition. This process precedes the actual product development process where each individual product variant is designed in detail. Figure 3-1 outlines framework for the flexible platform design process.

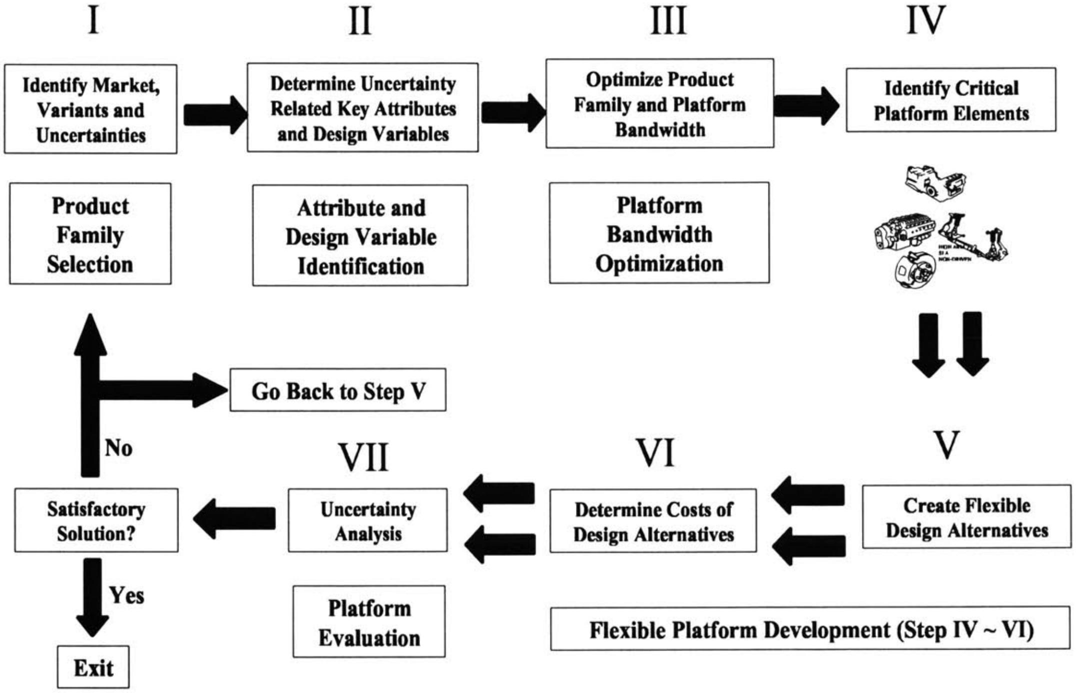


Figure 3-1: Flexible Product Platform Design Process

The process begins by identifying target market segments, product variants, and critical uncertainties that the new product platform must be able to accommodate (Step I). Once the initial product definitions are established, uncertainties related functional product attributes and related system-level design variables are identified (Step II). The identified set of design variables for each product in the product family is optimized to yield maximum product family revenues (Step III).

Through the optimization, optimized values of system-level design variables for each product variant is identified. Aggregating design variable values for all variants, the design variable bandwidths for the product family are determined. Given the requirement to achieve bandwidth for uncertainty related design variables, a critical set of elements, affected by the design variable change, is determined (Step IV). Using identified elements and given bandwidth requirements, flexible platform design alternatives are generated (Step V). Initial investment, variable costs, and switch costs for design alternatives are calculated (Step VI). The final platform evaluation step consists of uncertainty analysis (Step VII), wherein the benefit of each design alternative is estimated under various scenarios with varying degree of uncertainty. Finally, the best flexible platform design alternative is selected. Subsequent sections present mathematical formulations and detailed explanations for each step of the design framework.

3.3 Step I: Identify Market, Variants, and Uncertainties

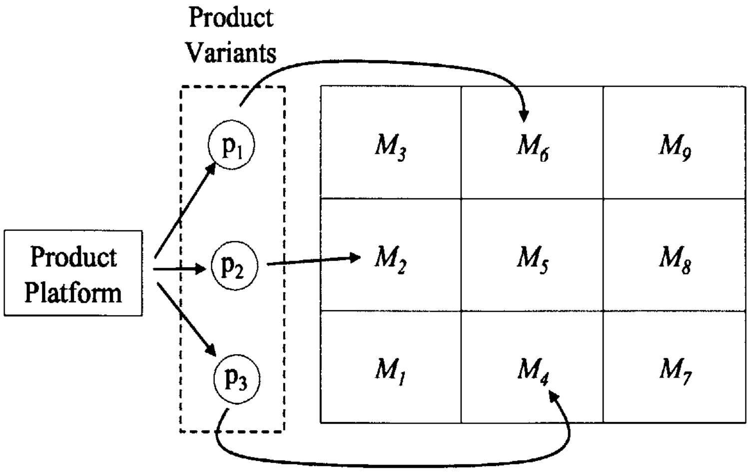


Figure 3-2: Market Segments and Product Variants

The first step of the process is to identify target market segments from a set of segments $\mathcal{M}$, desired product variants set $\mathcal{P}$, and a set of uncertainties $\mathcal{U}$ that are related to $\mathcal{M}$ and/or $\mathcal{P}$. It is assumed that all product variants in a product family set $\mathcal{P}$ will be placed on a common product platform. However, this may not be true in some cases where the differences between each variant is too great. In those situations, multiple platforms may be required. It is another research topic not covered in this thesis, but the work in this topic is done by Seepersad et. al. [72, 73]. Graphical representation of $\mathcal{M}$ and $\mathcal{P}$ is shown in Figure 3-2. Each set is expressed mathematically as follows:

$$\begin{aligned} \mathcal{M} &= [M_1, M_2, ..., M_{n_m}] \\ \mathcal{P} &= \left[p_1, p_2, ..., p_{n_p}\right] \\ \mathcal{U} &= [u_1, u_2, ..., u_{n_u}] . \end{aligned} \tag{3.1}$$

First, a product specific market segments need to be defined. A set of market segments $\mathcal{M}$ for a specific product is typically defined through clustering analysis [5, 39]. Defining market segments has several advantages. First, it allows companies to identify segments with significant opportunities in terms of sales volume and profitability. A market segment with a large number of customers can create an opportunity for high revenue products, while a market segment with a small number, but high-income customers can create an opportunity for high-quality luxury products with a high profit margin. Second, through examination of market segments and current product portfolios, companies can identify gaps in their product lines, thus creating a justification for developing additional product variants. Also, firms can strategically position their product families in key market segments. However, these advantages depend on how clearly and how accurately the initial market segments are defined.

There are several clustering methods available. The most popular is the hierarchical method. Two different approaches in the hierarchical method are the divisive and the agglomerate approaches. In the divisive approach, the entire sample population is initially treated as one big cluster, which is then divided into two clusters. Two divided clusters are further divided into smaller clusters, until each cluster only has one sample. The agglomerate approach takes exactly the opposite direction. It starts with several clusters of one sample each, and combines the closest two clusters into one cluster. The algorithm continues to merge clusters until the number of cluster becomes one. In many cases, the agglomerate approach is used.

Once the set of market segments $\mathcal{M}$ is defined, a set of product variants $\mathcal{P}$ can be positioned in the individual market segment. According to Ulrich and Eppinger a *product* is "something sold by an enterprise to its customers [83]." A product provides value to customers by offering customer-preferred attributes in material form or services. A product variant can be expressed as a vector of customer preferred product attributes ($\mathbf{J}_A$) and price (P).

$$p_i = \begin{bmatrix} \mathbf{J}_{A,i} \\ \mathrm{P}_i \end{bmatrix} \tag{3.2}$$

where p_i represents an individual product variant, $\mathbf{J}_{A,i}$ is the vector of customer preferred attributes, and P_i is the price of the product i. A product variant has specific values for each attribute in the attribute vector $\mathbf{J}_{A,i}$ and the specific price P_i. Therefore, the product variant set $\mathcal{P}$ can be expressed as a collection of specific product attributes' values and prices, as shown in Equation (3.3):

$$\mathcal{P} = \begin{bmatrix} \mathbf{J}_{A,1} & \mathbf{J}_{A,2} & \ldots & \mathbf{J}_{A,n_p} \\ \mathrm{P}_1 & \mathrm{P}_2 & \ldots & \mathrm{P}_{n_p} \end{bmatrix}. \tag{3.3}$$

The last item to be defined in this step is a set of critical uncertainties $\mathcal{U}$. A product platform is a large complex system with a very long life cycle. The platform must be designed not only to accommodate several product variants, but to be flexible to future uncertainties that will affect its product portfolio. Identifying critical uncertainties is a very important step, since where and how flexibility is incorporated into the product platform almost solely depends on the nature of uncertainties. Typical future uncertainties for systems like product platforms include variant demand, variant specification (e.g. attribute values, dimensions, styling), and addition/subtraction of new/existing variants. Other uncertainties (which are outside the scope of this thesis) are emergence of new technologies and shifts in regulations and standards.

3.4 Step II: Determine the Uncertainty Related Key Attributes and Design Variables

In the previous step, the market segments set $\mathcal{M}$, product variants set $\mathcal{P}$, and uncertainties set $\mathcal{U}$ are identified. One of the key objectives for companies is to strategically position their product variants in key market segments to generate maximum revenue. Each market segment M_j can be expressed as a range of customer-preferred attribute values and price, in which a specific product variant's $\mathbf{J}_{A,i}$ and the price P_i must fall within:

$$M_j = \left\{ \begin{array}{l} \mathbf{J}_{A,j} : (\mathbf{J}_{A,j})_{\min} \leqslant \mathbf{J}_{A,i} \leqslant (\mathbf{J}_{A,j})_{\max} \\ \mathrm{P}_j : (\mathrm{P}_j)_{\min} \leqslant \mathrm{P}_i \leqslant (\mathrm{P}_j)_{\max} \end{array} \right\} \tag{3.4}$$

Depending on the number of competitors, and the companies' product attributes values and customer's preferences for a specific market segment M_j, firms need to set their i^{th} product's $\mathbf{J}_{A,i}$ and P_i values within the established range of M_j to gain market share and a competitive position.

$\mathbf{J}_A$ can be expressed as function of a system-level design variables vector $\mathbf{X}_A$. Then Equation (3.3) can be expanded as:

$$\mathcal{P} = \begin{bmatrix} \mathbf{J}_{A,1}(\mathbf{X}_{A,1}) & \mathbf{J}_{A,2}(\mathbf{X}_{A,2}) & \dots & \mathbf{J}_{A,n_p}(\mathbf{X}_{A,n_p}) \\ \mathrm{P}_1 & \mathrm{P}_2 & \dots & \mathrm{P}_{n_p} \end{bmatrix} \tag{3.5}$$

Even though there can be many different product attributes within $\mathbf{J}_A$, the ones that are of special interest in this thesis are product attributes that are related to the set of uncertainties defined in Equation (3.1). A product attribute vector, related to a set of uncertainties $\mathcal{U}$, can be expressed as $\mathbf{J}_{\mathcal{U}}$, where $\mathbf{J}_{\mathcal{U}} \subset \mathbf{J}_A$. These attributes are significantly affected by uncertainties identified in Step I and need to be mapped to system-level design variables. The strategy here is to optimize the product family's system-level design variables and product attribute values for maximum revenue (given current preferences), design the product platform to meet the optimized requirement in design variables and attributes values, and then incorporate flexibility in the product platform to respond to future uncertainties specified, while being profitable.

The next step is to establish the relationship between the uncertainty specific product attributes $\mathbf{J}_{\mathcal{U}}$ and the $\mathbf{J}_{\mathcal{U}}$ related system-level design vector $\mathbf{X}_{\mathcal{U}}$, where $\mathbf{X}_{\mathcal{U}} \subset \mathbf{X}_A$. In mathematical terms it is expressed as

$$\mathbf{J}_{\mathcal{U}} = f\left(\mathbf{X}_{\mathcal{U}}\right). \tag{3.6}$$

Given the target market segment M_j assigned for each p_i, upper and lower bounds of the uncertainty specific system-level design variables vector $\mathbf{X}_{\mathcal{U},i}$ for a product variant p_i must be within the limits of M_j.

3.5 Step III: Optimize Product Family and Platform Bandwidth

In Step II, the product attributes vector $\mathbf{J}_A$ and its subset, $\mathbf{J}_{\mathcal{U}}$ for uncertainties set $\mathcal{U}$ is defined. Additionally, a system-level design variables vector $\mathbf{X}_{\mathcal{U}}$, related to $\mathbf{J}_{\mathcal{U}}$ is identified as well. Also, for each product variant p_i, a variant and uncertainty specific design variables vector $\mathbf{X}_{\mathcal{U},i}$ is defined. Upper and lower bounds of $\mathbf{X}_{\mathcal{U}}$ are implicitly stated in Equation (3.4), where upper and lower limit of attributes values are bounded by the market segment's limit values.

For each p_i, defined as function of $\mathbf{X}_{\mathcal{U},i}$ and its upper and lower bounds established, all p_i in the product variants set $\mathcal{P}$ need to be placed within their respective market segment space to generate maximum revenue as a portfolio. This can be stated mathematically:

$$\begin{aligned} &\text{maximize } \sum_{\mathrm{i}\,=\,1}^{n_p} R_{p_i}\left(\mathbf{J}_{\mathcal{U},i}\left(\mathbf{X}_{\mathcal{U},i}\right), \mathrm{P}_i\right) \\ &\text{subject to } \mathrm{h}\left(\mathbf{J}_{\mathcal{U},i}\left(\mathbf{X}_{\mathcal{U},i}\right)\right), \mathrm{g}\left(\mathbf{J}_{\mathcal{U},i}\left(\mathbf{X}_{\mathcal{U},i}\right)\right) \end{aligned} \tag{3.7}$$

where R_{p_i} is the total revenue generated by the i^{th} product variant, h and g are inequality and equality constraints that must be satisfied. Individual product variant revenue R_{p_i} is further explained in Equation (3.8):

$$R_{p_i} = ms_i\left(\mathbf{J}_{A,i}\left(\mathbf{X}_{A,i}\right), \mathrm{P}_i\right)\mathrm{P}_i D_T \tag{3.8}$$

where ms_i is the market share for the i^{th} product variant in the market segment set $\mathcal{M}$ and D_T is the total current demand existing for the market segment set $\mathcal{M}$. Market share is a function of product attributes values $\mathbf{J}_A$ and variant price P. However, in this thesis, only attributes related to $\mathbf{J}_{\mathcal{U}}$ and price P, will be perturbed, while other attributes will be fixed to a specific value for each product variant i (thus Equation (3.8)). Estimating a reliable market share for given values of $\mathbf{J}_{A,i}$ and P_i is, in itself, a very large research field. It is usually accomplished through conjoint analysis [1], where companies estimate customers' preference sensitivities for particular products by changing product's attribute values. In the case study presented in Chapter 5, a proprietary market simulator is used to obtain the market share for each product variant.

Once the maximum revenue generating solution for Equation (3.7) is obtained through optimization, $\mathbf{X}_{\mathcal{U},i}$ and $\mathbf{J}_{\mathcal{U},i}$ values for each product variant are determined, thus defining the bandwidth of the product platform in both the customer-preferred attribute space and the system-level design variable space. Figure 3-3 shows bandwidths of a hypothetical product platform in design variable and attributes space. There can be more number of design variables than the number of product attributes and vice versa.

For each design variable in $\mathbf{X}_{\mathcal{U}}$, where $\mathbf{X}_{\mathcal{U}} = [x_1, x_2, ..., x_{n_x}]$, a required value range is established. At this point, the system architect needs to analyze the results to see if bandwidths of design variables can actually be achieved in the product

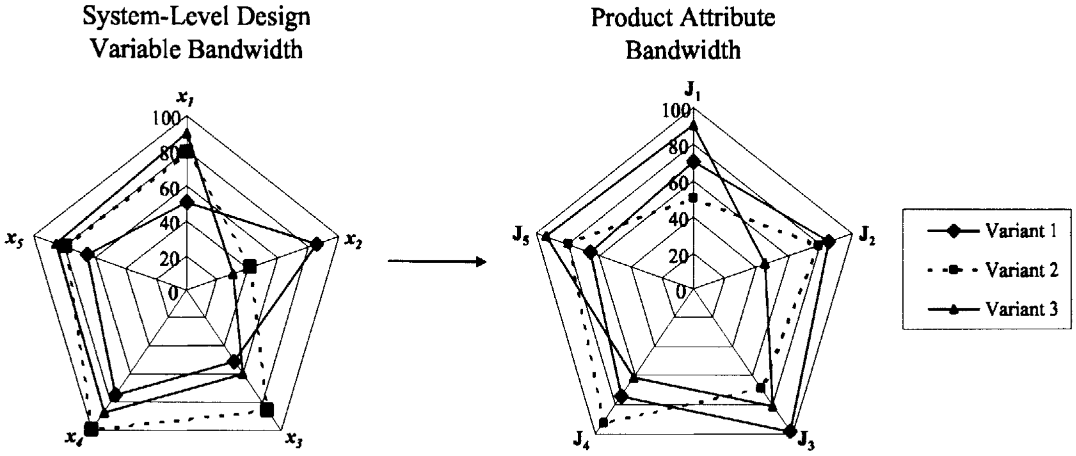


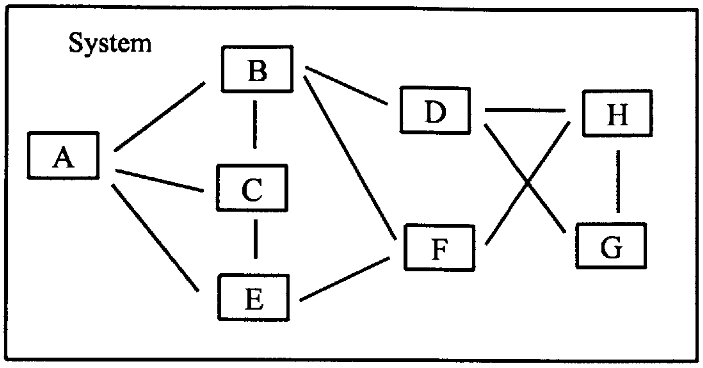
Figure 3-3: Platform Bandwidth in Design Variable and Product Attribute Space

platform. Sometimes it may be possible to accommodate bandwidths in all desired attributes and design variables. In other cases, compromises (in terms of design variable bandwidths, resulting in product variant performance penalties) must be made to build all variants off of a single platform. On the other end of the spectrum, if the bandwidths of design variables are very large, this can result in omission of product variants from the platform entirely.

3.6 Step IV: Identify Critical Elements

After establishing the platform bandwidth, each x, where $x \subset \mathbf{X}_{\mathcal{U}}$, must be mapped to a set of specific physical elements. This is a very important step, a prelude to identifying critical platform elements that need to be flexible to achieve the desired design variable bandwidth, dictated by the result of optimization in Step III. This step will be demonstrated using a generic example.

Figure 3-4 is a graphical and Design Structure Matrix (DSM) representation of a generic system. Within the system, there are eight elements (A - H) connected to each other, which makes up the whole system. Elements can be connected physically, or through information (e.g. computer programs). The DSM represents the system using a matrix format, with 1's indicating connectivity between elements.



	A	B	C	D	E	F	G	H
A	■	1	1		1			
B	1	■	1	1		1		
C	1	1	■		1			
D		1		■			1	1
E	1		1		■	1		
F		1			1	■		1
G				1			■	1
H				1		1	1	■

DSM

Figure 3-4: Graphical and DSM Representation of a Generic System

It is very important to establish the connectivity of the sub-system elements before mapping system-level design variable set $\mathbf{X}_{\mathcal{U}}$ to related product elements, which in Figure 3-4 consists of elements A through H. The reasons are 1) when the system-level design variable is required to be flexible, the architect needs to identify system elements affected by such change; 2) when the identified elements are changing, one must observe the change propagation sent to other elements (which may not be directly related to $\mathbf{X}_{\mathcal{U}}$) to estimate the propagation effect.

The next task is that, for every x in $\mathbf{X}_{\mathcal{U}}$ that needs to be flexible in terms of variable range, the architect must observe how the change Δx propagates throughout the entire system, if there is any propagation. Then, what initiates such changes, and why does flexibility needed to be embedded to accommodate such changes?

- The first reason is the bandwidths of design variables determined by the revenue optimization in Step III. This bandwidth is visible through the radar chart plotted (as seen in Figure 3-3).

- The second reason is that for certain variables, that are sensitive to the product family revenue and/or market share, might benefit from the flexibility in the future, even if the initial required bandwidth across the variants is zero or very small.

- The third reason is that changes might be required in response to changes in other coupled elements of the system through change propagation.

- The last reason, which is not considered in this thesis, is that in the future, unknown additional product variants might be added, possibly within the pre-established platform bandwidth. One of the difficulties with this in practice is that the true bandwidth of a platform can often be established via testing the prototype in the field.

For a given change, it is important to estimate how much change is required and how it propagates throughout the system. Figure 3-5 shows how change Δx can propagate throughout the system. This figure represents the final system configuration after the change (due to Δx), showing the direction of change propagation.

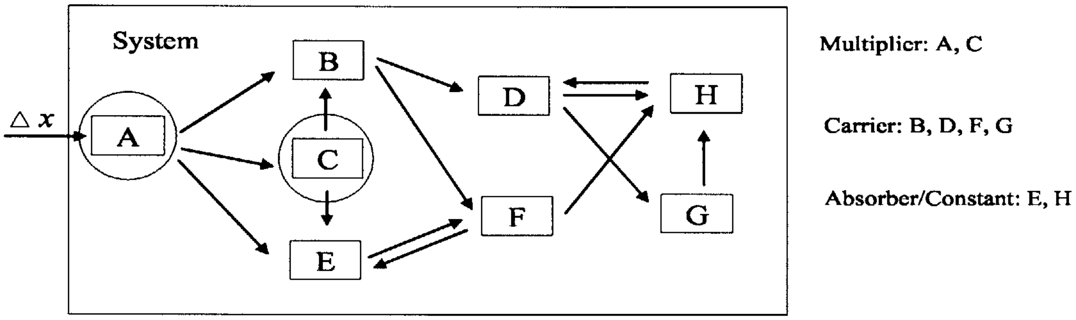


Figure 3-5: Change Propagation Due to Δx

The terms *multiplier, carrier, absorber* and *constant* are defined by Eckert et. al. [23] to classify elements that react to changes. *Multipliers* are elements that "generate more changes than they absorb." *Carriers* are elements that "absorb a similar number of changes to those that they cause themselves." *Absorbers* are elements that "can absorb more change than they themselves cause." Finally, *constants* are elements "that are unaffected by change." In Figure 3-5, each element is classified, with multipliers indicated as circled elements. Then the questions are: how can these classes of elements be identified quantitatively, and how does quantification of such elements guide the system architect to a better flexible product platform design?

The first question can be answered through the development of one or more quantitative metrics to measure the degree of change propagation for individual elements. Once each element's reaction to change can be measured quantitatively, then the system architect can identify, for a given design change, critical elements for embedding flexibility. To measure the degree of change propagation for a single element, a new metric is introduced. It is called the Change Propagation Index (CPI). For a single element i, CPI measures the degree of physical change propagation caused by this element when the change is required on the element. Equation (3.9) is shown below:

$$\mathrm{CPI}_i = \sum_{j=1}^{n_{out}} \Delta E_{out,j} - \sum_{k=1}^{n_{in}} \Delta E_{in,k} \tag{3.9}$$

In Equation (3.9), n_{out} is the number of elements to which the i^{th} element is connected, in the direction of outward propagation change; n_{in} is the number of elements to which the i^{th} elements is connected, in the direction of inward propagation change; $\Delta E_{out,j}$ is a binary number (0,1), indicating whether the j^{th} element is changed because of element i; $\Delta E_{in,k}$ is also a binary number for the k^{th} element indicating whether it is propagating change to i^{th} element. The introduced metric measures how the actual element physically propagates change to other elements.

However, just measuring the degree of physical change propagation is not enough. One must consider the economic impact caused by Δx, to the system and its relevant elements. For each element changed, the change related investment cost (switch cost) needs to be identified. This provides the system architect with two quantitative measures for each element: one indicating the degree of physical change propagation, and the other indicating the economic consequence of such change.

In Figure 3-5, the final state of change propagation is shown for a system, after it is altered by the design variable change Δx. This final state can be expressed in a matrix form, shown in Figure 3-6. The sum of each column indicates the total number of changes going outward from a specific element ($\sum \Delta E_{out}$). The sum of each row indicates the total number of changes coming into a specific element ($\sum \Delta E_{in}$). Subtracting $\sum \Delta E_{in}$ from $\sum \Delta E_{out}$ yields a CPI value for a specific element. Depending on the value, an element can be classified according to the terms defined previously. A positive CPI indicates that the element is a *multiplier* (marked as **M**); a zero CPI indicates that the element is a *carrier* (marked as **Ca**); a negative number indicates that the element is either an *absorber* (marked as **A**) or *constant*. If there are no outgoing changes from a particular element, and the element itself does not change, then it is classified as *constant*. Otherwise, the element is an *absorber*. The utilization of such a matrix is similar to both the Coupling Index (CI) and the Design Variety Index (DVI) matrices, introduced by Martin and Ishii [48].

Propagating Change

Receiving Change	A	B	C	D	E	F	G	H	E_{in}
A	■								0
B	1	■	1						2
C	1		■						1
D		1		■				1	2
E	1		1		■	1			3
F		1			1	■			2
G				1			■		1
H				1		1	1	■	3
E_{out}	3	2	2	2	1	2	1	1	
TPI	**3**	**0**	**1**	**0**	**-1**	**0**	**0**	**-2**	
Class	**M**	**C**	**M**	**C**	**A**	**C**	**C**	**A**	

Figure 3-6: Change Propagation in DSM

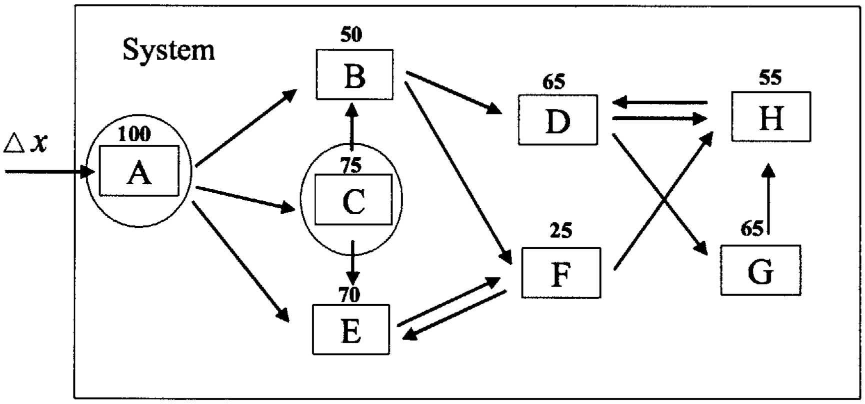


Figure 3-7: Economic Impact of the System for Δx

Figure 3-7 shows the changed state of the system, changed by Δx, with relevant switch cost (hypothetical) listed for each element involved in the change propagation. Note that for element A (the change initiating element), total incoming change is set to 0, since there is no component sending changes to that particular component. The switch cost is the cost of engineering design change and additional fabrication and assembly tooling/equipment investment for design change. For the case study presented in Chapter 5, the switch cost consists of tooling investments required for implementing the changed design. Observing CPI and the switch cost incurred for each element in the system, following recommendations can be made for selecting critical elements and designing them to be flexible:

- Multiplier elements require careful attention. These are elements that, through adding more changes, make the system harder to change. These are prime candidates for incorporating flexibility.
- One must investigate elements connected to the multiplier element to understand the nature of change. This information will be used to make a decision on which elements to incorporate flexibility (or add "*buffer*" to absorb the change, as Eckert calls it) for reducing, or even eliminating the change propagation.
- Carrier elements must be examined as well. For example, a carrier element might receive changes from five elements and sends out five changes, making it more expensive than a multiplier element that receives change from one element and sends it out to two elements.
- Elements with high switch costs, even though they may not be multipliers, also require special attention. These elements, through high switch costs, make it financially difficult to change the system.
- Elimination of physical propagation and reduction of economic impact must be carefully balanced. In some cases, physical propagation can be eliminated, but it may require prohibitive investment to do so. In other cases, economic impact may be reduced, but may results in more change propagation. All these factors must be weighted to reach a reasonable decision for incorporating flexibility.

Each and every element involved in the system needs to be investigated in order to determine the critical elements for incorporating flexibility. Effort must be made to: 1) eliminate the propagation of change by making the multiplier elements and/or other elements around it flexible, turning them into absorbers or carriers, and 2) redesign elements (with high switch cost) so when it is subject to change, it can be changed with significantly lower switch cost. One practical example comes from the automotive industry. When the engineers design a front motor compartment (for example) they have an option to design the compartment to accommodate a V8 engine, even though it may only require a V6 engine initially. This will incur extra upfront investment, but when the future situation requires implementation of a V8 engine configuration, the built-in option can reduce or eliminate the change propagation to other major parts of the vehicle.

3.7 Step V: Create Flexible Design Alternatives

With target elements identified in Step IV, the system architect needs to change these elements so they propagate smaller degrees of change and/or require lower switch cost than the inflexible design. This is accomplished by embedding flexibility into key elements, ones that have the greatest impact. According to de Neufville [20], flexibility is an *option*, where it has an "ability to adjust a design of a system in significant ways that enable the system managers to redirect the enterprise in a way that either avoids downside consequences or exploits upside opportunities." The option (flexibility), according to Hull [38], "gives the holder the right to do something. The holder does not have to exercise this right." However, this flexibility will incur additional investment and might result in additional system complexity. This raises important questions: how much flexibility is needed; and how should flexibility be embedded into these elements?

To answer the first question, one needs to examine the platform bandwidth obtained by the revenue optimization in Step III. The upper and lower limit values of $\mathbf{X}_A$, established through Equation (3.7), sets the range within which elements must be flexible. Additionally, sensitive system design variables in $\mathbf{X}_\mathcal{U}$ need to be examined. For future uncertainty in identified product attributes, it might be a good idea to incorporate flexibility in these design variables, so the attributes values can be changed easily when the need arises.

Addressing the second question about incorporating flexibility into identified elements, the system architect must consider several factors related to identified elements:

- Initial demand for each product variant in set $\mathcal{P}$
- Demand trend for each product variant in set $\mathcal{P}$
- Change of each product variant in set $\mathcal{P}$ due to $\mathcal{U}$
- Frequency of uncertain change.

The initial demand and expected demand trends of p_is in set $\mathcal{P}$ are very important when incorporating flexibility into a particular element. Embedded flexibility should be biased towards a particular p_i to yield favorable overall cost expenditure throughout the life of the platform to amortize investments in flexible parts and tooling. Also, adding flexibility to account for $\mathcal{U}$ may reduce the overall life cycle cost. In Chapter 4, these factors are addressed through the case study of a single flexible element design using a vehicle floor pan example. Considering all factors discussed, the architect can generate a set of different platform design alternatives.

The last factor listed - the frequency of specification changes - is an important one. The more frequent the specification change, the more valuable the flexibility will be. The issue regarding the change frequency is addressed in the case study of the vehicle product platform, presented in Chapter 5.

One of the challenges in this stage is the non-uniqueness of the design space. For a given functional requirement of achieving desired platform bandwidth, multiple flexible designs can be generated. A creative design process is necessary, and such processes are well documented by Pahl and Beitz [61]. After the flexible design alternative generation is finished, the system is then divided into two portions: 1) the product platform portion, which consists of common elements that stay constant, and flexible elements that, with minor modification, can be used for multiple number of product variants, and 2) the unique portion, which consists of unique elements, customized for a single variant. How and where to divide such system is an ongoing research topic. One of the best known methods is the DSM based decomposition [24], where the system elements can be grouped into different modules thus creating "platform module" and "unique module." At the end of Step V, the product platform is defined.

3.8 Step VI: Determine Costs of Design Alternatives

Flexible design alternatives are generated in Step V to achieve the platform bandwidth requirement set in Step III, and to minimize change propagation arising from specific design changes. As stated in the previous section, the flexibility incurs extra upfront costs initially, but results in lower switch cost when the system is required to change. To determine whether generated design alternatives are flexible to change, accurate cost estimates for each alternative need to be calculated. Costs are divided into following categories:

- Initial capital investment cost K_{init}, which include fabrication and assembly equipments and corresponding tooling investments;
- Variable cost C_{total}, which is the unit cost of each product multiplied by the number of products produced;
- Switch related capital investment cost K_{switch}, which consists of design change related investment costs.

The initial capital investment cost K_{init} is the required upfront investment cost for all relevant elements, needed to initiate the production of product family $\mathcal{P}$. In the manufacturing industry, it usually includes investment costs for fabrication and assembly lines, along with required tooling and development costs. The variable cost C_{total} is the total recurring cost to produce the product family $\mathcal{P}$. The switch-related capital investment cost K_{switch} is perhaps the most critical cost. The switch cost occurs when the product platform or product variants require change due to future uncertainties. If the platform is rigid, that is, not designed to accommodate change, the switch cost may be very expensive. If the platform is flexible to change, the switch cost should be lower than the switch cost of the inflexible platform.

To verify that generated design alternatives are more flexible than the original design, CPIs and switch costs for the same set of changes (identified in Step IV) are calculated. For a particular change, one design is more flexible if it incurs lower switch costs than the other design. However, one must consider the extra "price," paid upfront, to make the system flexible. Whether the upfront investment is worthwhile depends on whether the flexibility is truly needed and can be amortized over the course of the product platform life cycle.

The price of the option, or flexibility, paid upfront is additional cost related to the flexible design, in real options terminology. This initial investment allows system architects to change particular aspects of the product platform or product variants at a later time, with significantly reduced switch costs, when surrounding circumstances necessitate such changes. With upfront investment cost, variable cost, and switch cost identified, the benefit of each design alternative must be evaluated through uncertainty analysis.

3.9 Step VII: Uncertainty Analysis

From the previous step, the cost of flexibility, including initial investment costs, variable costs, and switch costs, have been calculated for each design alternative generated in Step V. Once all costs are identified, design alternatives must be evaluated under scenarios with various degree of uncertainty, to determine their economic performance. The underlying hypothesis is that flexibility has more value as the degree of uncertainty grows. For each design alternative, the expected future benefit, expressed in terms of the expected present value can be generically stated as:

$$E\left[NPV\right]_i = f\left(R_{T,i}, K_{\text{init},i}, C_{\text{total},i}, K_{\text{switch},i}, \mathcal{U}\right) \tag{3.10}$$

where the total expected benefit $E[NPV]$ for the i^{th} design alternative, is a function of the total product family revenue $R_{T,i}$, the initial capital investment $K_{\text{init},i}$, the total variable cost $C_{\text{total},i}$, and the switch cost $K_{\text{switch},i}$ incurred due to $\mathcal{U}$, as defined in Step I.

After evaluating the proposed design alternatives under several scenarios, the system architect can select the most beneficial design for a given uncertainty set $\mathcal{U}$. There might be a situation where none of the design alternatives are satisfactory. In this case, the architect can go back to Step I to reformulate the problem and boundary conditions, or go back to Step V and rework the design alternatives (see loop in Figure 3-1). Finally, the system architect can define the product platform as a set of common and flexible elements for all product variants in the product family, based on the results of the uncertainty analysis.

3.10 Chapter Summary

In this chapter, a flexible product platform design process is introduced. The proposed process begins by defining the target market segments, product variants, and uncertainties. The product variants' information from this step is mapped to system-level design variables and optimized for maximum revenue, thus establishing boundaries for the product platform bandwidth in the system-level design variable space. It is then mapped to the platform elements space, and using the newly introduced metrics, is then classified as different element classes. Flexibility is then embedded into critical elements, generating different design alternatives. Generated design alternatives are then evaluated under scenarios of various uncertainty to determine the most economically beneficial design. In each step of the proposed process, several alternative tools and methodologies can be used to accomplish the desired objective. Table 3.1 lists popular methods and tools that can be used for each design step.

In next two chapters, the developed design process is demonstrated through detailed case studies. Chapter 4 presents a detailed case study of single elements design, where an automotive vehicle floor pan is designed with flexibility. Chapter 5 presents a case study, wherein an automotive vehicle platform is flexibly designed to respond

Table 3.1: Popular Methodologies and Tools for Individual Process Step

Design Step	Available Methodologies and Tools
Step I	Clustering Analysis [39] Conjoint Analysis [1]
Step II	Principal Component Analysis [22] Quality Function Deployment [36] Response Surface Method [55]
Step III	Gradient Based Optimization [6] Heuristic Based Optimization [28, 43]
Step IV	Change Propagation Analysis [23] Engineering Expertise [61] Quality Function Deployment [36]
Step V	Brainstorming [61] Concept Screening Matrix [83] Concept Scoring Matrix [83]
Step VI	Parametric Cost Model [12, 34, 41, 42]
Step VII	Decision Tree Analysis [15] NPV Analysis [19] Real Options Analysis [71, 81]

to a set of future uncertainties.

Chapter 4

Flexible Platform Component Design under Uncertainty

This chapter demonstrates a portion of the proposed design process (Chapter 3) through a case study of single flexible component design. Several research papers have been published in the area of design under uncertainty. Li and Azarm proposed a framework for product design selection [45] under uncertainty and competition. Martin and Ishii [49] demonstrated their design process through design of water cooler for future design changes, but did not carry out the uncertainty analysis to examine the value of their design. In this chapter, the main focus is to demonstrate the part of the proposed design process by designing flexible platform components, using multidisciplinary design optimization framework and uncertainty analysis. Subsequent sections outline the mathematical formulation for a single flexible component design and is demonstrated through a case study, where flexible design alternatives of an automobile floor pan are generated, economically optimized, and analyzed under future demand and specification uncertainty. This chapter is based on a journal article by Suh et. al. [79].

4.1 Theoretical Formulation

The overview of the framework is shown in Figure 4-1. For each phase, the corresponding step number of the proposed process from Chapter 3 is shown. First, critical uncertainties for selected platform component are identified (Step I). Second, several flexible component design alternatives are generated in response to these uncertainties (Step V). Next, each design is optimized economically, while satisfying the component performance requirements (Step VI). Economically optimized designs are then evaluated in terms of long term cost by calculating the total expected cost expenditure over the lifetime of component production - expressed in terms of present value ($E[NPC]$) - accounting for future uncertainties. A Monte Carlo simulation is used to evaluate the $E[NPC]$ over the total platform component lifetime (Step VII). Mathematical problem statements for each step are discussed below.

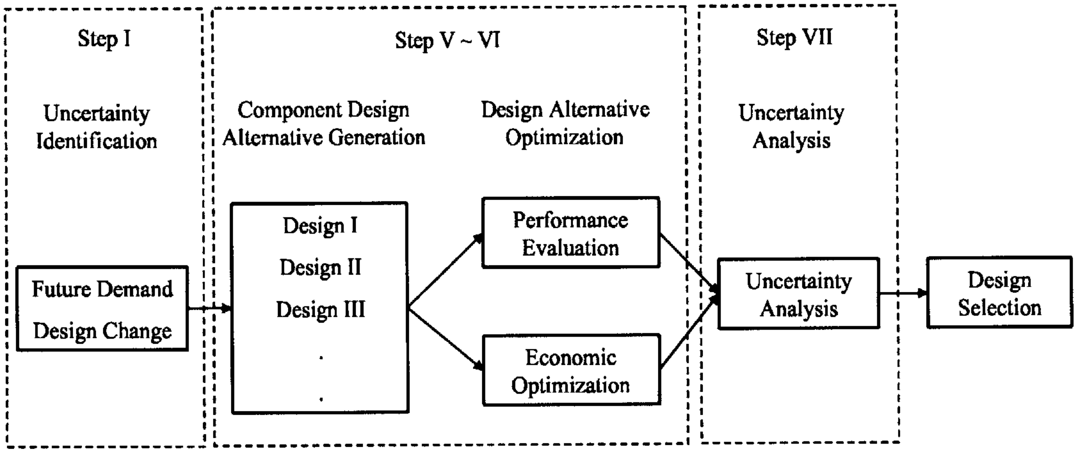


Figure 4-1: Flexible Platform Component Design Process

4.1.1 Uncertainty Identification

Define a set of critical uncertainties $\mathcal{U}_{\text{comp}}$.

$$\mathcal{U}_{\text{comp}} = [u_{\text{comp},1}, u_{\text{comp},2}, \ldots, u_{\text{comp},n_u}] \tag{4.1}$$

where $u_{\text{comp},i}$ is one of n_u individual uncertainties identified for the selected product platform component. Possible uncertainties for platform components are future demand and design specification changes for particular platform component variants.

4.1.2 Component Design Alternative Generation

Generate a set of component design alternatives $\mathcal{V}_{\text{comp}}$, comprised of n_v different design alternatives for a specified number of platform component variants.

$$\mathcal{V}_{\text{comp}} = \left[v_{\text{comp},1}, v_{\text{comp},2}, \cdots, v_{\text{comp},n_v}\right] \tag{4.2}$$

where each design alternative $v_{\text{comp},i}$ can be expressed as a vector function of two vectors.

$$v_{\text{comp},i} = \left[\mathbf{J}_Z\left(\mathbf{X}_{\text{comp}}\right), \mathbf{J}_C\left(\mathbf{X}_{\text{comp}}\right)\right] \tag{4.3}$$

$\mathbf{J}_Z$ is a component performance vector, expressed as function of component design vector $\mathbf{X}_{\text{comp}}$, and $\mathbf{J}_C$ is a component economic vector, which can also be expressed as functions of $\mathbf{X}_{\text{comp}}$. $\mathbf{J}_C$ is further decomposed into

$$\mathbf{J}_C\left(\mathbf{X}_{\text{comp}}\right) = \left[c_i\left(\mathbf{X}_{\text{comp}}\right), K\left(\mathbf{X}_{\text{comp}}\right)\right]; i = 1, ..., n_c \tag{4.4}$$

where $c_i(\mathbf{X}_{\text{comp}})$ is the variable unit cost of the i^{th} component out of n_c components in the family, and $K(\mathbf{X}_{\text{comp}})$ is the total non-recurring investment cost for that particular design alternative.

4.1.3 Design Alternative Optimization

Each design in the flexible component design alternative set $\mathcal{V}_{\text{comp}}$ is optimized for minimum economic cost, while the component performance objective $\mathbf{J}_Z$ must be satisfied.

$$\begin{array}{c}\text{Minimize } \mathbf{J}_C\left(\mathbf{X}_{\text{comp}}\right) \\ \text{Subject to } \mathrm{h}\left(\mathbf{X}_{\text{comp}}\right), \mathrm{g}\left(\mathbf{X}_{\text{comp}}\right)\end{array} \tag{4.5}$$

The performance vector $\mathbf{J}_Z$ is part of optimization constraint $\mathrm{h}(\mathbf{X}_{\text{comp}})$ and $\mathrm{g}(\mathbf{X}_{\text{comp}})$, where a particular design alternative must satisfy a specific level of performance requirement.

4.1.4 Uncertainty Analysis

Once all design alternatives in $\mathcal{V}_{\text{comp}}$ are optimized, they are economically evaluated, under uncertainty, to determine the expected lifetime cost expenditure expressed in terms of present value ($E[NPC]$):

$$E\left[NPC\right]_i = f\left(\mathbf{J}_{C,i}\left(\mathbf{X}^{*}_{\text{comp},i}\right), \mathcal{U}_{\text{comp}}\right); \; i = 1, ..., n_v \tag{4.6}$$

Comparing $E[NPC]$ of all flexible design alternatives in the set $\mathcal{V}_{\text{comp}}$, the best design is selected.

The proposed design process is demonstrated through the case study of a vehicle floor pan, an important vehicle platform component that requires dimensional flexibility to accommodate a vehicle family with two different wheelbase configurations.

4.2 Case Study: Automotive Floor Pan

The vehicle floor pan is a part of the body component that has been well studied in the automotive industry. Most studies, however, focus on optimization of its structural performance as part of Body in White (BIW). No literature, to author's knowledge, mentioned long term economic impact of such optimized floor pan design, especially the flexible floor pan that must satisfy requirements of multiple vehicle variants.

A major automotive manufacturer is developing a new vehicle platform for its family of vehicles. Several critical platform decisions are made *a priori*. The proposed vehicle platform strategy is to share a common underbody structure, which consists of common front and rear compartments, and the flexible floor pan, a part of the vehicle platform. The floor pan is an important component that connects the front compartment and the rear compartment of the automotive underbody structure. The width of the common underbody is fixed and is the same for all vehicles, and the only dimensional variation is vehicle length, determined by the vehicle wheelbase. The wheelbase is adjusted by incorporating dimensional flexibility into the floor pan. It is decided that only two variants of the floor pan (long and short) will be produced for this platform at any given time since vehicles from this platform will be either long wheelbase or short wheelbase vehicles. Figure 4-2 shows a CAD representation of the underbody structure and the flexible floor pan.

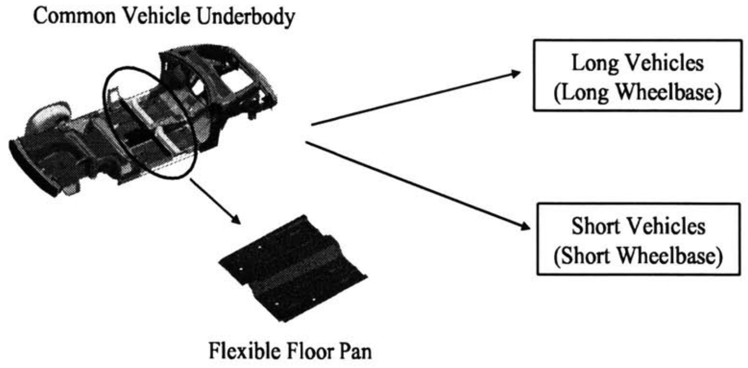


Figure 4-2: Vehicle Underbody Structure

All floor pans are to be fabricated from steel using transfer press technology. The objective is to create the most cost efficient flexible design to achieve dimensional flexibility in vehicle length by adding geometric flexibility into the floor pan. The life of the vehicle platform is set to 15 years, and it is updated every five years. Since the floor pan is a part of the platform, its life cycle is identical to the time line of the platform.

In this case study, the theoretical formulation presented in Section 4.1 is implemented to the vehicle floor pan. First, critical uncertainties related to the floor pan are identified. Second, several flexible floor pan designs are generated. For each flexible floor pan design, the floor pan is optimized for minimum mass, which in turn, minimizes investment and variable costs, while satisfying structural performance requirements. Once component variant unit costs and investment cost of optimized floor pans are calculated, total expected lifetime cost expenditure, expressed in terms of net present value ($E[NPC]$), is calculated using component variant unit costs and investment costs during the uncertainty analysis stage. Comparing $E[NPC]$ for each flexible design, the best design is selected.

4.2.1 Uncertainty Identification

The first step is to identify future uncertainties related to the component. In this case study, two critical uncertainties are identified. They are future demand for long and short floor pans $(D_S(t), D_L(t))$, and potential future changes in the floor pan length itself $(L_S(t), L_L(t))$, as function of time, as shown in Equation (4.7):

$$\begin{aligned} \mathcal{U} &= [u_1, u_2] \\ u_1 &= [D_S(t), D_L(t)] \\ u_2 &= [L_S(t), L_L(t)] \,. \end{aligned} \tag{4.7}$$

Future demand for long and short floor pans is determined by aggregating future demand for vehicles that use short and long floor pans. In addition, floor pans' geometric specification during the lifetime of the platform could be uncertain. In this study, the floor pan lengths for both long and short floor pans are treated as uncertain. Traditionally, one assumes that platform specifications will not change over time. However, since platforms are usually long-lived compared to the variants that are derived from them, there is a need for flexibility in order to accommodate uncertainty in variant specification change in the future. This need for flexibility flows down to individual components of the platform, such as the floor pan examined here.

4.2.2 Component Design Alternative Generation

The second step is to generate flexible design alternatives for embedding dimensional flexibility into the floor pan. After considering platform constraints and other design criteria, four design alternatives are generated and shown in Figure 4-3.

The first alternative is a customized (inflexible) design, where two separate floor pans are designed for short and long variants. Floor pans are fabricated using separate stamping dies and tools, requiring separate investments for floor pans of different

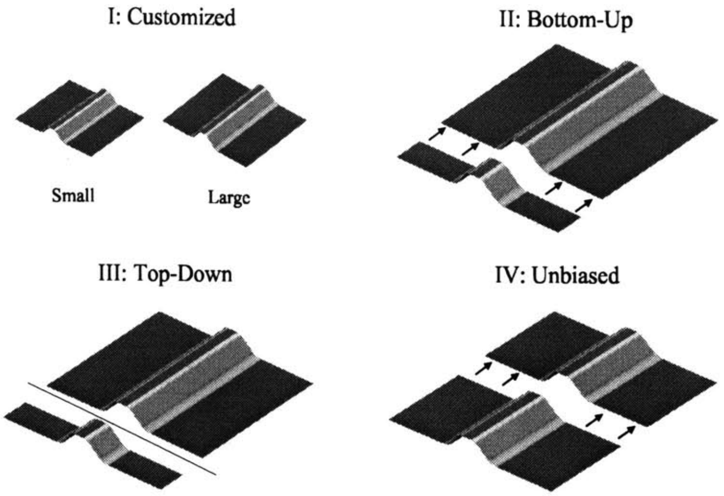


Figure 4-3: Proposed Floor Pan Design Alternatives

length. This is the baseline design, with no geometric flexibility embedded into the floor pan itself.

For the second design, called "bottom-up" design, the main floor pan is designed to fit the short floor pan length specification. To satisfy the long floor pan length requirement, an extension piece is spot welded to the main floor pan. This design allows the addition of floor pans with different lengths through the addition of the extension piece with dimensional restriction $L_{min} \leq L$, where L_{min} is the minimum floor pan length achievable by this design, bounded by the length of the short floor pan. Separate stamping dies are required for the short floor pan and the extension piece. Moreover, additional investments are required for spot welding facilities due to the extra welding process for the long floor pan.

The third design, called "top-down" design, incorporates flexibility into the floor pan in a different way. The main floor pan is designed to meet the long floor pan length requirement. To manufacture the short floor pan, the end of the original floor pan is simply trimmed to meet the geometric specification. This design requires stamping and blanking dies for fabrication of the long floor pan, plus additional investments for short floor pan fabrication (trimming die). Because of the additional tooling investments (non-recurring cost), extra labor for fabrication, extra time required, and the recycling cost of trimmed piece (recurring production cost), the unit cost of the short floor pan is greater than the long floor pan. This assumes that the long floor pan is manufactured first, then is trimmed for the short floor pan length requirement. The floor pan has the dimensional restriction $L \leq L_{max}$, where L_{max} is the maximum floor pan length achievable by this design, bounded by the length of the original floor pan.

The last design is the most flexible design, where two equal-length pieces are welded together to achieve any floor pan length requirement with lower and upper bound $L_{min} \leq L \leq L_{max}$. This design requires stamping and blanking dies for fabrication of two equal length pieces, plus additional investments for welding facilities. The cost of floor pan fabrication and assembly is the same for both the long and short floor pans, unbiased toward any floor pan size in terms of the unit cost, since the same sub-components and manufacturing processes are used. This is the design with the highest degree of flexibility, where sub-components can be adjusted (by sliding) to any floor pan length within the pre-established lower and upper bound. Key dimensions for short and long floor pans are shown in Table 4.1.

Table 4.1: Floor Pan Geometric Specifications

Key Dimensions	Short Floor Pan	Long Floor Pan
Length (mm)	1180	1305
Width (mm)	1445	1445
Thickness	To be determined	To be determined

Design II and Design IV require additional spot welding for sub-component assembly. Extra spot welding is required *in addition* to spot welding required for a standard floor pan assembly. Following the automotive industry welding practice, the long floor pan for Design II and all floor pans for Design IV require 35 additional spot welding connections each, assuming 50 mm clearance between each weld connection. Given the overall floor pan dimensions, floor pan geometry will be optimized for minimum overall mass.

Four different design alternatives have been presented, each with its own advantages and disadvantages. In the subsequent section, an optimization process for each design alternative is presented in order to quantify the benefits and costs of each alternative.

4.2.3 Design Alternative Optimization

Optimization Framework

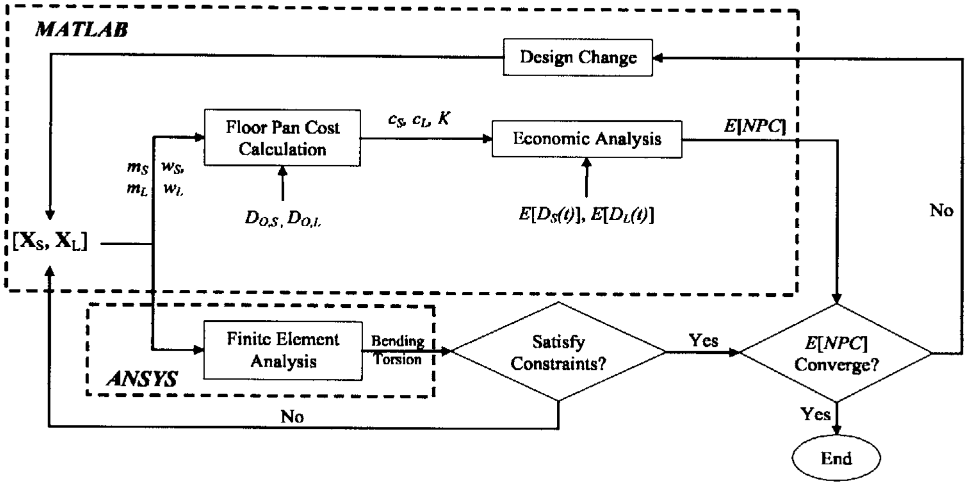


Figure 4-4: Design Alternative Optimization Flow Chart

Figure 4-4 shows the flow diagram of the multidisciplinary optimization for each floor pan alternative. Given geometric design vectors for short and long floor pans $(\mathbf{X}_S, \mathbf{X}_L)$, finite element models of short and long floor pans are generated (see Figure 4-5) and analyzed for bending and torsion requirements. Concurrently, masses of the floor pans (m_S, m_L), calculated from floor pan design vectors, are passed onto the cost model, yielding the total investment cost (K) and the unit cost for short and long floor pans (c_S, c_L), given the initial annual demand for each floor pan $(D_{o,S}, D_{o,L})$ and the total number of welding connections (w_S, w_L). Cost data is then passed onto the economic analysis model, where the total expected lifetime cost expenditure is calculated in terms of present value (NPC), given the expected, deterministic future demand for short and long floor pans $(E[D_S(t)], E[D_L(t)])$, based on historical data. The mathematical statement in Equation (4.5) is implicitly embedded in this optimization framework, since minimizing the mass of the floor pan will minimize the investment and production costs of floor pans, which in turn, will minimize total cost expenditure over the specified time horizon. This is true since the heavier floor pan results in higher material cost, and more costly machine investment. Once the the NPC converges to a minimum value while satisfying structural constraints, the optimization loop stops. The finite element analysis model, cost model, and economic analysis model, which are used in the optimization framework, are explained in subsequent sections.

Finite Element Analysis Model

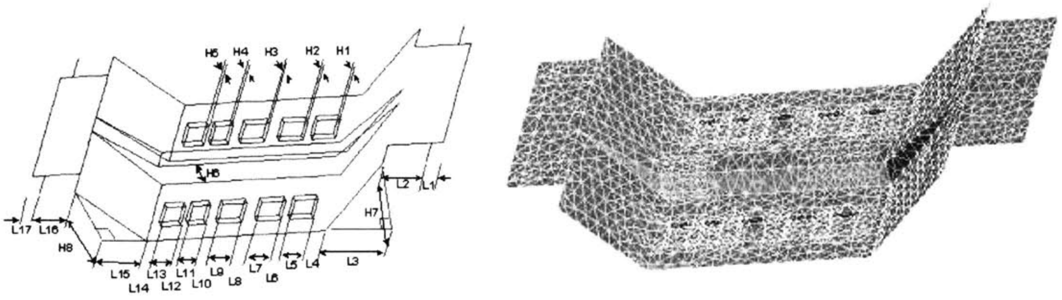


Figure 4-5: Design Features and Finite Element Model of Simplified Underbody

In this case study, a simplified finite element model of the underbody is created and a finite element analysis is conducted. In the automotive industry, the floor pan is usually analyzed as part of the BIW structure, not alone. Since the actual finite element model of automotive body was not available, it was necessary to use simplified underbody model, as shown in Figure 4-5. The commercial finite element analysis software package ANSYS is used. Both ends near the front and rear axles are fixed. The geometry of the floor pan is controlled by design vectors $\mathbf{X}_S$ (for the short floor pan) and $\mathbf{X}_L$ (for the long floor pan). Each design vector has 31 design variables - 17 length variables, 8 height variables, 5 width variables, and a thickness variable. Figure 4-5 shows the finite element analysis model with design variables. All design variables affect the structural performance, but only the thickness is used for subsequent cost analysis.

The displacements obtained in the bending and torsion analysis are used to compute the bending and torsion stiffness. In an overall design involving the entire underbody platform, the interactions with other components must be considered because the floor pan affects the entire vehicle stiffness and bending performance.

Cost Model

A process-based cost model, developed at MIT [12, 34, 41, 42], is utilized to construct the cost relationships in this case study. The following assumptions are made.

- The investment costs consist of line equipment and tooling investments for the blanking, stamping and welding processes. Transfer press technology is assumed for the fabrication of the floor pan, with long and short floor pans sharing the same press line for fabrication and welding processes.
- Welding lines for all designs are assumed to be flexible, i.e. they can accommodate any floor pan lengths within the pre-established boundary. Flexible welding tool investment costs are assumed to be twice the costs of inflexible welding tools.
- Blanking die investment is 10% of a new stamping die investment.
- Only two different floor pan lengths (long and short) are produced at any given time.
- Production volume of the floor pan is equal to the demand for the floor pan.

The MIT process-based cost model is used to calculate the unit cost of the floor pan as a function of floor pan mass and the annual demand. Once c_S, c_L, and K are determined, they are passed onto the economic analysis model.

Economic Analysis Model

Given the total investment cost and the unit cost of short and long floor pans, the model calculates the total expected cost expenditure for each design alternative in terms of current net present value. The following assumptions are made for the economic analysis model:

- The total life cycle of the vehicle platform is set to 15 years ($T = 15$). This assumes that there will be three generations of vehicle models with five years of production life cycle each.
- Blanking dies, stamping dies and welding tools are refurbished every five years when vehicle models are remodeled. Costs for refurbishing are assumed to be 25% of a new die and tool cost, assuming no engineering design changes. In this case study, it is assumed that unless there is a change in floor pan lengths, there will be no new investment costs for floor pans other than refurbishing costs.
- Investment for new tooling or refurbishing occurs a year before the start of the new model production. For this case study, the investment occurs during year 0, 5 and 10.

The following figure shows the fixed investment schedule for the floor pan production.

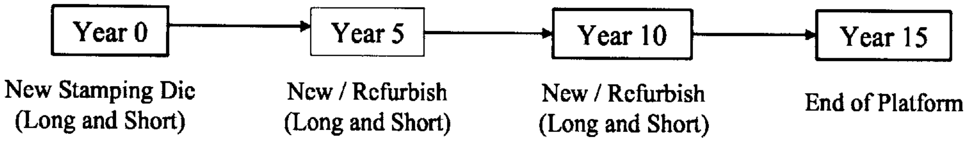


Figure 4-6: Investment Time Line for Floor Pan

Net present cost (NPC) is the total present value of future cost expenditure over a fixed time period, including the initial investment. In this case study, for each proposed flexible design alternative, the total expected lifetime cost expenditure is used as a measure of the economic performance, given uncertainties in future demand. NPC is calculated using Equation (4.8).

$$NPC = \sum_{t=0}^{T} \frac{TC_t}{(1+r)^t} \tag{4.8}$$

where T is the number of time periods and TC_t is the total cost incurred at time period t. The discount rate r captures the time value of money. Discount rates typically used in industry can be as high as 20% per year [19]. In this case study, an annual discount rate of 6% is used. The equation for calculating TC at time period t is

$$TC_t = C_{\text{total},t} + K_t \tag{4.9}$$

where $C_{\text{total},t}$ is the total variable cost from the component production and K_t is the total capital investment at time period t when a specific flexible design alternative is implemented. The total variable cost $C_{\text{total},t}$ for the time period t is

$$C_{\text{total},t} = \sum_{i=1}^{n_c} \left(c_i E\left[D_{t,i}\right]\right) \tag{4.10}$$

where c_i is the unit cost of i^{th} component variant and when a specific flexible design alternative is implemented at time t. $E[D_{t,i}]$ is the expected demand of the i^{th} component variant at time t (see Equation (4.13)). The component variant unit cost c_i is

$$c_i = c_{f,i} + c_{a,i};\ i = 1...n_c \tag{4.11}$$

where $c_{f,i}$ is the fabrication cost of the i^{th} component variant and $c_{a,i}$ is the assembly cost of the i^{th} component variant. Fabrication cost consist of material, labor, energy, equipment, tooling, building depreciation, maintenance and overhead cost. Assembly cost also consists of material, labor, energy, equipment, tooling, building depreciation, maintenance and overhead cost. Detailed explanation of these cost elements are presented in Chapter 5, Section 5.7. The fabrication costs are calculated by the cost model, and passed onto the economic analysis model. The assembly cost is predetermined from the proprietary assembly cost model as a function of the number of welding connections and the total expected annual production volume. Finally, K_t, the total capital investment cost at time period t, is

$$K_t = K_{\text{line},t} + K_{\text{tool},t} \tag{4.12}$$

where $K_{\text{line},t}$ is the total line investment cost and $K_{\text{tool},t}$ is the total tooling investment cost at time period t. Line investment cost is one-time initial investment to setup press machines and assembly machines. Tooling investment cost is the tooling required for component fabrication and assembly, and must be refurbished every five years, at 25% of the new tooling cost.

In this economic analysis model, future demand for short and long floor pans are estimated using historical sales data (1997 - 2003) of the vehicles that are planned to be built on this particular vehicle platform. The assumption is that the past historical trend will continue in the future. Expected demand (without demand volatility) for a particular component at time t is

$$E\left[D_t\right] = D_o e^{(\alpha t)};\ t = 1, ..., T_f \tag{4.13}$$

where D_o is the initial annual demand, α is the drift coefficient indicating the trend of demand, and T_f is the number of time periods in the future. The drift coefficient (α) and the volatility coefficient (σ_v) are for a particular vehicle sold, and can be calculated from Equation (4.14) and Equation (4.15), assuming historical data are available. The volatility coefficient σ_v is an important parameter required for future uncertainty analysis later on.

$$(\alpha - \frac{1}{2}\sigma_v^2) = \frac{\sum\limits_{t=1}^{T_h} (\ln D_{h,t} - \ln D_{h,t-1})}{T_h} \tag{4.14}$$

$$\sigma_v = \text{stdev}\left[\ln\left(D_{h,t}\right) - \ln(D_{h,t-1})\right]_{t=1}^{t=T_h} \tag{4.15}$$

T_h is the total number of historical time periods observed and $D_{h,t}$ is the historical vehicle demand at time t. Once floor pans for each design alternative are optimized, the optimum designs are evaluated under future uncertainty.

Table 4.2 lists required parameters for the economic analysis model and uncertainty analysis later on. The initial annual vehicle demand (D_o), trend coefficient (α) and volatility coefficient (σ_v) are obtained from historical data (1997 - 2003) of real vehicles that are planned to be developed on this particular vehicle platform.

Table 4.2: Economic Analysis Parameters

Parameters	Short Floor Pan	Long Floor Pan
D_o	60,000	405,000
α	-5.52%	2.09%
σ_v	13.27%	7.35%

Optimization Results

The objective of the optimization is to minimize the net present cost of floor pan fabrication and assembly over the life of the product platform, which is set to 15 years, given forecasted deterministic demand for each floor pan. Using the optimization framework described in the previous section, the optimal $\mathbf{X}_S$ and $\mathbf{X}_L$ are obtained, yielding results shown in Table 4.3. Optimized floor pan masses, thicknesses and NPC for each design alternative are listed.

Table 4.3: Optimization Results for Individual Design Alternatives

Design Alternatives	I		II		III		IV	
Floor Pan Length	Long	Short	Long	Short	Long	Short	Long	Short
Mass (kg)	16.06	14.37	16.26	14.54	16.06	14.52	16.06	16.06
Thickness (mm)	0.94	0.93	0.94	0.94	0.94	0.94	0.94	0.94
NPC (Normalized)	100.0		**99.9**		100.8		113.6	

In the optimization, the floor pan thickness is treated as a continuous design variable. NPC values for design alternatives are normalized by the NPC value of Design I. Design II, III and IV have uniform thicknesses for long and short floor pans since they are using the same floor pan for both lengths. Also, masses for the long floor pan in Design II and both floor pans in Design IV account for the 15 mm overlap required for spot welding. Long and short floor pans for Design I have different thicknesses, since the floor pans are customized for different lengths. From the optimization, with deterministic demand, Design II (bottom-up) resulted in the smallest cost expenditure. While the cost differences between alternatives appear small, one must keep in mind that profit margins are very tight in the automotive industry. We will see that these small differences are amplified, once uncertainty and flexibility are considered.

4.2.4 Uncertainty Analysis

Uncertainty analysis of floor pan design alternatives during the lifetime of a vehicle platform is critical for estimating the overall economic performance of each flexible design alternative. In this case study, the identified uncertainties are future demand for each floor pan, and the potential engineering change (floor pan length) during major remodeling of the vehicle family every five years. For the future floor pan demand, even though expected production demand is known, the actual demand from customers is very much uncertain. It is assumed that the floor pan length change occurs within pre-defined dimensional limits $L_{min} \leq L \leq L_{max}$.

It is further assumed that the initially chosen design alternative will be implemented throughout the life of the platform. Geometric Brownian Motion (GBM) is used to model uncertain future demand for short and long floor pans, assuming the historical trend continues in the future within a pre-established yearly volatility. GBM is also used to simulate future vehicle demand in the work by Georgiopoulos et. al. [27], to calculate the vehicle portfolio profit. Annual demand for different floor pans varies from year to year with increasing uncertainty as the future forecast horizon increases. Floor pan demand at time $t+1$ can be estimated by

$$D_{t+1} = D_t e^{[(\alpha - \frac{\sigma_v^2}{2})\Delta t + \sigma_v \varepsilon \sqrt{\Delta t}]} \tag{4.16}$$

Where D_t is the demand at time t, α is the drift coefficient, σ_v is the volatility coefficient from Equation (4.15), Δt is the unit change in time (a year for this case study), and ε is a normally distributed random number with N(0,1). Substituting Equation (4.16) into Equation (4.10) and calculating the actual NPC for time period

t in Equation (4.8), the actual NPC for each design alternative can be calculated. Figure 4-7 shows an example plot of the expected demand and one possible outcome of the actual demand over the specified time period.

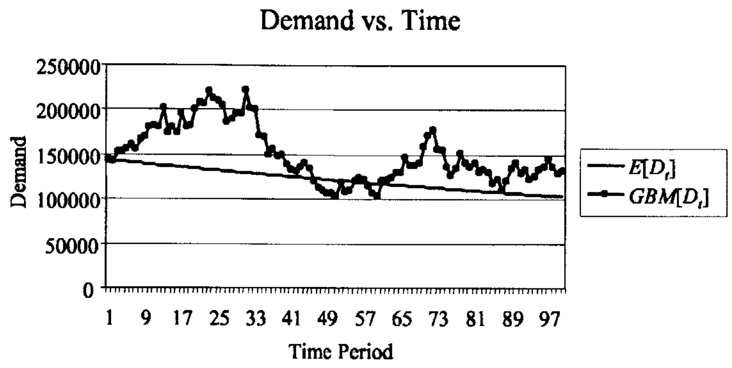


Figure 4-7: Example of Future Demand Forecast Model Using GBM

Simulating the actual demand scenarios many times through the Monte Carlo simulation, expected NPC can be calculated as

$$E[NPC] = \frac{\sum_{i=1}^{\#\text{Simulation}} NPC_i}{\#\text{Simulation}} \tag{4.17}$$

Deterministic Analysis

Before the actual uncertainty analysis, a deterministic analysis based on the fixed floor pan production volume is performed. Figure 4-8 shows deterministic cost expenditure from the floor pan production over the lifetime of the vehicle platform (expressed in terms of NPC) as a function of floor pan production volume ratio (long:short). The initial ratio for this case study is shown as a dashed line. The crossover point is the production volume ratio where, when crossed, one design starts to perform better than the other design. The assumption is that the annual production volume ratio remains constant (based on the total long and short floor pan production volume of 465,000 units) throughout the life of the vehicle platform. The NPC values are normalized with respect to the NPC value of Design I when the production volume ratio is 0:10.

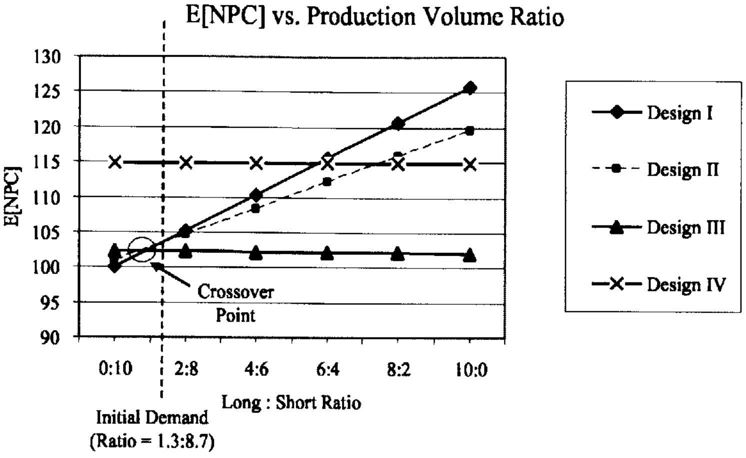


Figure 4-8: *NPC* of Each Design Alternative vs. Product Volume Ratio

Design III has the best economic performance over most ranges in terms of overall cost expenditure. Additionally, Design III has very little sensitivity to the change in the production volume ratio. This is due to the fact that the unit cost difference between the long and short floor pan is very small, making it insensitive to the production volume ratio change. The slope of Design III is negative, while the other lines have positive slopes. This is due to the fact that for Design III, the short floor pan is more expensive than the long floor pan, i.e. the more long floor pans are produced, the smaller the total costs. Design IV, the design with the highest degree of flexibility, does not perform well compared to the other design alternatives. However, this design is also not sensitive to the production volume ratio, since the unit costs for short and long floor pans are the same. Finally, if there is a case where the initial production volume ratio is positioned near the crossover points between each design *NPC* line, the future trend of the production volume ratio becomes an important criterion for the selection of the best design alternative.

The results indicate that under deterministic conditions, with current demand trends, it would be best to choose Design II, since it has the smallest net cost expenditure. However, since the actual future demands for both long and short floor pans are uncertain, we need to capture all possible instances of future demand scenarios to make the best design selection. In the next section, results of the uncertainty analysis are presented.

4.2.5 Simulation Results

Four different scenarios are evaluated, in ascending order of increasing uncertainty. They are summarized in Table 4.4.

Table 4.4: Evaluated Scenarios

Scenarios	Short Floor Pan (Year 5, 10)	Long Floor Pan (Year 5, 10)
I	Fixed	Fixed
II	Uncertain	Fixed
III	Fixed	Uncertain
IV	Uncertain	Uncertain

Initially, it is assumed that there is no uncertainty in floor pan lengths (Scenario I), i.e. there is only demand uncertainty. Next, the length of one floor pan is treated as uncertain (Scenario II and III), its length requirement changing at year 5 and year 10. Finally, lengths of both floor pans are treated as uncertain (Scenario IV). Subsequent sections outline how the uncertainty affects each design alternative, and the results are presented in Table 4.5.

Scenario I: No Floor Pan Length Change

Since there is no uncertainty in floor pan lengths in this scenario, the only investment costs incurred in year 5 and 10 are refurbishing costs of fabrication dies. Monte Carlo simulation is performed to estimate the expected lifetime cost expenditure for each design alternative. Each simulation comprises 25,000 runs.

Scenario II: Uncertain Short Floor Pan Length

This time, the short floor pan length is treated as uncertain. The short floor pan length changes occur in year 5 and 10, when the vehicle family goes through major redesign. Each design alternative will incur different investment costs in years 5 and 10.

- Design I: A new stamping die and blanking die for the short floor pan are required. Long floor pan dies are refurbished only.
- Design II: New investments for both short floor pan *and* the extension piece are required. For this design, flexibility does not have any benefit over the inflexible design.
- Design III: The blanking die that trims the long floor pan into the short floor pan must be redesigned.
- Design IV: No new investments, other than refurbishing costs, are required. Flexibility is already built in.

Again, Monte Carlo simulation is performed for each design alternative.

Scenario III: Uncertain Long Floor Pan Length

This time, the long floor pan length is treated as uncertain. The long floor pan length changes occur in year 5 and 10, when the vehicle models are redesigned. Each design alternative will incur different investment costs.

- Design I: A new long floor pan stamping die and a blanking die is required. Short floor pan dies are refurbished only.
- Design II: A new extension piece is required to accommodate the new length. Blanking and stamping dies for a new extension piece are required. Short floor pan dies are refurbished only.
- Design III: A new stamping die and blanking die for the long floor pan are required. The blanking die for the short floor pan is refurbished only.
- Design IV: No new investments, other than refurbishing costs, are required. Flexibility is already built in.

Scenario IV: Uncertain Short and Long Floor Pan Lengths

Finally, both long and short floor pan lengths are treated as uncertainties. The floor pan length changes occur in year 5 and 10 when the entire vehicle family goes through a major change up. Each design alternative will incur different investment costs.

- Design I: New stamping and blanking dies for both long and short floor pan are required.
- Design II: Investment costs for the short floor pan and extension piece are required.
- Design III: New investment costs for the large floor pan (blanking and stamping dies) and blanking die (for short floor pan trimming) are required.
- Design IV: No new investments, other than refurbishing costs, are required. Flexibility is already built in.

Simulation Results

The following table lists $E[NPC]$ of each design alternative for all evaluated scenarios. Values are normalized with respect to the $E[NPC]$ value of Design I for Scenario I.

Table 4.5: $E[NPC]$ of Design Alternatives for Simulated Scenarios

	Design I	Design II	Design III	Design IV
Scenario I	100.0	**99.9**	100.8	113.6
Scenario II	**100.9**	101.2	100.9	113.6
Scenario III	101.0	**100.3**	101.8	113.6
Scenario IV	101.9	**101.2**	101.9	113.6

From the simulation, it appears that Design II has the best economic performance among all designs in most scenarios (except Scenario II). Design III, another flexible design, had equal or worse economic performance than the inflexible Design I. This can be attributed to the fact that the production volume trend (shown in Figure 4-8) shifted to the region where Design I and Design II are more favorable. Another interesting result is that Design IV, the most flexible design, had the worst economic performance overall, regardless of degrees of uncertainty. This raises a possible future research question, "how much flexibility is optimal when the degree of uncertainty is known?"

The final analysis consists of comparing the difference between the economic performance of flexible designs to that of the inflexible design as the degree of uncertainty increases. Figure 4-9 shows the *NPC* difference between flexible designs (Design II, III, and IV) and the inflexible design (Design I) as the degree of uncertainty in floor pan length increases. Numbers are normalized with respect to the cost difference between Design II and Design I, for degree = 0.

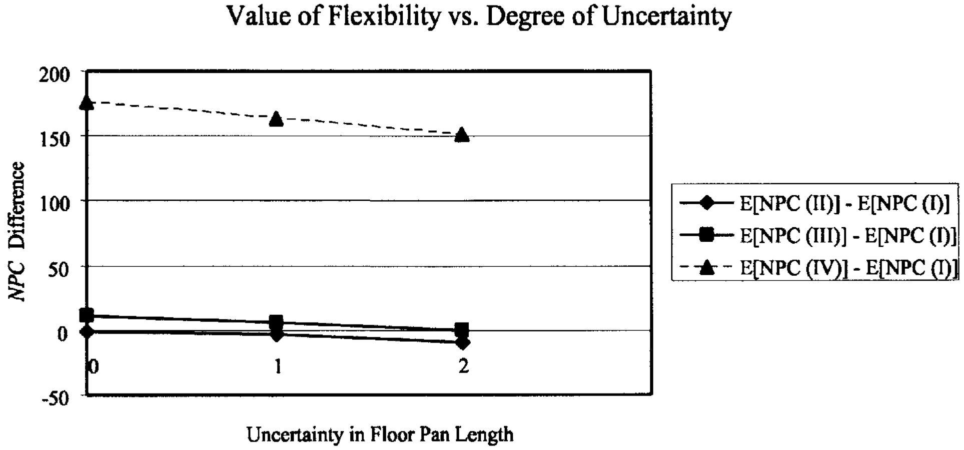


Figure 4-9: Value of Floor Pan Flexibility

The abscissa represents the degree of uncertainty in the floor pan lengths. The floor pan lengths can be certain for both long and short floor pans (degree = 0), uncertain for one of the floor pans, long or short (degree = 1), or uncertain for both floor pans (degree = 2). The ordinate represents the difference between the average cost expenditure of flexible designs (Design II, III, and IV) and the inflexible design (Design I). A negative value indicates an overall cost savings of the particular design alternative with respect to Design I. As observed in Figure 4-9, it is clear that flexibility has more value as the degree of uncertainty increases.

4.2.6 Discussion

The analysis results reveal important issues that must be considered when designing flexible platform components. They are: the way flexibility is incorporated into the component, the degree of flexibility, and the production volume ratio trend between variants in the product family.

First, the way flexibility is embedded into a component has very significant economic consequences in terms of expected net present cost over wide production volume ratio range. Design I and Design II were sensitive to the production volume ratio, while Design III and IV were economically robust to uncertain production volume ratios, due to small differences in long and short floor pan manufacturing costs.

Second, consideration must be given to the degree of future uncertainty. As demonstrated in previous section, the value of flexible designs increased as the degree of uncertainty increased. However, Design IV, the design with "continuous" flexibility, was too expensive and it failed to give the best return even when the degree of uncertainty increased. However, as the frequency of design change increases, Design IV will be more valuable, since its switch cost is zero.

Finally, the future trend of the production volume ratio between variants in the same product family is an important factor. When the initial production volume ratio is near the crossover point (shown in Figure 4-8), the future production volume ratio trend must be observed carefully in order to select the best design. In this case study, while Design III was the most cost efficient option over most production volume ratio, it did not do well due to the volume ratio shift towards the region where other designs (Design I and II) are more efficient.

The case study provides a stepping-stone for flexible complex systems design (e.g. product platforms). For critical elements in the complex system, the architect can apply the knowledge and insight from this study to incorporate flexibility into those elements. As result, complex systems can respond to future uncertainties more easily. However, one must first identify critical elements in the system, then observe their effect to the system when they change to respond to uncertainty. This is not covered in the case of single component design, but is addressed in Chapter 5.

4.3 Chapter Summary

This chapter presented a case study of flexible platform component design. Embedding flexibility allows manufacturers to respond to changing market needs with a minimum increase in investment costs and complexity. Once important product platform criteria and future uncertainties are identified, several flexible design alternatives are generated. Each design alternative is optimized for minimum cost expenditure while satisfying performance constraints. Uncertainty analysis is performed to determine the best design alternative. In the case study, flexible design alternatives for a vehicle floor pan are generated and evaluated for lifetime cost expenditure under uncertain demand and uncertain geometric specifications.

Results revealed that *how* flexibility is built into the component has significant economic consequences over the lifetime of the platform component. Additionally, it is demonstrated that as the degree of future uncertainty increases, the value of component-embedded flexibility increases. Analysis also demonstrated that too much flexibility may not result in the best economic performance, which gives rise to the question "what is the optimal degree of flexibility?" Production volume trends for component variants are very important factors to consider when there are several competing flexible design alternatives. In Chapter 5, a full-scale case study is presented for a vehicle platform, where a BIW must be made flexible to a specified set of future uncertainties, using knowledge gained from the single component design.

Chapter 5

Case Study: Automotive Vehicle Platform Design

5.1 Case Study Background

In Chapter 3, a new flexible platform design process is introduced. This chapter demonstrates the proposed design process framework through a new automotive vehicle platform case study, where the new platform must accommodate a family of vehicle variants, and be flexible to deal with future uncertainties, using common and flexible elements.

A major automotive company is planning to add a new product platform to its portfolio of platforms. The new platform will accommodate three vehicle variants, each belonging to a distinct vehicle market segment defined by the company. All three variants are passenger sedans. Also, the new platform will replace two older platforms that were bases for aforementioned vehicle variants. Additionally, three vehicles will have different requirements in styling, production volume, and certain key design parameters, including the length of the wheelbase. Table 5.1 shows the initial production volume and wheelbase specifications for three vehicle variants.

Since the new platform must accommodate vehicle models which were originally produced from two platforms, the bandwidth of the vehicle platform may be increased. Additionally, the new platform must be flexible enough to accommodate the

Table 5.1: Individual Vehicle Information

Vehicle Variants	p_1	p_2	p_3
Annual Production Volume	280,000	125,000	60,000
Wheelbase	Short	Short	Long

initial vehicle variant differentiation, styling, and uncertain changes in the future. To achieve these objectives, the system architect must identify a critical subset of vehicle elements, incorporate flexibility into these elements to design the flexible vehicle platform, and evaluate the flexible design under various degrees of uncertain scenarios to determine if flexible design has more value than the inflexible design. In subsequent sections of this chapter, the process presented in Chapter 3 is demonstrated. In this case study, a Body in White (BIW), an important vehicle sub-system, is investigated in detail. At the end, the final BIW product platform elements are defined, along with recommendation on when to implement such flexible BIW platform design.

5.2 Step I: Identify Market, Variants, and Uncertainties

5.2.1 Market Segments

The automotive market is divided into several market segments, each market segment clustered according to the type, size, and price of vehicle. For the specific company in the case study, the vehicle market segment is initially divided into five different segments, grouped according to vehicle type, such as sedan, sport, utility, pickup and van. Each segment is then further divided into smaller segments, according to vehicle size and price. Figure 5-1 shows all of the vehicle market segments, with further sub-division of sedan market segments into smaller segments.

The vehicle market segment set $\mathcal{M}_{\text{veh}}$ can be expressed as:

$$\mathcal{M}_{\text{veh}} = \left[M_{\text{ULXSDN}}, M_{\text{PLXSDN}}, M_{\text{LLXSDN}}, \ldots\right], \tag{5.1}$$

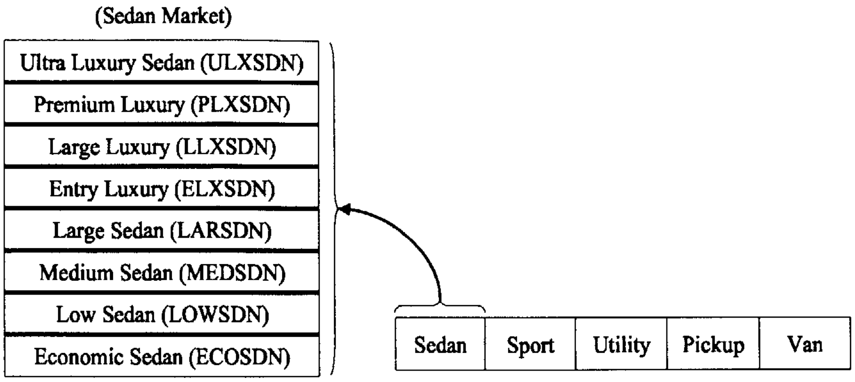


Figure 5-1: Automotive Market Segmentation

where each market segment is mathematically expressed as ranges of customer preferred attributes set $\mathbf{J}_A$ and the price P, as described in Equation (3.4). For automobiles, there are several attributes that influence customers' preferences for certain classes of vehicles. A detailed discussion of $\mathbf{J}_A$ for this case study is presented in later sections.

5.2.2 Product Variants

Since all three candidate vehicle variants are sedans assigned to different sedan market segments, the case study will closely focus on sedan market segments in particular. Let's define the product family $\mathcal{P}_{\text{veh}}$ as:

$$\mathcal{P}_{\text{veh}} = [p_1, p_2, p_3], \tag{5.2}$$

where each p_i in set $\mathcal{P}_{\text{veh}}$ is described by specific values of $\mathbf{J}_A$ and P. Detailed explanations of $\mathbf{J}_A$ and P for this automotive market is presented in the next section. Three variants are positioned in following market segments:

Table 5.2: Market Segment Designation for Each Product Variant p_i

Variant	$M_{\text{veh},i}$	Market Segment
p_1	M_{MIDSDN}	Mid Size Sedan
p_2	M_{LARSDN}	Large Sedan
p_3	M_{LLXSDN}	Large Luxury Sedan

For each p, the lower and upper limits of $\mathbf{J}_A$ is established by the boundary of its assigned market segment $M_{\text{veh},i}$. Specific values for lower and upper limits of $\mathbf{J}_A$ for each market segment $M_{\text{veh},i}$ is listed in Table B.3 in Appendix B.

5.2.3 Uncertainties

With market segments $\mathcal{M}_{\text{veh}}$ and the vehicle variants set $\mathcal{P}_{\text{veh}}$ defined, the last task in this step is to identify a set of uncertainties $\mathcal{U}_{\text{veh}}$, where each uncertainty u is related to the product platform and family in one way or another. In this case study, the following set of uncertainties is defined:

$$\mathcal{U}_{\text{veh}} = \begin{bmatrix} D_{\mathcal{P}}(t) & S_{\mathcal{P}}(t) \end{bmatrix}. \tag{5.3}$$

$D_{\mathcal{P}}$ is the future demand of the vehicle family $\mathcal{P}$ as a function of time t, and $S_{\mathcal{P}}$ is the styling change of the vehicle family as a function of time t. The identified uncertainty set $\mathcal{U}_{\text{veh}}$ will be used to design and evaluate a flexible product platform through the case study.

5.3 Step II: Determine Critical Key Attributes and Design Variables

5.3.1 Key Attributes

For automobiles, the customer-preferred set $\mathbf{J}_A$ has several attributes. Many of the attributes are listed in Figure 5-2. Another useful set of vehicle attributes are published by Cook [16].

Some attributes are related directly to vehicle performance, and some attributes are "perceived" by customers. From these attributes, four attributes related to the uncertainties $\mathcal{U}_{\text{veh}}$, are identified. They are:

$$\mathbf{J}_{\mathcal{U}_{\text{veh}}} = [RM,\ IE,\ FE,\ AC_{50\text{ - }70}] \tag{5.4}$$

Performance Attributes	Customer Perceived Attributes	Other Attributes
50 – 70 mph Acceleration ($AC_{50\text{-}70}$) Fuel Economy (*FE*) Reliability (JD Powers) Towing Capacity Turning Radius	Brake Pedal Feel Ease of Ingress/Egress (*IE*) Handling on Curves Interior Quietness Passenger Roominess (*RM*) Quality of Workmanship Ride Visibility	Price (P)

Figure 5-2: Customer Preferred Vehicle Attributes

RM is customer perceived vehicle roominess, IE is the ease of front ingress/egress, FE is the fuel economy, and AC_{50-70} is the acceleration time interval from 50 to 70 mph. RM and IE are scores between 0 - 100, and represents the percentage of customers who are either "very satisfied" or "satisfied" with a specific vehicle. These scores are past data, obtained through a market survey of customers who owned the vehicle for six months or less. RM and IE, are selected as key attributes which are related to one of the uncertainties identified - styling. Vehicle styling is mostly influenced by the shape of BIW. Similarly, RM and IE are attributes which are also influenced by the BIW shape in key places as well. Since the styling cannot be quantified easily, RM and IE are used as constraint attributes that must maintain certain level of scores, while styling changes in the future, thus addressing the styling uncertainty.

Another uncertainty addressed is vehicle family demand. For individual vehicle variants, its demand is determined by values of vehicle attributes listed in Figure 5-2. However, in this case study, four attributes - FE, AC_{50-70}, RM and IE - are investigated in detail. The reason for selecting these attributes are: 1) These four attributes are the most important attributes for market segments where $\mathcal{P}_{\text{veh}}$ are targeted, and 2) FE and AC_{50-70} are vehicle performance attributes affected by the vehicle size, thus affected by RM and IE. Other attributes values, not included in $\mathrm{J}_{\mathcal{U}_{\text{veh}}}$, are treated as constants in this case study.

5.3.2 Design Variables for Key Attributes

Once the set of key attributes $\mathbf{J}_{\mathcal{U}_{\text{veh}}}$ is identified, the next step is to establish the mapping relationship between the attribute space and the system-level design variable space, described by the system-level design variable set $\mathbf{X}_{\mathcal{U}_{\text{veh}}}$. For many engineering performance attributes, mapping from the attribute space to the system-level design space can be straightforward and analytical. However, in this case study, two attributes, RM and IE, are customer perceived attributes, and establishing the analytical relationship between two spaces is no longer clear.

In order to identify relevant system-level design variables for RM and IE, the principal component analysis [22, 40] is used to develop the attribute translator model. The theoretical formulation of the analysis is well documented in aforementioned references. In this thesis, a brief description of the analysis for two attributes (IE and RM) is presented.

The analysis starts with the assumption that there exists a set of design variables that influences people's perception of vehicle roominess (RM) and ease of front ingress/egress (IE). Shown in Figure 5-3 are relevant system level design variables, identified for each attribute. Dimensions in the figure are SAE (Society of Automotive Engineers) standard dimensions [2], and the explanation of dimensions is listed in the nomenclature section.

The first step is to gather relevant data for different vehicles. RM scores and dimensions for 94 vehicles, produced between 1997 to 2001, are collected for the analysis. For IE scores and dimensions, 57 vehicles, produced between 1995 to 2000, are used. See Appendix A for gathered data. Using collected data, principal components are identified through singular value decomposition. RM and IE scores can then be expressed as linear regression of obtained principal components. IE and RM scores for each p_i in set $\mathcal{P}_{\text{veh}}$ can be expressed as

$$\begin{aligned} IE_i &= f\left(\mathbf{X}_{IE,i}\right) \\ RM_i &= f\left(\mathbf{X}_{RM,i}\right) \end{aligned} \tag{5.5}$$

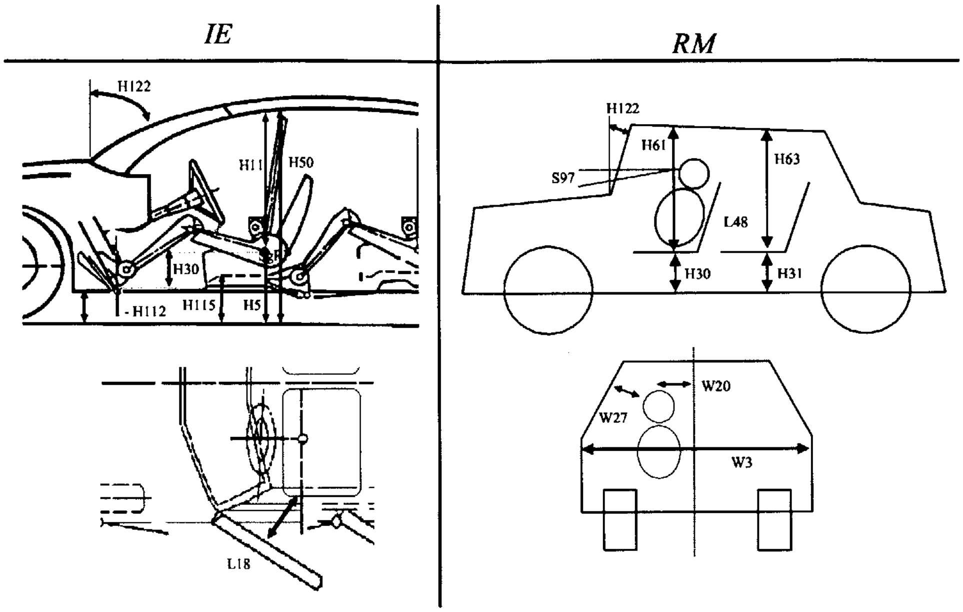


Figure 5-3: System Level Design Variables for *IE* and *RM*

where

$$\begin{aligned} \mathbf{X}_{IE,i} &= [H5_i, H11_i, H30_i, H50_i, H112_i, H115_i, H122_i, L18_i] \\ \mathbf{X}_{RM,i} &= [H30_i, H31_i, H61_i, H63_i, H122_i, L48_i, S97_i, W3_i, W20_i, W27_i]\,. \end{aligned} \tag{5.6}$$

These two models and important dimensions were developed and found by Dr. Sangdon Lee at GM (2002). Once the equations for RM and IE are defined, the next step is to establish the relationship between RM, IE, FE and AC_{50-70}. It is observed that RM and IE affects FE and AC_{50-70} through changes in mass and aerodynamic drag. The statistical analysis results show that for one point improvement in RM (in 0 - 100 scale), the vehicle mass increases by about 25 lbs, and for one point improvement in IE, approximately 12.5 lbs of mass is added to the total vehicle mass. Aerodynamic drag is also affected by RM and IE, since improvement in RM and IE scores generally result in a larger vehicle, which increases the frontal area and the aerodynamic drag of the vehicle. Using the statistical analysis results, FE and AC_{50-70} for each p_i in set $\mathcal{P}_{\text{vch}}$ can be expressed as functions of IE and RM:

$$\begin{aligned} FE_i &= f\left(IE_i, RM_i\right) \\ AC_{50-70,i} &= f\left(IE_i, RM_i\right). \end{aligned} \tag{5.7}$$

After establishing coupling equations for identified attributes, now is the time to define independent variables, dependent variables, and constants. As it is shown in Figure 5-3, RM and IE share many system-level design variables, which are themselves coupled (similar to a coupled system example, presented in Chapter 1 in FRDP form). The following design variables are selected as independent design variables for each p_i in $\mathcal{P}_{\text{veh}}$, which will be used for optimization in Step III:

$$\mathbf{x}_{\mathcal{U}_{\text{veh}},i} = \left[L48_i,\ W3_i,\ W20_i,\ H5_i,\ H50_i,\ \mathrm{P}_{w,i}\right]. \tag{5.8}$$

- $L48$: One vehicle variant is a long wheelbase vehicle, while the other two vehicles have short wheelbases. Differences in wheelbase dimension require different $L48$ for long and short wheelbase vehicles. One needs to determine values of $L48$ that can bring the maximum revenue to the vehicle family through optimum RM scores.
- $W3$: From the principal component analysis, it was determined that $W3$ is one of the most sensitive dimensions that affects RM.
- $W20$: Another design variable that affects RM.
- $H50$: The overall BIW height dimension that highly affects IE and RM through influencing several important dependent variables.
- $H5$: Important dimension for IE.
- P_w: Weighted Average Price of a Vehicle Variant.

The individual variant's price $\mathrm{P}_{w,i}$ is the weighted average price of the variant's different trim level. For some product variants, there are many different trim levels (e.g. V6 engine variant, V8 engine variant, manual transmission, automatic transmission), all with different prices. The $\mathrm{P}_{w,i}$ is obtained by:

$$P_{w,i} = \sum_{j=1}^{n_{\text{trim}}} \frac{ms_{ij} P_j}{ms_i} \tag{5.9}$$

where n_{trim} is the number of different trim levels for vehicle variant i, ms_{ij} is the total market share of j^{th} trim level vehicle for i^{th} variant, P_j is the price of j^{th} trim level vehicle, and ms_i is the total market share for the i^{th} vehicle variant.

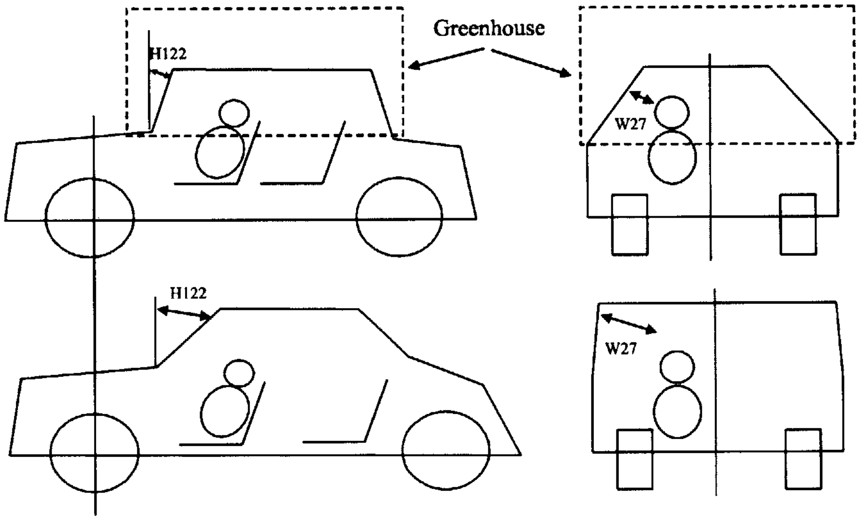


Figure 5-4: Vehicle Styling Differentiation with $W27$ and $H122$

There are several dependent variables which are expressed as functions of independent design variables, defined in Equation (5.8). Dependent variables are $H11$, $H30$, $H31$, $H61$, $H63$, and $S97$. The last task is to identify constants, which are either common or unique for each vehicle variant. They are $L18$, $W27$, $H112$, $H115$, and $H122$. $L18$, $H112$, and $H115$ are the same for all vehicle variants. $W27$ and $H122$ are variant-unique, for styling differentiation purposes through different greenhouse (passenger compartment above the belt line) design, as shown in Figure 5-4.

5.4 Step III: Optimize Product Family and Platform Bandwidth

5.4.1 Product Family Optimization

In Chapter 2, the system goal of the product platform is to provide a system to a company to maximize profit through product variety and cost reduction. To maximize the profit, the first task is to position each vehicle variant of the vehicle family $\mathcal{P}_{\text{veh}}$ in the corresponding market segment $M_{\text{veh},i}$ within the established market segment set $\mathcal{M}_{\text{veh}}$ to generate maximum revenue as a product family. Using relationships defined in previous sections, the revenue maximization problem for the vehicle variant set $\mathcal{P}_{\text{veh}}$ can be formulated as shown in Equation (5.10).

$$\begin{aligned} &\text{maximize } \sum_{i=1}^{3} R_i;\ R_i = ms_i\left(\mathbf{J}_{\mathcal{U}_{\text{veh}},i}, \mathrm{P}_{w,i}\right)\mathrm{P}_{w,i} D_T \\ &\text{with respect to } \left\{\mathbf{X}_{\mathcal{U}_{\text{veh}},i}, \mathrm{P}_{w,i}\right\} \\ &\text{subject to } \mathrm{h}\left(\mathbf{J}_{\mathcal{U}_{\text{veh}},i}\left(\mathbf{X}_{\mathcal{U}_{\text{veh}},i}\right)\right), \mathrm{g}\left(\mathbf{J}_{\mathcal{U}_{\text{veh}},i}\left(\mathbf{X}_{\mathcal{U}_{\text{veh}},i}\right)\right) \end{aligned} \tag{5.10}$$

In the equation, the individual vehicle market share ms_i is a critical value that cannot be easily obtained. This information is obtained through a proprietary market simulation software, which simulates the North American automotive market for the 2002 model year, as a function of aforementioned vehicle attributes. The market simulation model is integrated into the overall optimization framework with an Excel based attribute translator model and commercial optimization software (iSIGHT). This is necessary to yield realistic results from the market model. One of the limitations of the market model is that if it is not constrained through engineering models, it results in a unrealistic solution (e.g. it would suggest a large SUV with 50 mpg fuel economy as one of the top selling vehicle variants). Another issue, which is outside of this research scope, is the simulation model accuracy. For the sub-models in the framework, its results are within their tolerance limits of expected values.

For the optimization variable constraints, lower and upper bounds of independent design variables and corresponding vehicle attributes are listed in Appendix B. Figure 5-5 shows the simulation model framework for the product family revenue optimization.

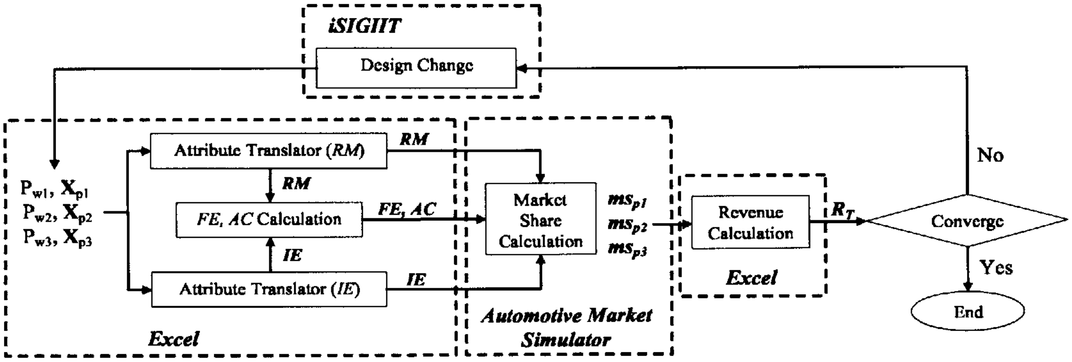


Figure 5-5: Revenue Optimization Framework for Vehicle Family $\mathcal{P}_{\text{veh}}$

Using the developed optimization framework, the $\mathbf{X}_{\mathcal{U}_{\text{veh}}}$ for each vehicle variant in the product family $\mathcal{P}_{\text{veh}}$ is optimized for maximum product family revenue. Once all optimized attribute values and design variable values are determined, the vehicle platform bandwidths, both in design space and the attribute space, are determined.

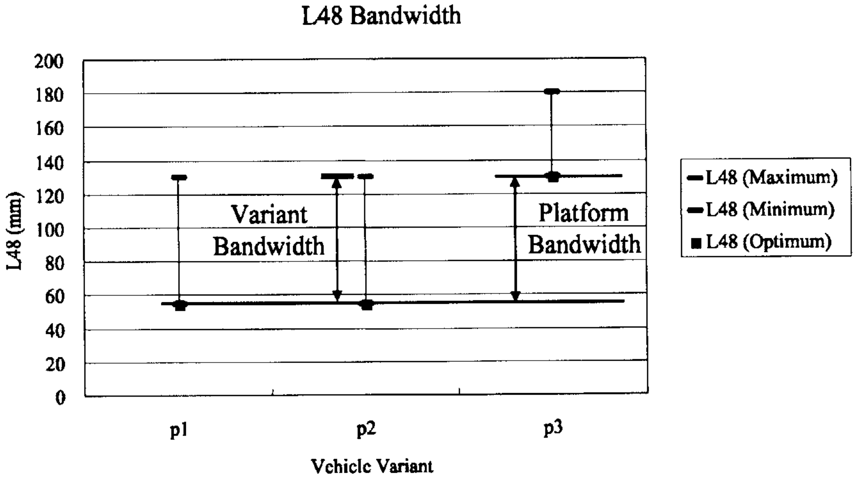


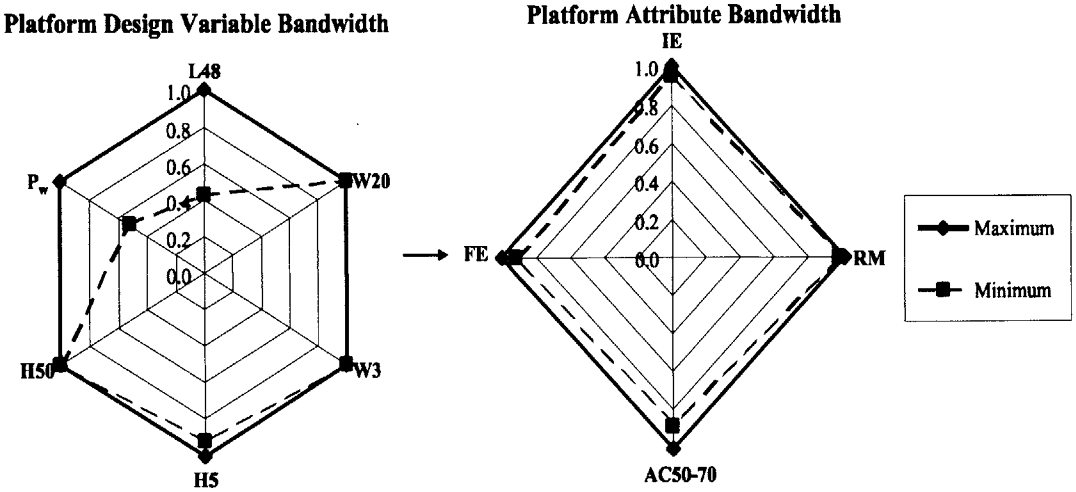
Figure 5-6: $L48$ Bandwidth for Vehicle Variants and Platform

Figure 5-6 shows bandwidth of design variable $L48$ for each vehicle variant and the optimized value. Taking the maximum and minimum $L48$ values, the bandwidth of this design variable for the vehicle family is established. Bandwidth plots for all independent design variables are presented in Appendix B. Since there are six independent design variables, their bandwidths can be shown in one chart, using the radar chart format. Tables 5.3 lists optimized values (normalized) of $\mathbf{X}_{\mathcal{U}_{\text{veh}}}$ and $\mathbf{J}_{\mathcal{U}_{\text{veh}}}$. They are normalized with respect to the maximum value of each design variable among three vehicle variants.

Table 5.3: Optimized $\mathbf{X}_{\mathcal{U}_{\text{veh}}}$ and $\mathbf{J}_{\mathcal{U}_{\text{veh}}}$ for $\mathcal{P}$ (Normalized)

Variants	$L48$	$W20$	$W3$	$H5$	$H50$	P_w	IE	RM	AC_{50-70}	FE
p_1	0.42	1.00	1.00	0.92	1.00	0.52	0.95	0.97	0.89	1.00
p_2	0.42	1.00	1.00	1.00	1.00	0.61	1.00	0.99	0.99	0.99
p_3	1.00	1.00	1.00	0.95	1.00	1.00	0.97	1.00	1.00	0.91

Figure 5-7 shows the radar chart for platform bandwidth (normalized) in both design variable and attribute spaces. The origin indicates the absolute zero, meaning that the value of the design variable is zero.


Platform Design Variable Bandwidth

Platform Attribute Bandwidth

Figure 5-7: Design Variables and Attributes Bandwidths for Vehicle Family $\mathcal{P}_{\text{veh}}$

It can be seen that for some design variables, values for all vehicle variants are either the same or very close, indicating very small or no bandwidth required for those design variables. Three independent variables, $H5$, $L48$ and P_w require significant bandwidths. Design variable P_w is the domain of the marketing or planning, and will be used during the uncertainty analysis phase (Step VII) to calculate the overall product family profit. The next task is to perform a sensitivity analysis of the optimum solution, to identify additional design variables which are sensitive.

5.4.2 Sensitivity Analysis

The sensitivity of the product family revenue with respect to the product design variable set $\mathbf{X}_{\mathcal{U}_{\text{veh}}}$ for p_1, is shown in Figure 5-8.

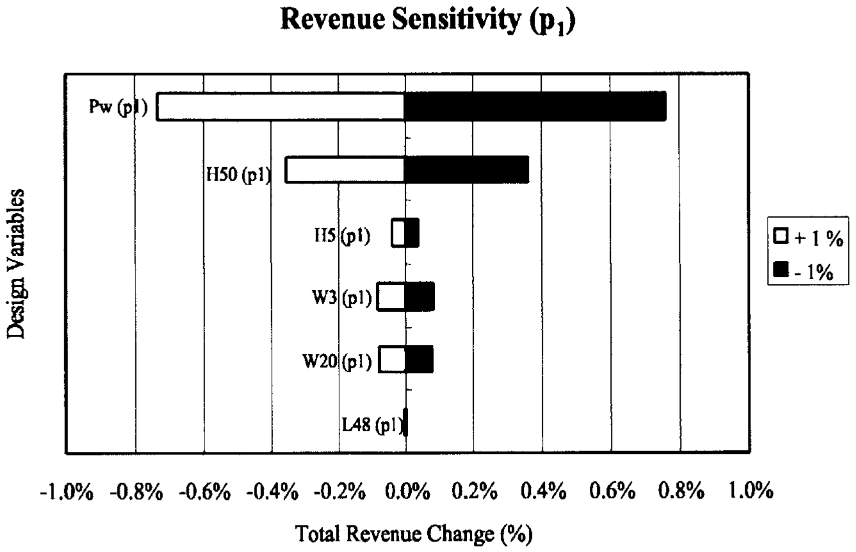


Figure 5-8: Revenue Sensitivity Chart (p_1)

The sensitivity chart shows the percent change in total vehicle family revenue per percent change in each design variable. First, and foremost, it is noted that, with exception of $L48$, all other design variables are negatively correlated with total revenue. It means that when these design variable values increase, it decreases total family revenue. The reason for this phenomenon is that as the vehicle size increases to improve IE and RM, it degrades FE and AC_{50-70} values, resulting in decreased market share and total family revenue.

Sensitivity analysis results show that the weighted average vehicle price P_w is the most sensitive parameter that influences the entire vehicle family revenue. However, since we are interested in system-level design variables directly related to customer attributes, focus will be on geometric system-level design variables. The most sensitive design variable is $H50$, the upper body opening to ground - front. It has significant affect on total revenue, especially for p_1. This is due to the high market share commanded by p_1. Detailed sensitivity analysis results are presented in Appendix B.

$H50$ is a highly sensitive design variable since it affects several vehicle attributes, which in turn, affects the total revenue generated. However, referring back to Table 5.3, $H50$ values for all three vehicle variants are the same, thus not requiring any differentiation. It is also observed that the optimized values of $H50$ are all located at the lower bound of the design variable value, indicating it is an active constraint, which will decrease even more if the constraint was not present. This is due to the affect of $H50$ on FE and AC_{50-70}. If $H50$ decreases, it negatively affects RM and IE. However, FE and AC_{50-70} improves (due to the vehicle size reduction), resulting in overall revenue increase of the vehicle variant. Even though this particular dimension does not require any differentiation currently, incorporating flexibility for this particular dimension may be advantageous. The reason is that when the customer's preference changes in the future (e.g. they want roomier car, or cars with better ingress/egress features), the company can respond to this uncertainty with much more ease.

In this section, results for optimization and sensitivity analysis of the vehicle family $\mathcal{P}_{\text{veh}}$ are presented. Results show that some design variables require bandwidths in order to achieve the desired vehicle performance level, thus achieving the maximum revenue. Some variables are highly sensitive, becoming a desirable candidates to incorporate flexibility. Once these critical design variables are identified, they need to be mapped to the physical space, where the critical platform elements must be identified to incorporate flexibility. For a single component, this is relatively easy, but for complex systems, such as product platforms, it may be very difficult. Step IV demonstrates this mapping process.

5.5 Step IV: Identify Critical Elements

5.5.1 Identifying Basic Elements

In Section 5.4, the bandwidths of the vehicle platform in the attribute and design variable space are established through vehicle family revenue optimization. Figure 5-9 shows the independent design variables and differentiating constants ($H122$, $W27$).

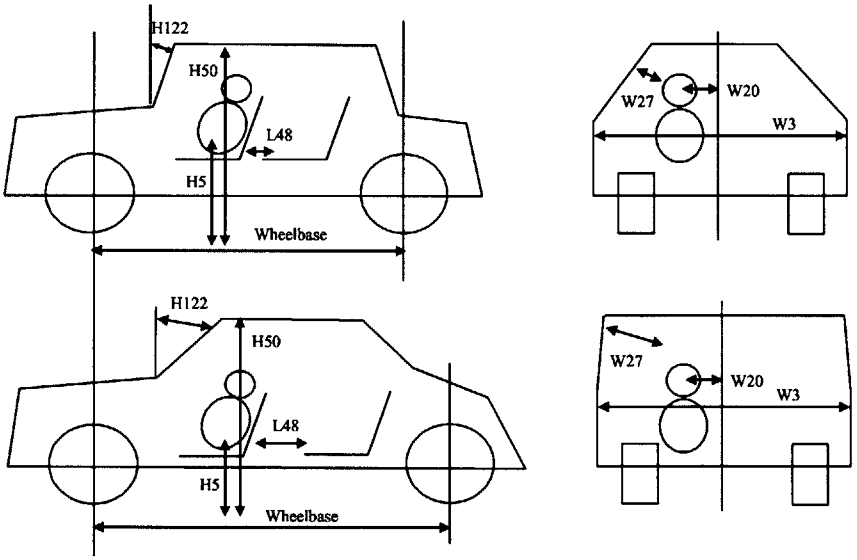


Figure 5-9: Design Variables Requiring Flexible Bandwidth

In the beginning, it is stated that this case study will investigate BIW in detail. One then needs to select design variables which are BIW related and study the effect of those variables on the BIW. To this end, four design variables are selected. They are $L48$, $W27$, $H122$, and $H50$.

In Section 5.1, it is initially stated that vehicle variants have two different wheelbases. This difference in wheelbase is reflected in the initial $L48$ lower and upper limit declaration. Then $L48$ for each variant is optimized for RM which resulted in maximum revenue. $W27$ and $H122$ require differentiations to achieve styling distinction of product variants in the product family. $H50$ is a very sensitive dimension, if made flexible, can add value under future uncertainty. $H5$ is a design variable related to interior seating, so it is not selected. For $W3$ and $W20$, results of the optimization yielded values which are either same or very close. Desired ranges of these values can be achieved through the differentiation of interior trim. Therefore, $W3$ and $W20$ are omitted from this analysis. Once BIW related design variables and their bandwidths are decided, change propagation analysis for these variables need to be performed to identify critical BIW elements.

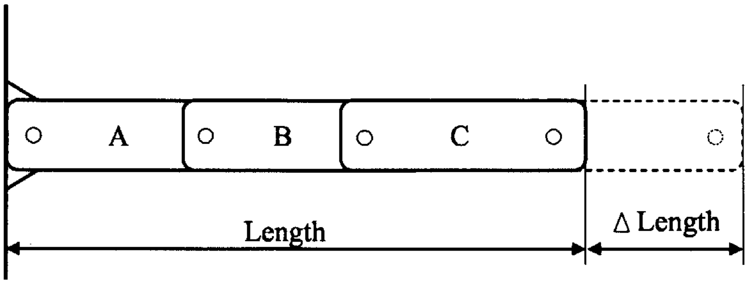


Figure 5-10: Example of Non-Unique Lever Design

The challenge of this phase is the non-uniqueness of the physical elements space. Identified design variables can be mapped to the physical elements space in many ways, generating many non-unique solutions. Figure 5-10 shows a simple example of such case. The lever is constructed out of smaller levers A, B, and C to meet the length requirement. If the length must be increased by ΔLength, it can be achieved in number of ways. Only one lever's length can be changed (A, B, or C), or it can be combination of two levers (A + B, A + C, B + C), or it can be combination of all three levers. To address this problem, the system architect must decompose the system to bound the physical element space, thus constraining the physical space with which one must work with.

The BIW of a passenger car is shown in Figure 5-11, with proposed system-level decomposition. It is decomposed into a three box configuration. The front box is the motor compartment, the second box is the passenger compartment, and the last box is the cargo compartment. Since the key attributes mentioned, RM and IE respectively, are attributes that are directly related to the passenger compartment in addition to the styling aspect, the system architect must investigate the passenger compartment to identify critical elements as candidates for incorporating flexibility.

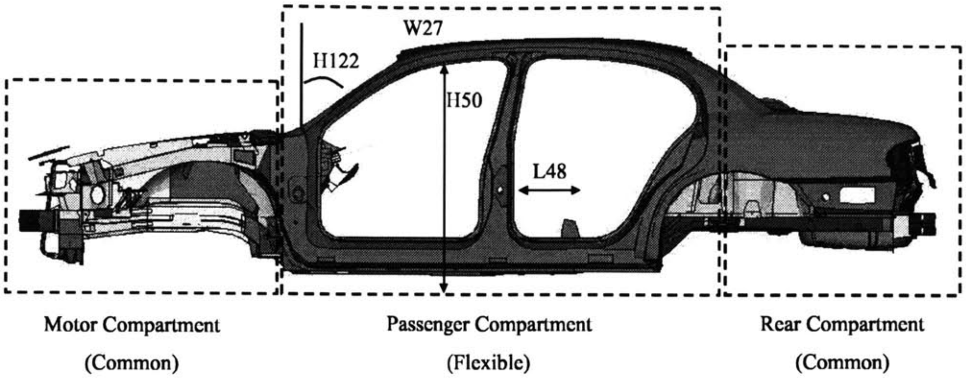


Figure 5-11: Body in White (BIW) of a Passenger Sedan

The motor compartment and cargo compartment are assumed to be common.

Once the boundary of the "flexible" domain is established, components in the BIW structure need to be identified. Body components can be decomposed down to several levels. In this case study, the BIW is decomposed down to its individual component level, where individual components are end-items, supplied to the BIW assembly line directly. The architecture of the body is a Body Frame Integral structure, consists of steel body. There are 21 components (excluding the motor compartment components) which are part of passenger and cargo compartments. Next, the connective relationship between individual components needs to be established and expressed in DSM format. The CAD data of a current production vehicle (shown in Figure 5-12) is used to construct the DSM (shown in Figure 5-13). This is the CAD model of current p_2. Figure 5-12 is the same CAD model as shown in Figure 5-11 without the front motor compartment.

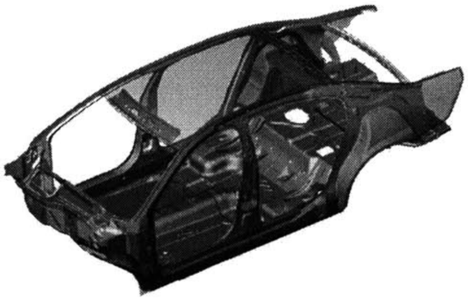


Figure 5-12: CAD Model of Current p_2

Components Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Body Outer Panel (RH) ASM	1	■		1																1		
Body Outer Panel (LH) ASM	2		■		1															1		
Body Inner Panel (RH) ASM	3	1		■		1		1		1		1							1		1	1
Body Inner Panel (LH) ASM	4		1		■		1		1		1		1						1		1	1
Front Body Hinge Panel (RH) ASM	5			1		■				1					1							
Front Body Hinge Panel (LH) ASM	6				1		■				1				1							
Center Pillar Support (RH) ASM	7			1				■		1												
Center Pillar Support (LH) ASM	8				1				■		1											
Rocker Inner Panel (RH) ASM	9			1		1		1		■					1	1	1					
Rocker Inner Panel (LH) ASM	10				1		1		1		■				1	1	1					
Rear Wheel Housing (RH) ASM	11			1								■					1	1				
Rear Wheel Housing (LH) ASM	12				1								■				1	1				
Plenum Panel ASM	13													■	1							
Dash Panel ASM	14					1	1			1	1			1	■	1						
Front Floor Panel ASM	15									1	1				1	■	1					
Rear Floor Pan ASM	16									1	1	1	1			1	■					
Rear Reinforcement A	17											1	1					■				
Rear Reinforcement B	18			1	1														■			
Roof Panel	19	1	1																	■	1	1
Front Roof Support	20			1	1															1	■	
Rear Roof Support	21			1	1															1		■

Figure 5-13: Design Structure Matrix of BIW Components

For achieving required bandwidths for previously specified system-level design variables, the architect must 1) identify components that need to change, and 2) how such changes propagate throughout the BIW. To see the change propagation more easily, network representation is constructed (see Figure 5-14). The link represents a physical connection, where each component is connected to another by spot welding.

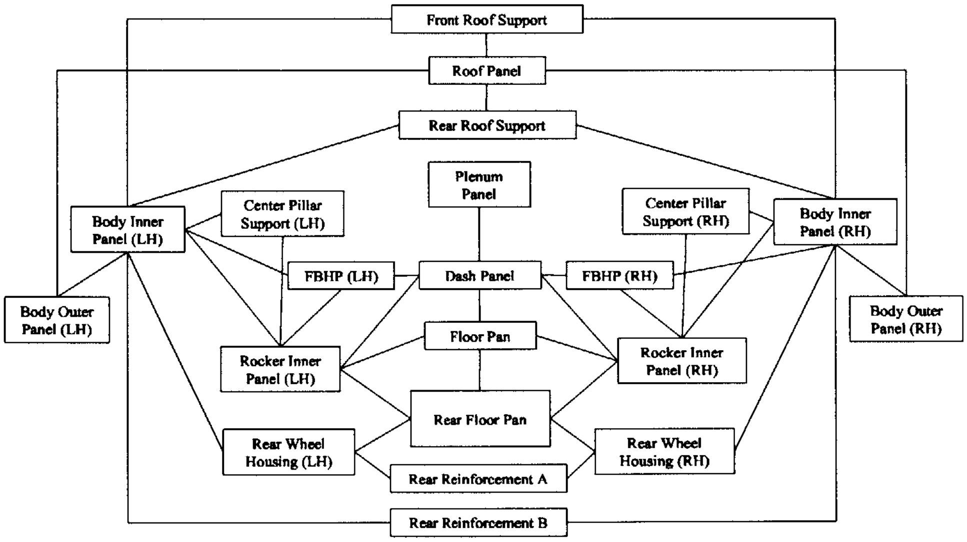


Figure 5-14: Network Representation of Body in White

There are four system-level design variables, mentioned previously, that require differentiations for each vehicle variant. Additionally, styling uncertainty is a key factor that causes body change to occur. For each specified design variable change, one must identify multipliers and carriers that send out significant amount of change to other components. Once these components are identified, the architect can design them to reduce the degree of change propagation or switch cost by incorporating flexibility into the multiplier/carrier component itself or components that the multiplier/carrier component is propagating changes to. The following section presents change propagation analysis for specified design variable changes.

5.5.2 Change Propagation Analysis: Lengthwise and Styling

As a result of revenue optimization in Step III, it was determined that the vehicle platform must achieve bandwidth for *L*48 - the second row knee clearance. This requires BIW to be differentiated in the length direction through different wheelbase. Another source of the length change comes from the styling differentiation in the lengthwise direction. We need to investigate cases where length and styling requirement changes in the future, within the optimized *L*48 bandwidth.

The change originates from the body outer panel, the outermost body component that is perceived by the customer, and the most important component for the vehicle styling. The change propagates throughout the BIW, and the final change propagation state is shown in the DSM form in Figure 5-15.

Component Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Change Received
Body Outer Panel (RH) ASM	1	■																					0
Body Outer Panel (LH) ASM	2		■																				0
Body Inner Panel (RH) ASM	3	1		■																			1
Body Inner Panel (LH) ASM	4		1		■																		1
Front Body Hinge Panel (RH) ASM	5					■																	0
Front Body Hinge Panel (LH) ASM	6						■																0
Center Pillar Support (RH) ASM	7							■															0
Center Pillar Support (LH) ASM	8								■														0
Rocker Inner Panel (RH) ASM	9			1						■													1
Rocker Inner Panel (LH) ASM	10				1						■												1
Rear Wheel Housing (RH) ASM	11											■											0
Rear Wheel Housing (LH) ASM	12												■										0
Plenum Panel ASM	13													■									0
Dash Panel ASM	14														■								0
Front Floor Panel ASM	15									1	1					■							2
Rear Floor Pan ASM	16																■						0
Rear Reinforcement A	17																	■					0
Rear Reinforcement B	18																		■				0
Roof Panel	19	1	1																	■			2
Front Roof Support	20			1	1															1	■		3
Rear Roof Support	21			1	1															1		■	3
Total Change Propagated Outwards (E_{out})		2	2	3	3	0	0	0	0	1	1	0	0	0	0	0	0	0	0	2	0	0	
CPI		2	2	2	2	0	0	0	0	0	0	0	0	0	0	-2	0	0	0	0	-3	-3	
Component Class		M	M	M	M					Ca	Ca					A				Ca	A	A	

Figure 5-15: Change Propagation DSM for BIW Length Change

It shows CPI values for all components affected by the length change, and classifies each component into four pre-defined classes, depending on the value of CPI. A total of ten components are affected by the lengthwise direction change. Once these components are identified, then the switch cost for making such a change needs to be calculated. Switch related investment costs for all components are calculated using the process based cost model [41]. The investment cost consists of blanking tool investment, stamping tool investment, and welding tool investment cost. Table 5.4 list initial investment costs and BIW length related switch costs for the ten identified components. The assumption is that these components are customized for each vehicle variant, and if there is any changes in BIW, they would be changed as well. Costs are normalized with respect to the initial investment cost of the body outer panel.

Table 5.4: BIW Length Change Related Investment Cost for Critical Components (Same for All Variants)

Component Name	Initial Investment	Switch Cost
Body Outer Panel (RH & LH)	100.0	100.0
Body Inner Panel (RH & LH)	134.3	134.3
Rocker Inner Panel (RH & LH)	45.9	45.9
Floor Pan	120.5	120.5
Roof Panel	39.9	39.9
Front Roof Support	3.5	3.5
Rear Roof Support	3.5	3.5

Figure 5-16 summarizes all change propagation related information into a graphical format. Above the name of a particular component, its component class (for this particular change) and related switch cost is listed.

Once all critical BIW components, with relevant switch costs are identified, this information is used to generate flexible BIW design alternatives in Step V. For detailed comparison of change propagation and economic impacts of inflexible BIW design and flexible BIW design, see Appendix C.

Final comment on the length related change propagation is that the degree of propagation may depend on the magnitude of the dimensional change. For example, if the length changes by only a small amount, only a small portion of BIW component

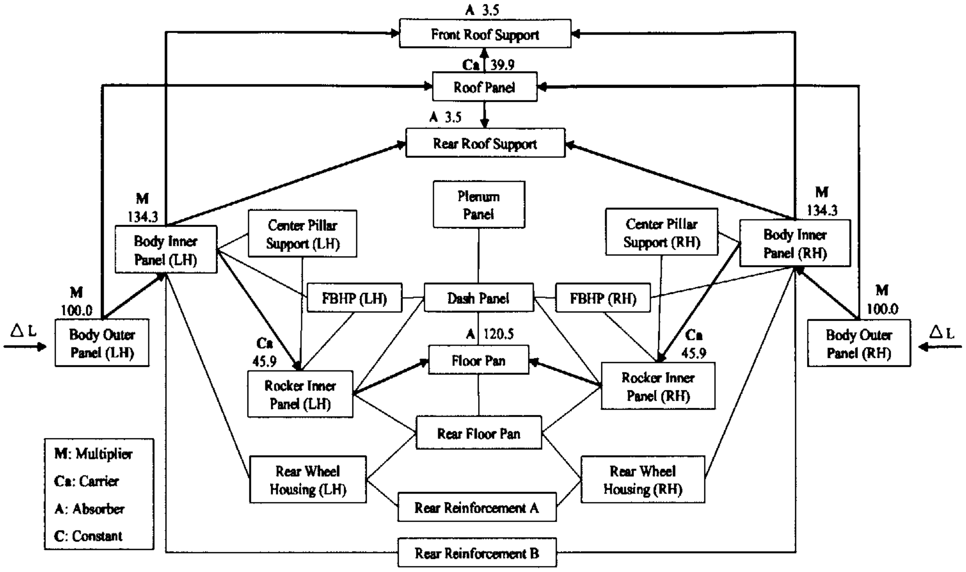


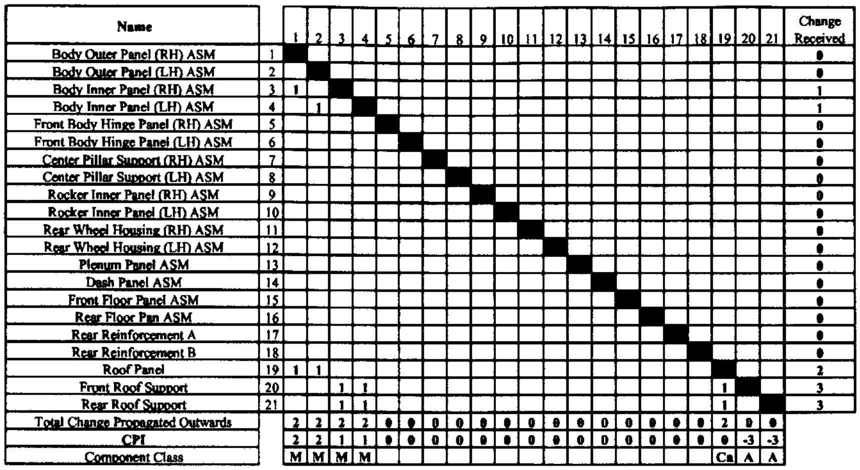
Figure 5-16: Change Propagation for BIW Length and Styling Change

may be affected. However, as the magnitude of length change increases beyond certain threshold, it may require significant structural change, resulting in greater degree of change propagation and possible addition of extra components to accommodate change. This is a very important issue to consider, but is not covered in this thesis.

5.5.3 Change Propagation Analysis: Styling Only

There are three dimensions that affect styling. They are $H50$, $H122$, and $W27$. As seen in Figure 5-9, vehicle styling can be differentiated by changing the greenhouse (vehicle body segment above the belt line) related dimensions, thus not affecting the vehicle length. $H122$ and $W27$ values are unique for each vehicle variant, requiring differentiations in related BIW elements. For $H50$, the optimization results from Step III indicated that it is the same for all three vehicle variants. Therefore, even when the vehicle styling changes, value of $H50$ must remain the same. Change propagation analysis is performed to determine components that are affected by differentiating aforementioned dimensions. Figure 5-17 shows the DSM for change propagation, along with relevant CPI values for components involved.

A total of seven components are affected by such change. If these components



Name		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Change Received
Body Outer Panel (RH) ASM	1	■																					0
Body Outer Panel (LH) ASM	2		■																				0
Body Inner Panel (RH) ASM	3	1		■																			1
Body Inner Panel (LH) ASM	4		1		■																		1
Front Body Hinge Panel (RH) ASM	5					■																	0
Front Body Hinge Panel (LH) ASM	6						■																0
Center Pillar Support (RH) ASM	7							■															0
Center Pillar Support (LH) ASM	8								■														0
Rocker Inner Panel (RH) ASM	9									■													0
Rocker Inner Panel (LH) ASM	10										■												0
Rear Wheel Housing (RH) ASM	11											■											0
Rear Wheel Housing (LH) ASM	12												■										0
Plenum Panel ASM	13													■									0
Dash Panel ASM	14														■								0
Front Floor Panel ASM	15															■							0
Rear Floor Pan ASM	16																■						0
Rear Reinforcement A	17																	■					0
Rear Reinforcement B	18																		■				0
Roof Panel	19	1	1																	■			2
Front Roof Support	20			1	1															1	■		3
Rear Roof Support	21			1	1															1		■	3
Total Change Propagated Outwards		2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	
CPI		2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3	-3	
Component Class		M	M	M	M															Ca	A	A	

Figure 5-17: Change Propagation DSM for BIW Styling Change

are variant-unique and must be redesigned every time styling changes, it will result in significant switch cost. Table 5.5 lists initial investment cost and switch cost for the involved components. Again, the cost is normalized with respect to the initial investment cost of the body outer panel.

Table 5.5: BIW Styling Change Related Investment Cost for Critical Components

Component Name	Initial Investment	Switch Cost
Body Outer Panel (RH & LH)	100.0	100.0
Body Inner Panel (RH & LH)	134.3	134.3
Roof Panel	39.9	39.9
Front Roof Support	3.5	3.5
Rear Roof Support	3.5	3.5

The final state of change propagation is shown in Figure 5-18. The component class, along with its normalized switch cost, is shown above each component involved.

For styling change, propagation analysis results for both inflexible BIW design and flexible BIW design (generated in Step V) are listed in Appendix C.

5.5.4 Critical Elements Selection

From the change propagation analysis, ten components are identified as key components that change as results of required vehicle differentiation and future changes

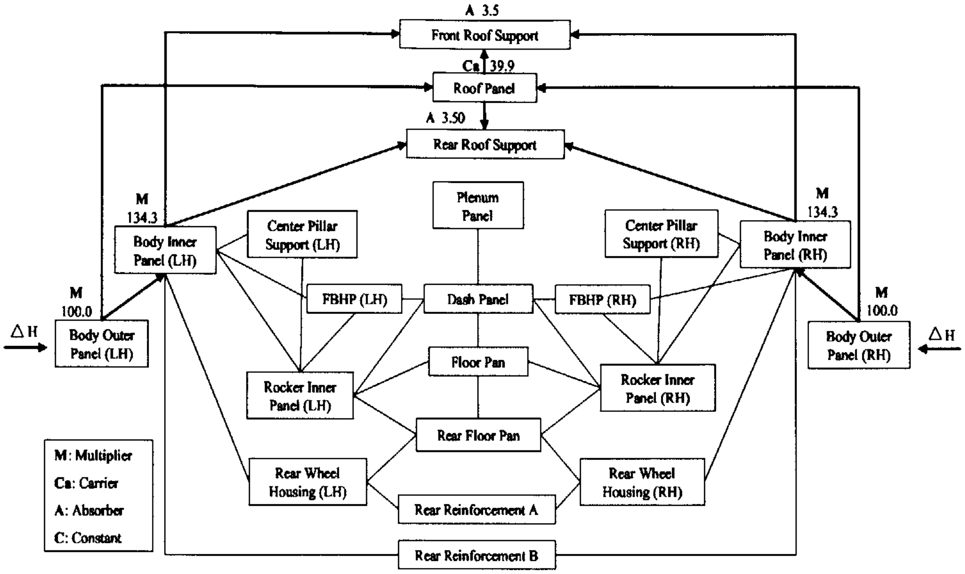


Figure 5-18: Change Propagation for BIW Styling Change

in styling. Table 5.6 summarizes information gathered from the change propagation analysis.

Table 5.6: Critical Components for Flexible BIW Design

Component Name	Class	Switch Cost (Length)	Switch Cost (Styling Only)
Body Outer Panels (RH & LH)	Multiplier	100.0	100.0
Body Inner Panels (RH & LH)	Multiplier	134.3	134.3
Rocker Inner Panels (RH & LH)	Carrier (Length Only)	45.9	-
Floor Pan	Absorber (Length Only)	120.5	-
Roof Panel	Carrier	39.9	39.9
Front Roof Support	Absorber	3.5	3.5
Rear Roof Support	Absorber	3.5	3.5

Four components - body outer and inner panels (RH & LH) - are multipliers for both cases. Switch costs for these components are very high, since every time design changes they must be completely redesigned and tooling reinvested. Four panels are key components that need to be designed to incorporate flexibility. Rocker inner panels are only affected when the vehicle length changes. The floor pan is an absorber by definition, since it does not send out any change to other components. However, to accommodate incoming changes, it requires significant amount of switch cost. The roof panel incurs high investment cost as well. The front and rear roof supports are small components with relatively small switch costs.

For the specified set of critical system-level design variables, it is determined that only ten components need to be changed. These are critical components that, if made flexible, can make the vehicle platform flexible to uncertainties in styling and individual vehicle differentiation. In the next section, the flexible vehicle platform design is presented in detail.

5.6 Step V: Create Flexible Design Alternatives

In Section 5.5, critical BIW components that are affected by the specified uncertainties and attributes are identified through the change propagation analysis. The task is to reduce the magnitude of change propagation through flexible component design, or reduce the economic impact. The knowledge gained about flexible single component design from Chapter 4 is used to incorporate flexibility in identified BIW components.

5.6.1 Passenger Compartment Decomposition Strategy

In order to satisfy the required dimension bandwidths and differentiation in vehicle styling, the following system-level decomposition strategy is proposed to make the BIW flexible to change.

The passenger compartment is decomposed into three sub-compartments. The lower front passenger compartment remain common for all three vehicle variants. The lower rear passenger compartment must be flexible in order to accommodate the design variable bandwidth for $L48$. The upper passenger compartment, also known as the "greenhouse," will be either unique or flexible for differentiation in $W27$, $H122$ and the overall vehicle styling. The decomposition for upper compartment is made right on the vehicle belt line, the line between the door and the window.

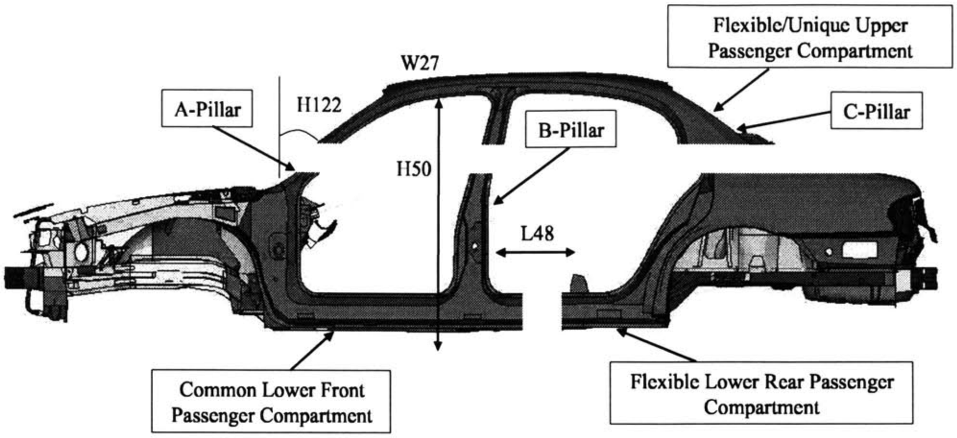


Figure 5-19: BIW System Decomposition Strategy

The vertical decomposition occurs behind the B-pillar, to give flexibility for $L48$ adjustment. Latest models from the Mercedes-Benz, namely E-500 and CLS-500, are good examples of how styling can be differentiated by differentiating the greenhouse. Their shape differs above the belt line, with E-500 in more traditional sedan styling, while CLS-500 has more sporty appearance. Two vehicle models were inspected in detail, comparing similarities. Body outer panels for both cars, when compared, had identical A-pillar and C-pillar contours, but different B-pillar. The reason for such differentiation is that for CLS-500, B-pillar is widened to compensate for its hard-top configuration (no window frame).

Once the system-level decomposition strategy is defined, the system architect must examine each component to incorporate flexibility to achieve the overall decomposition strategy goal. In Section 5.5, key components for required design variable changes are identified. The decomposition strategy for two key components, body outer panel and body inner panel, are presented here. Components are decomposed so it would be more economical to change when the design requirement changes. It is assumed that the proposed decomposition meets quality and manufacturing criteria.

5.6.2 Single Component Decomposition: Body Outer Panel

The body outer panel is a critical component that is visible to customers. It probably is the most sensitive component to styling changes. Figure 5-20 shows how the component can be decomposed.

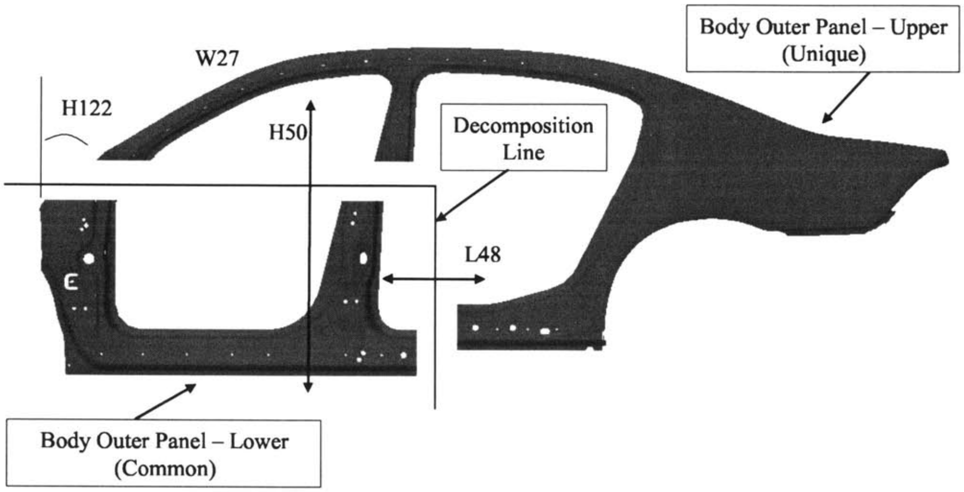


Figure 5-20: Body Outer Panel Decomposition

The lower body outer panel is common for all three vehicle variants. The upper body outer panel is customized for each vehicle variant for styling differentiation, as well as critical design variables differentiations as shown. Note that the panel is not decomposed exactly as suggested in Figure 5-19. This is due to the fact that, if decomposition is made on the C-pillar section, it will be easily seen by the customer, thus creating a quality problem. The proposed decomposition line can be covered by the front and rear doors. Common and unique portion of the body outer panel are welded together to create the body outer panel for each vehicle variant. The welding interfaces for all three vehicle variants are also common. When the styling or length of the vehicle changes, only unique portion of the body outer panel need to be redesigned. Common portion and the welding interface remains the same. The proposed decomposition will incur extra investment in blanking, stamping and welding tools, but when the design changes, will result in lower switch costs.

5.6.3 Single Component Decomposition: Body Inner Panel

The body inner panel design is affected by the body outer panel design. It is also connected to other important inner components, such as rocker inner panels, front body hinge panels, and rear wheel housing. This component is also a multiplier and incurs high switch cost whenever a change occurs. To reduce the impact of change, it is decomposed into three different pieces as shown in Figure 5-21.

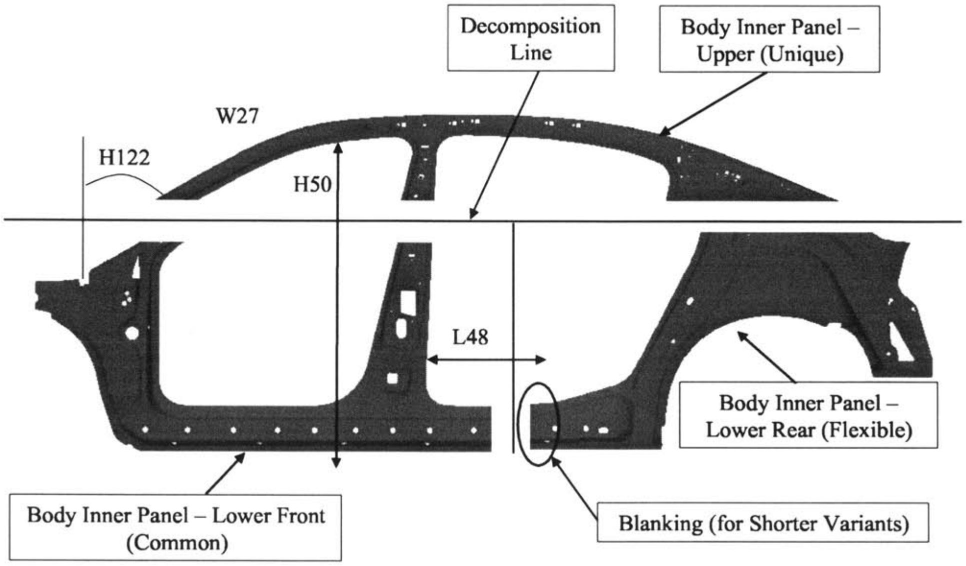


Figure 5-21: Body Inner Panel Decomposition

The lower front body inner panel is common for all three vehicle variants, and the upper body inner panel is customized for each variant, similar to the upper body outer panel. However, for the body inner panel, there is a flexible piece (lower rear body inner panel) as shown in the figure. This piece must be designed to meet the $L48$ bandwidth requirement, while meeting the manufacturing and quality requirements as well. One way to achieve these requirements is to design the flexible piece to meet the long vehicle specification, then to meet the short vehicle specification, trim the end (where it is welded to the common piece). This will results in flexible design, while minimizing potential manufacturing and quality defects by reducing the number of additional welding points. The wheel house section of the piece is common for all three vehicles, since it is usually designed to accommodate the biggest tires used by the vehicle family. This particular component is decomposed in a similar way as proposed in Figure 5-19, since it is not seen by the customers.

5.6.4 Other Components

From the remaining six components - rocker inner panel (RH & LH), floor pan, roof panel, front roof support and rear roof support - the roof panel is the only component that must be designed uniquely for each variant every time the design change, since it must comply to the styling restrictions imposed by the particular design change. The flexible floor pan design was discussed in detail in Chapter 4. In this case study, the flexible floor pan design used is "top-down" design, where the floor pan is designed for long variants, then trimmed down for short variants. This design is the compromise between economic benefit and manufacturing/quality criteria, which is not mentioned in this thesis. Rocker inner panels and roof supports are designed in the same way as the floor pan, to achieve the flexibility required.

5.6.5 Flexible Assembly Process

Assembly related investment is perhaps the biggest cost driver during the initial investment phase. The automotive industry is no exception. In order to accommodate the flexible component designs proposed in the previous section, the BIW assembly line must also be flexible. Shown in Figure 5-22 is the BIW assembly process (based on the actual process) and the proposed area to incorporate flexibility.

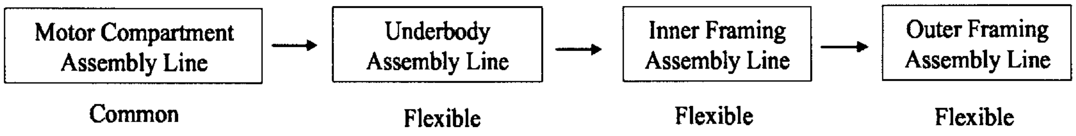


Figure 5-22: Flexible BIW Assembly Line

The motor compartment is common for all vehicle variants, requiring no flexibility in the assembly process. However, remaining downstream processes do require flexibility in assembly tooling to accommodate different vehicle variants. A detailed assembly sequence for the underbody assembly line is shown in Figure 5-23.

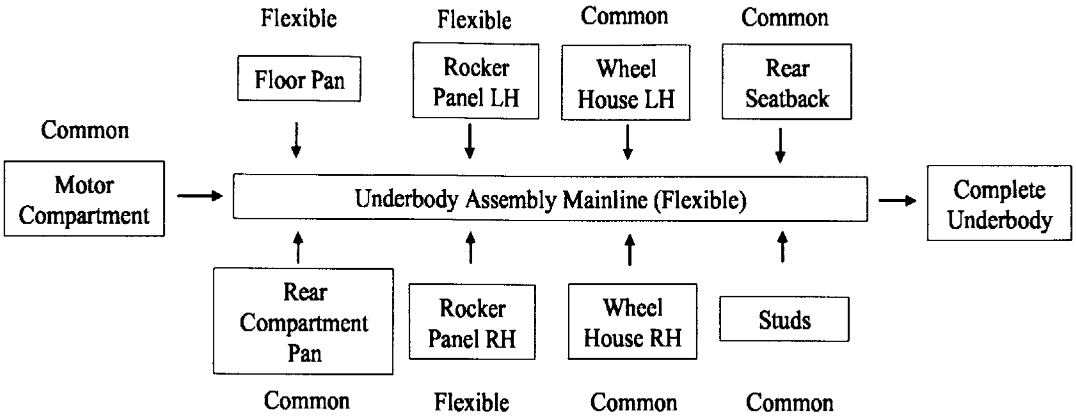


Figure 5-23: Detailed Underbody Assembly Line

Each component coming in is labeled as either common components or flexible components, which requires dedicated or flexible tooling (and additional welding line in some cases), respectively. In this particular assembly line, the floor pan and rocker inner panels are flexible components that require flexible assembly processes. Finally, the underbody assembly line itself requires flexible assembly tooling.

5.6.6 Vehicle Platform Elements Selection

As a result of the system decomposition strategy, several components and assembly processes became "flexible" elements, as parts of the vehicle platform. Table 5.7 shows platform element comparison between the inflexible BIW design and the flexible BIW design.

Note that in the inflexible BIW design, components and processes are divided into either common or unique elements. In the flexible BIW design, several unique elements are redesigned to become flexible elements. Change propagation analysis results and economic impact results of the newly designed flexible components are shown in Appendix C.

In this section, a system level BIW decomposition strategy is presented. Following the overall decomposition strategy, each individual component is decomposed according to its requirements. Additionally, it is determined that some sections of the

Table 5.7: BIW Platform Elements Comparison (Inflexible vs. Flexible)

Elements	Inflexible BIW	Flexible BIW
Common Platform Elements	Motor Compartment Rear Compartment	Motor Compartment Rear Compartment Body Outer Panels - Lower Body Inner Panels - Lower Front
Flexible Platform Elements	None	Body Inner Panels - Lower Rear Rocker Inner Panels Floor Pan Roof Panel Supports (FR & RR) BIW Assembly Line
Unique Elements	Body Outer Panels Body Inner Panels Rocker Inner Panels Floor Pan Roof Panel Roof Panel Supports (FR & RR) BIW Assembly Line	Body Outer Panels - Upper Body Inner Panels - Upper Roof Panel

BIW assembly line required flexibility to accommodate flexible components. Finally, a flexible BIW platform is defined.

5.7 Step VI: Determine Costs of Design Alternatives

In the previous section, the overall system decomposition strategy for BIW and flexible design for each component is presented. The next step is to determine the cost of flexible BIW design. For this case study, the process based cost model, developed at MIT [12, 34, 41, 42], is used to determine the capital investment cost and the unit cost of each vehicle. As it is mentioned in the previous section, the architecture of BIW is Body Frame Integral, using steel as its material. Company-specific cost parameters are used for accurate cost calculation. The following sections explain the details of capital investment cost and the unit cost of each vehicle.

5.7.1 Capital Investment Cost

Capital investment cost is divided into component fabrication related investment costs and the BIW assembly related investment costs. Figure 5-24 shows the capital investment cost decomposition.

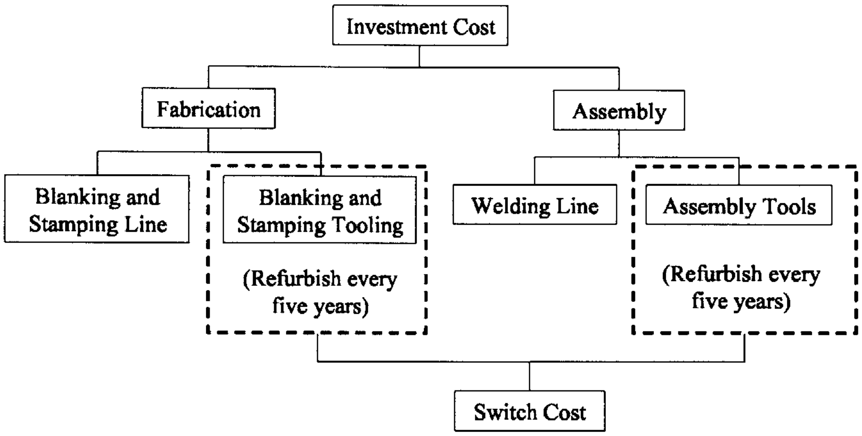


Figure 5-24: BIW Related Capital Investment Cost Decomposition

Fabrication Related Investment

Fabrication related investment cost is divided into two different categories: line investments and tooling investment. To manufacture BIW components, blanking and stamping press lines are required. Several different types of presses are required, depending on the size of the components. For ten critical BIW components, four types of presses are used: transfer, tandem, progressive, and roll form. Presses are treated as equipment, that is, amortized over a specified number of years, longer than the total life of the product platform (15 years). Line investment cost for ten components are determined as a function of their mass and the annual expected production volume.

Tooling investment consists of blanking and stamping die investments. Tooling investment cost are amortized over the life of vehicle production, which is five years in this case. Stamping die cost is a function of component's material, mass, and the press technology used. Blanking die investment is assumed to be 10% of the stamping die cost. Blanking and stamping dies are refurbished every five years at 25% of the cost of new dies, given no engineering design changes occur in the components. If any design change occurs, it is assumed that a new die will be designed.

Assembly Related Investment

BIW assembly investment cost is divided into two categories: line investment and tooling investment. Line investment consists of equipment costs that are required to assemble the BIW. Tooling investment consists of assembly fixture investment. Line investment is amortized over a fixed period of time, similar to the blanking and stamping line investment.

Assembly fixtures can either be flexible or fixed. Investment cost of flexible assembly fixtures is assumed to be twice that of the fixed assembly fixture cost. However, since the flexible assembly fixture is not model specific, it is treated as "equipment" rather than tools, and its cost is amortized over the life of the product platform. The refurbishing costs of assembly fixtures (both flexible and fixed) are assumed to be 25% of the new fixture investment, occurring every five years. The switch cost occurs when the engineering design changes BIW. Fixed tooling will require 100% of its tools to change, while the flexible tooling does not require any change.

Despite the longer amortization period for flexible tooling, it will result in higher up-front investment cost and higher refurbishing cost than the fixed tooling. However, when the BIW design changes more often, its switching cost is significantly less than the situation where fixed tooling is used.

Another important consideration is the production capacity. Since there is an absolute capacity limit for a single BIW assembly line, multiple lines are required to assemble required number of BIW units. The relationship between capacity utilization and flexibility is a very important field, but is outside of this thesis scope.

Classifying Different Investment Cost Types

In this case study, we are interested in three types of investment costs: initial investment cost, refurbish cost, and switch cost.

- Initial investment cost (K_{init}): It is the upfront investment cost required for BIW fabrication and assembly. The investment occurs a year before the beginning of the actual production. It includes investment in equipment and tooling.

- Refurbish cost (K_{ref}): It is the cost to refurbish fabrication and assembly tooling, given no engineering change in BIW design. The cost is incurred every five years, and the cost is committed a year before the actual refurbishing takes place. The refurbishing cost is assumed to be 25% of the cost of new tools.

- Switch cost (K_{switch}): Switch cost occurs when the BIW design is changed. It is the investment cost for accommodating such change, which in this case is the cost of new fabrication and assembly tooling. If BIW design change occurs more frequently than every five years, some tools will be replaced with new ones, thus they do not require refurbishment. This changes total refurbishing costs.

5.7.2 BIW Unit Cost

The unit cost of BIW usually depends on the choice of material, the cycle time of production, the mass of its components and the annual production volume. Figure 5-25 shows the cost decomposition for the BIW unit cost.

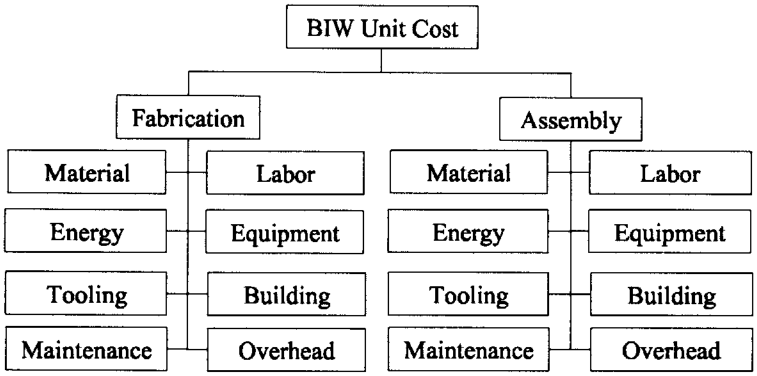


Figure 5-25: BIW Unit Cost Decomposition

Costs are divided into fabrication related costs and assembly related costs and are the total sum of listed costs.

- Materials: cost of materials used. For BIW component fabrication, it is the cost of the steel sheet used. For assembly, it is the cost of spot welds.
- Labor: cost of direct labor required to perform fabrication and assembly operations, divided by the annual production volume of the component.
- Energy: cost of energy used per unit fabrication and assembly.
- Equipment: cost of amortized equipment investment cost, divided by the annual production volume of the component.
- Tooling: cost of fabrication/assembly tooling, amortized over the component production life, divided by the annual production volume of the component.
- Building: cost of amortized building investment cost, divided by the annual production volume of the component.
- Maintenance: maintenance cost of component related equipment, tooling and building, divided by the annual production volume of the component.
- Overhead: cost of indirect labor required to perform fabrication and assembly operations, divided by the annual production volume.

5.7.3 Investment and Unit Cost of Critical BIW Components

In Section 5.6, a flexible BIW design is generated. The costs of the flexible design and the original inflexible design, customized for each vehicle, need to be determined in order to evaluate its economic benefits under future uncertainties. Table 5.8 shows, for each vehicle variant, initial estimated annual production volume, expected volume trend, maximum expected production volume during the life of the vehicle platform, and the number of required BIW assembly lines per particular product variant.

The number of required assembly lines is based on the maximum expected production volume during the lifetime of the vehicle platform (15 years). In each assembly line, over 200,000 units of BIW can be assembled per year. Assembly lines with fixed tooling are dedicated to one vehicle variant, while assembly lines with flexible

Table 5.8: Individual Vehicle Information

Vehicle Variants	p_1	p_2	p_3
Annual Production Volume	280,000	125,000	60,000
Annual Volume Trend	6.11%	-0.34%	-5.52%
Maximum Expected Annual Volume	650,000	125,000	60,000
BIW Assembly Lines Required	3	1	1

tooling can accommodate all vehicle variants. Following assumptions are made for determining relevant costs:

- The life of the vehicle platform is set to 15 years, corresponding to three cycles of nominal vehicle design change (five years each).

- From the analysis in Step IV and V, only ten components (body outer and inner panels, rocker inner panels, floor pan, roof panels, front and rear roof supports) require differentiation while the other components remain common. For this case study, only costs related to these components are calculated, thus the cost difference is quantified.

- Two design alternatives are considered. The first design alternative is the inflexible BIW design, where ten differentiating components are uniquely customized for each vehicle variant. The second design alternative utilizes flexible components, as defined in Step V of the design process. The assembly process for inflexible BIW design assumes fixed tooling, while the process for flexible design utilizes flexible tooling in identified assembly sequences, as shown in Figure 5-22.

- Fabrication and assembly tools are refurbished every five years, at 25% of the new tooling cost, assuming no engineering change occurs.

- Once the initial investment costs and unit costs are determined, they are assumed to be fixed for the remainder of the platform life.

For two design alternatives compared, fabrication and assembly conditions are different, and are listed in Table 5.9.

Table 5.9: BIW Design Alternative Comparison

Design Alternatives	Inflexible BIW Design	Flexible BIW Design
Identified Components	Customized for Each Variant (One Piece Components)	Flexible (Decomposed Components)
Assembly Process	Customized for Each Variant (Dedicated Tooling)	Flexible (Flexible Tooling)

Investment Costs

For each design alternative, the initial capital investment cost, refurbishing cost, and the switch cost are calculated. As it is stated in the initial assumption, investment costs for ten components are calculated. Table 5.10 lists normalized values of initial investment cost, refurbishing cost, and switch cost of inflexible and flexible BIW designs. Values are normalized to the initial investment cost of customized BIW designs.

Table 5.10: Normalized Investment Costs

Design Alternatives	Customized BIW	Flexible BIW
Initial Investment Cost (K_{init})	100.0	134.2
Refurbish Cost (K_{ref})	10.6	17.9
Switch Cost (K_{switch}) (BIW Styling Change Only)	31.9	5.4
Switch Cost (K_{switch}) (BIW Styling and Length Change)	42.3	5.5

Numbers indicate that the flexible BIW design, with flexible assembly lines, requires approximately 34% more upfront investment cost than the inflexible BIW design. The inflexible BIW design is also more cost efficient in terms of refurbishing costs. However, the flexible BIW design, with flexible assembly line, far outperforms the inflexible design in terms of switch cost when the styling and the length of BIW need to be changed. This shows the costs and benefits of flexible BIW design, where extra investment is required initially, but changes can be accommodated with significantly lower investment costs.

Observing the investment costs, it is clear that the flexible BIW design is more expensive to implement, but has the potential to perform more economically when the frequency of styling change increases. It will be demonstrated in Step VII of the process, the uncertainty analysis phase, when adding flexibility is worthwhile and when is not.

Unit Costs

The total unit costs of ten BIW components for each vehicle variant are calculated. Total unit costs include all cost elements shown in Figure 5-25, and are calculated as function of annual production volume, component mass (for fabrication), and number of spot welding required (for assembly). Table 5.11 lists normalized unit BIW cost (ten components only) of each vehicle variant for two different design alternatives being compared. Unit costs are normalized with respect to the unit cost of p_1 for customized BIW.

Table 5.11: BIW Unit Cost of Vehicle Variants for Different Design Alternatives

Variants	Inflexible BIW	Flexible BIW
p_1	100.0	104.2
p_2	107.0	107.4
p_3	122.7	115.8

Note that for p_1 and p_2, unit cost of flexible BIW design is higher, as expected, due to high investment cost to amortize, and additional welding costs for flexible components. However, the unit BIW cost of p_3 for flexible BIW design is lower than the cost of the inflexible BIW design. This is due to the effect of common component sharing, where the flexible BIW shares more common components with smaller variants, thus lowering the unit cost through economies of scale.

In this section, the nature of capital investment cost and unit cost are explained in detail. Using the process based cost model, relevant investment costs and unit costs for inflexible and flexible BIW designs are calculated. A cost comparison showed that the flexible design will cost more to implement than the inflexible BIW design, but incurs significantly lower switch cost when the vehicle design changes. Higher investment also affects BIW unit costs, resulting in higher unit cost for flexible BIW design. However, some vehicle variants benefitted from common components sharing, resulting in lower unit cost than the inflexible BIW design based variants. Whether or not this additional cost of flexibility is beneficial, has not yet been determined.

5.8 Step VII: Uncertainty Analysis

5.8.1 Problem Formulation

In Step VI, all relevant economic costs for inflexible and flexible BIW design are calculated. Costs include initial investment cost (K_{init}), refurbishing cost (K_{ref}), switch cost (K_{switch}), and BIW unit cost. Using identified costs, uncertainty analysis can be performed to evaluate the economic feasibility of each design under various degrees of uncertainty. The following assumptions are made prior to the uncertainty analysis.

- All costs in this section are normalized with respect to the initial investment cost of the inflexible BIW design (identified in Section 5.7).
- The economic evaluation period is set to 15 years, corresponding to three cycles of vehicle design change (five years each).
- Fabrication and assembly tools are refurbished every five years,unless they are being replaced.
- Geometric Brownian Motion is used for future demand prediction.
- The demand of individual vehicle variants is equal to the production volume.
- The demand of individual vehicle variants cannot exceed the maximum assembly lines capacity set by the number of assembly line designated for each variant (for inflexible BIW design).
- The same capacity rule applies to the flexible BIW design for equivalent comparison to the inflexible BIW design, even though the flexible tooling in all assembly lines enable flexible capacity utilization for flexible BIW design.

- Styling changes and length changes occur within the design variable bandwidths defined from the results of optimization in Step III.
- When the styling changes, it is assumed that all three vehicle variants change together.
- To calculate the total vehicle family lifetime profit for each design alternative, the net present value (discounted cash flow) method is used.
- The annual discount rate is set to 6%.

Table 5.12 lists demand forecast related parameters for each vehicle. α is the demand trend coefficient, and σ_v is the demand volatility coefficient. These parameters are calculated from the actual vehicle sales data (annual) between 1997 - 2003. Equations (4.14) and (4.15) are used.

Table 5.12: Individual Vehicle Information

Vehicle Variants	p_1	p_2	p_3
Initial Production Volume	280,000	125,000	60,000
Trend Coefficient (α)	6.11%	-0.34%	-5.52%
Volatility Coefficient (σ_v)	11.25%	6.62%	13.27%

Assuming a 15 year time horizon, expected demand for each vehicle variant (no volatility) is shown in Figure 5-26. Expected demands are calculated using Equation (4.13) in Chapter 4, using coefficients from Table 5.12.

Within the boundary of pre-stated assumptions, expected demand trend, and volatility, two BIW design alternatives are evaluated under several different scenarios. Table 5.13 lists descriptions of various scenarios, in which two designs are evaluated for the economic performance.

Scenarios I through IV are scenarios with various degree of uncertainty. It starts with investigation of scenarios with uncertain production volume. Styling change uncertainty is added to increase the degree of uncertainty in Scenario III and IV, in addition to annual production volume uncertainty. Scenarios V through VIII investigate instances where styling is changing above the vehicle belt line only, but

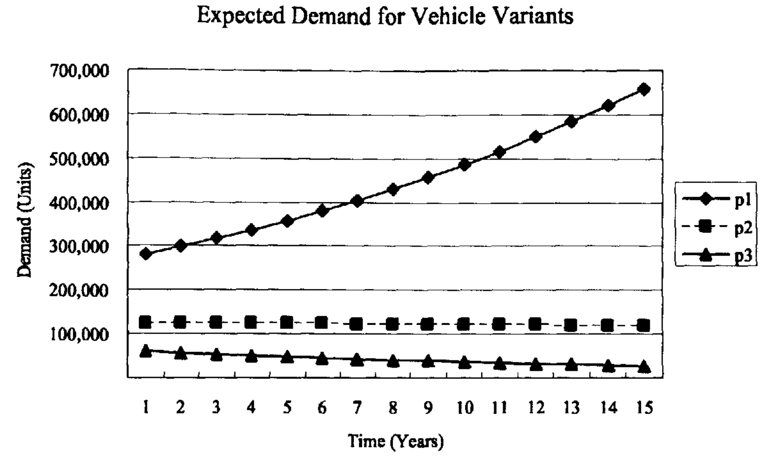


Figure 5-26: Expected Demand for p_1, p_2, and p_3 for the Life of the Platform

Table 5.13: Evaluated Scenarios

Scenario	Scenario Description
I	Production Volume (PV) with future trend (no volatility)
II	PV with future trend and volatility (uncertain PV)
III	Styling change above belt line every five years
IV	Styling + length change every five years
V	Styling change above belt line every four years
VI	Styling change above belt line every three years
VII	Styling change above belt line every two years
VIII	Styling change above belt line every one year
IX	Styling + length change every four years
X	Styling + length change every three years
XI	Styling + length change every two years
XII	Styling + length change every one year

with increasing frequency, and under uncertain future demand. Scenarios IX through XII investigate instances where the styling is changing in the length direction with increasing frequency, but within the $L48$ bandwidth defined from the optimization in Step III of the process. Length change results in higher switch costs, since more component changes are required.

Net present value (NPV) of the total product family profit is used to measure the economic performance of each design alternative. The net present value is obtained by the following equation:

$$NPV = \sum_{t=0}^{15} \frac{CF_t}{(1+r)^t} \tag{5.11}$$

where

$$CF_t = \sum_{i=1}^{3} (R_{i,t} - C_{\text{total},i,t}) - K_{\text{Init},t} - K_{\text{ref},t} - K_{\text{switch},t} \tag{5.12}$$

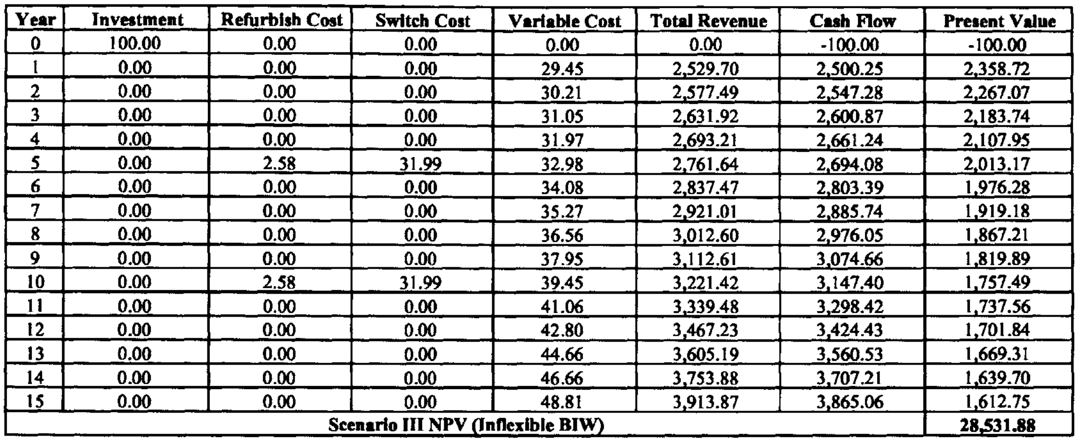
and

$$\begin{aligned} R_{i,t} &= D_{i,t}\mathrm{P}_{w,i} \\ C_{\text{total},i,t} &= D_{i,t}c_{\text{veh},i}. \end{aligned} \tag{5.13}$$

NPV is the total sum of time discounted cash flow over period of 15 years; CF_t is the total cash flow at time t; r is the discount rate; $R_{i,t}$ is the revenue generated by the sale of i^{th} vehicle variant at time t; $C_{\text{total},i,t}$ is the total variable cost incurred to produce the i^{th} variant; $K_{\text{Init},t}$ is the investment occurs at time t; $K_{\text{ref},t}$ is the refurbishing related investment occurs at time t; $K_{\text{switch},t}$ is the switch related investment occurs at time t; $D_{i,t}$ is the demand of i^{th} vehicle variant at time t; $\mathrm{P}_{w,i}$ is the weighted average price of the i^{th} vehicle variant, obtained from Step III; and $c_{\text{veh},i}$ is the unit cost of the i^{th} vehicle variant. In this case study, since only the BIW of the vehicle is investigated, the unit cost of BIW will be used as the unit cost c_{veh}.

5.8.2 Scenarios I - IV

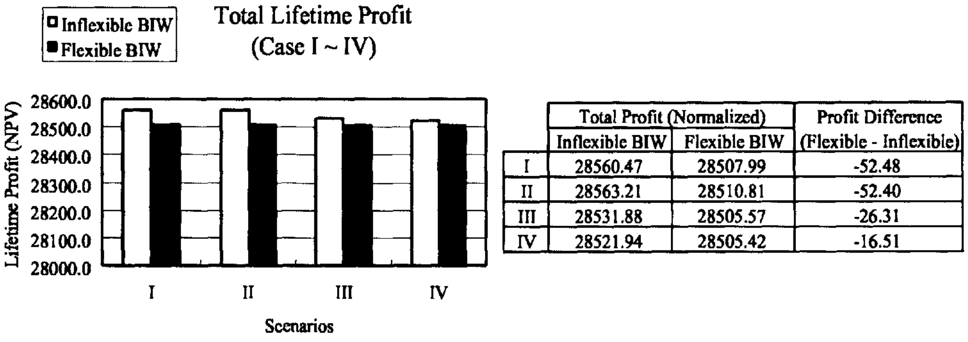
Figure 5-27 shows the detailed cash flow schedule over the life of the vehicle platform for Scenario III (Inflexible BIW). The first column shows the time period in years. The second column shows the amount of initial investment and the time period it is invested. The third column shows the time line for switch cost investments when uncertain change occurs. The fourth column shows the total variable cost occurred for the particular time period. The fifth column shows the total revenue generated from sales of three vehicle variants in the product family. The sixth column shows total cash flow (not discounted) for each specific time period. The seventh column shows time discounted value of the cash flow from the sixth column. Total profit, in present value, is shown at the bottom of the seventh column. Detailed cash flow schedules for all scenarios are presented in Appendix D and E.



Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.21	2,577.49	2,547.28	2,267.07
3	0.00	0.00	0.00	31.05	2,631.92	2,600.87	2,183.74
4	0.00	0.00	0.00	31.97	2,693.21	2,661.24	2,107.95
5	0.00	2.58	31.99	32.98	2,761.64	2,694.08	2,013.17
6	0.00	0.00	0.00	34.08	2,837.47	2,803.39	1,976.28
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	0.00	36.56	3,012.60	2,976.05	1,867.21
9	0.00	0.00	0.00	37.95	3,112.61	3,074.66	1,819.89
10	0.00	2.58	31.99	39.45	3,221.42	3,147.40	1,757.49
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	0.00	42.80	3,467.23	3,424.43	1,701.84
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	0.00	46.66	3,753.88	3,707.21	1,639.70
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario III NPV (Inflexible BIW)							**28,531.88**

Figure 5-27: Calculation of *NPV* for Scenario III (Inflexible BIW)

In order to perform the uncertainty analysis, Monte Carlo simulation is conducted to determine the range of future vehicle demand. For each scenario (with exception of Scenario I, where no uncertainty is present), simulation consists of 25,000 runs to represent a full range of outcomes.



	Total Profit (Normalized)		Profit Difference
	Inflexible BIW	Flexible BIW	(Flexible - Inflexible)
I	28560.47	28507.99	-52.48
II	28563.21	28510.81	-52.40
III	28531.88	28505.57	-26.31
IV	28521.94	28505.42	-16.51

Figure 5-28: Total Profit for Each Design (Scenarios I - IV)

Figure 5-28 shows the total average lifetime profit in *NPV* for each design, over the life of the product platform. The table next to the graph shows the normalized profit for each design, along with the profit difference between the inflexible BIW and

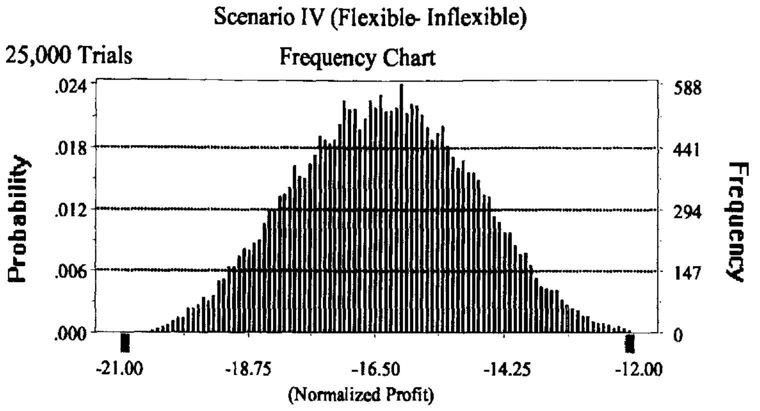


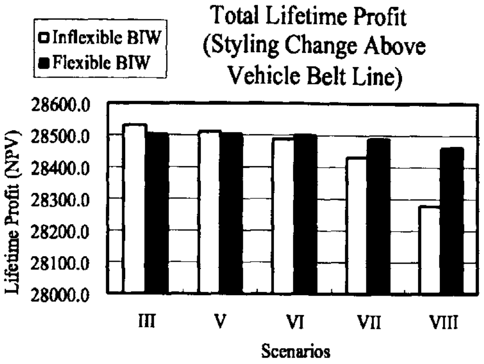
Figure 5-29: Profit Difference of Two BIW Designs (Scenario IV)

the flexible BIW design. For scenarios II - IV, profit values represents the average value of the Monte Carlo simulation.

In Scenarios I - IV, the inflexible BIW design performed better than the flexible BIW design. Even for Scenario IV, where the uncertainty is greatest among all four scenarios, inflexible BIW design outperformed the flexible BIW design. The profit difference distribution between the flexible BIW and inflexible BIW design for Scenario IV is shown in Figure 5-29. Profit difference ranges from -21 to -12, in normalized value, with an average profit difference value around -16. Results suggests that under these circumstances, the flexible BIW design should not be implemented. However, when the frequency of styling change increases, results may be different.

5.8.3 Scenarios V - VIII

In Scenarios V - VIII, styling for all vehicles is changed in increasing frequency. In these scenarios, styling is changed above the vehicle belt line only (no length change), thus not affecting any length related components. The rationale for increasing styling change frequency is that there might be a situation where, to maintain current demand trend, the company must change vehicle styling more frequently to refresh the product family every few years or so. Mean lifetime profit for each design alternative is calculated, and the Monte Carlo simulation is performed. Results are shown in Figure 5-30.



	Total Profit (Normalized)		Profit Difference
	Inflexible BIW	Flexible BIW	(Flexible - Inflexible)
III	28531.88	28505.57	-26.31
V	28512.33	28502.30	-10.03
VI	28489.39	28498.47	9.07
VII	28429.29	28488.42	59.13
VIII	28276.26	28462.83	186.57

Figure 5-30: Total Profit for Each Design (Scenarios III, V - VIII)

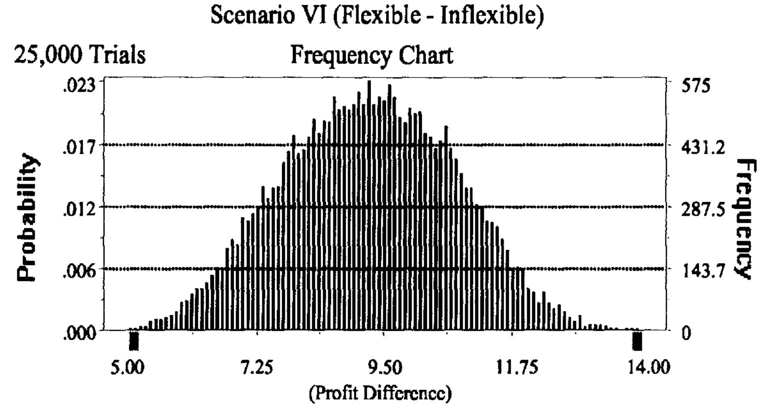
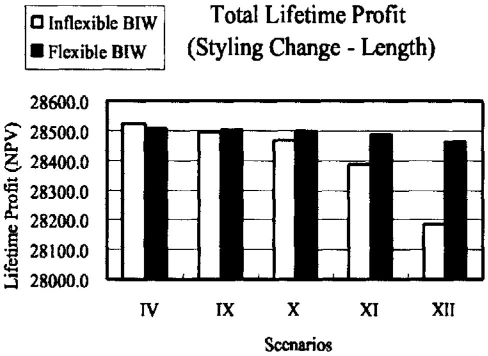


Figure 5-31: Profit Difference of Two BIW Designs (Scenario VI)

As the frequency of styling change increases, the profit difference between the inflexible BIW design and the flexible BIW design initially decreases. The crossover point occurs when the styling change frequency increases from every four years to every three years. When the styling changes every three years (Scenario VI) or more frequent, the flexible BIW design outperforms the inflexible BIW design in terms of total profit. Figure 5-31 shows the profit difference distribution between the flexible BIW design and the inflexible BIW design for Scenario VI, where the styling changes every three years. From the distribution graph, it is clear that, given current demand trend and volatility, the flexible BIW will always gain more profit than the inflexible BIW design, even though the difference may be small. The cause of this trend is due to the switch cost incurred every time vehicle styling changes. Total profit of flexible BIW design did not decrease as rapidly as that of inflexible BIW design. This is due to the low switch cost of flexible BIW design, making it more robust under increasing uncertainty.

5.8.4 Scenarios IX - XII

Scenarios IX through XII evaluates situations where styling changes result in a vehicle length change, within the established *L*48 bandwidths from the optimization results in Step III.



	Total Profit (Normalized)		Profit Difference
	Inflexible BIW	Flexible BIW	(Flexible - Inflexible)
IV	28521.94	28505.42	-16.51
IX	28495.90	28502.05	6.15
X	28465.56	28498.11	32.55
XI	28386.04	28487.76	101.73
XII	28183.59	28461.43	277.84

Figure 5-32: Total Profit for Each Design (Scenarios IV, IX - XII)

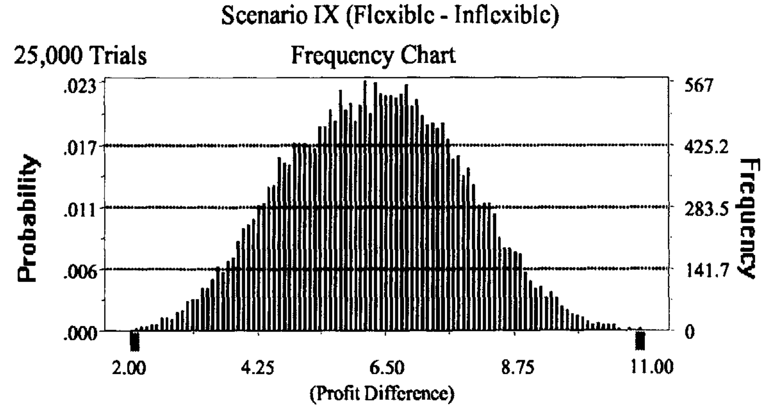


Figure 5-33: Profit Difference of Two BIW Designs (Scenario IX)

Since there are more components and tooling that require modifications when the vehicle length changes, switch costs for both designs are higher. However, due to significantly lower switch cost, the flexible BIW has better economic performance once the styling changes every four years (Scenario IX) or more often. Figure 5-33 shows the Monte Carlo simulation result for Scenario IX, displaying the range of profit difference between the flexible BIW design and inflexible BIW design.

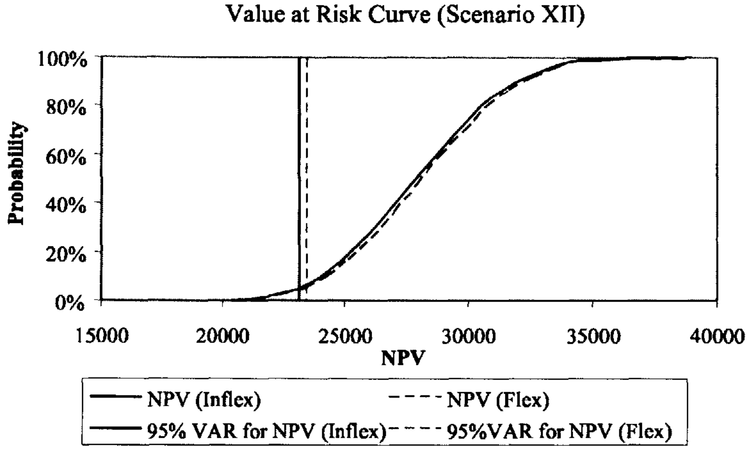


Figure 5-34: Value at Risk Curve for Scenario XII

Finally, Value-at-Risk curve for Scenario XII is plotted for both inflexible BIW design and flexible BIW design in Figure 5-34. According to Hassan and de Neufville et. al. [35], the flexibility usually change both the expected values and its distribution. The changes in distribution illustrate how flexibility reduces losses and exploits opportunities. In Figure 5-34, value of flexibility is evident. The 95% NPV line for flexible BIW design is to the right of the inflexible BIW design, indicating higher profits. Value-at-Risk curve can provide important information for the decision makers to appreciate the value of flexibility.

5.8.5 Value of Flexibility for H50 Dimension

During the sensitivity analysis in Step III of the process, it is determined that $H50$ is a very sensitive variable, if flexible, can influence the total product family revenue. It is also determined that $H50$ is an active constraint. If the constraint is relaxed, how does this affect total revenue, and how long does it take to break even? Table 5.14 shows results for the break even analysis. The constraint on $H50$ is relaxed by 1%

from its current lower limit. It is assumed that all three variants' $H50$ are changing at the same time. Again, costs are normalized with respect to the initial investment cost for inflexible BIW Design.

Table 5.14: Break Even Analysis Results for $H50$ Change

Design	Inflexible BIW	Flexible BIW
Switch Cost (K_{switch})	31.9	5.4
Additional Annual Revenue	12.7	12.7
Break Even Point	2.5 Years	0.5 Years

The results clearly shows the superiority of the flexible design, when $H50$ is changed for additional revenue. Given the same amount of revenue increase, the flexible design is able to break even within six months, while the inflexible design required approximately two and half years to break even. This shows that if such sensitive dimensions can be changed with lower switch cost, it will bring more profit to the company than designs with high switch cost.

5.8.6 Discussion

Evaluating two different BIW designs under scenarios of various uncertainties produced interesting results. When uncertainty is not present, or very small, the inflexible BIW design performed better. However, as the degree of uncertainty increased, the profit difference between two designs decreased, and at certain point, the flexible BIW design started to show more economic benefit. The reason is that the magnitude of switch costs for the inflexible BIW design is much higher than the flexible BIW design, and when the frequency of design change increased, the flexible BIW design became more robust to change in terms of economic profit, outperforming the inflexible design. Figure 5-35 shows recommended situations when the flexible BIW design should be implemented.

The recommendation is that, under uncertain styling change frequency with given vehicle family demand trend and volatility, it is beneficial to implement the flexible BIW design if styling changes every three years or less , or if styling in length direction changes every four years or less. While the actual styling change is an exogenous

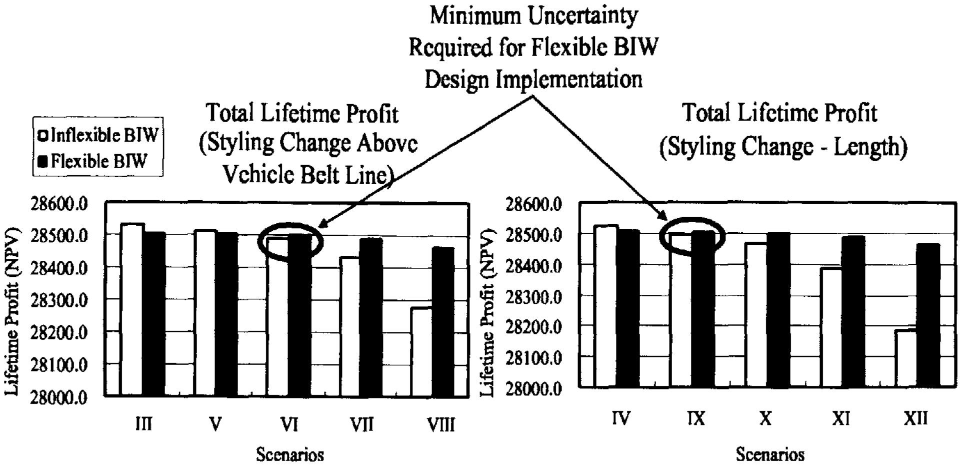


Figure 5-35: Recommended Situations for Implementing Flexible BIW Design

uncertainty (since vehicles are not designed ten years ahead of their release), the frequency of the styling change is a controlled decision variable that can be decided by the management of the company. Given this situation, Figure 5-35 offers decision makers a useful quantitative guideline to make decision on whether the flexibility should be implemented into the BIW or not.

Another important outcome is that the results quantitatively demonstrated increasing value of flexibility as the uncertainty increased, again confirming the results in options analysis. In this case study, expected economic profit of flexible BIW design became greater than the profit of inflexible BIW design once the frequency of design change increased above certain level, thus showing the value of flexibility.

Additional analysis of the sensitive dimension change ($H50$) showed that the flexible BIW design clearly had cost advantage when such situation arises. When the customer's preference on vehicle RM and IE changes, it can be easily accommodated through adjustment of $H50$, without too much burden of economic impact.

Finally, it is demonstrated that a small critical subset of flexible BIW components allowed the whole BIW to be flexible to uncertainties defined in the beginning of the design process. Ten BIW components and the flexible assembly process made BIW flexible to future styling changes, while being economically robust in terms of total life time profit. This supports the initial research hypothesis, which stated "if a critical subset of elements within the product platform is made flexible, it can make the whole platform flexible to a specified set of uncertainties." Is this true for any engineering system? An answer to this question requires more extensive research into different types of engineering systems, and is left as promising future work.

5.9 Chapter Summary

In this chapter, the design process introduced in Chapter 3 is applied to a vehicle platform case study, designed to accommodate three different vehicle models, while being flexible to future demand and styling changes. The process is followed step by step, using combination of quantitative analysis and expert engineering knowledge for each step.

Two specified uncertainties are mapped to quantifiable vehicle attributes, then to critical system-level design variables which require bandwidth and/or are sensitive to aforementioned attributes. Once the system-level design variables bandwidths are determined through a revenue optimization, critical BIW components are identified. Flexible design alternatives are generated for critical components of the BIW. The cost of flexible design, both in component fabrication and the assembly process, are calculated using the process based cost model. Uncertainty analysis is performed to determine the economic benefits of inflexible and flexible BIW designs.

The results showed that the flexible design gains more value as the degree of uncertainty increases in the future. It is also demonstrated that, for a specific set of uncertainties, if a critical subset of the platform is made flexible, then the vehicle platform became flexible to respond to aforementioned uncertainties, confirming the initial research hypothesis.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Product platforms are engineering systems with long life cycles. The research focused on embedding flexibility in them, so that they can actively respond to future uncertainties in a more economical way.

Chapter 1 introduced the motivation for flexible platform design, published research up to date, research gap analysis, problem formulation, and the boundary of the research scope. Chapter 2 investigated product platforms from various perspectives, and presented several business cases which implemented product platform strategies. Chapter 3 presented a theoretical framework for flexible platform design process. Chapter 4 demonstrated a part of the proposed design process through a single platform element case study, where a vehicle floor pan was designed to be flexible to future uncertainties in demand and specification changes. In Chapter 5, a detailed case study is presented, where a vehicle platform is designed to accommodate three different vehicle variants, while remaining flexible to future styling changes and demand.

In this thesis, a design process is developed to help architect flexible product platforms and its elements. The process is demonstrated using real industry case studies. It is demonstrated that using the proposed process, critical platform elements can be identified, and flexibility can be incorporated into these elements in a way to benefit from future uncertainties. It is shown that embedding flexibility results in an initial investment increase, but has the benefit of reduced switch cost when exogenous uncertainties require changes to the product family. It is also quantitatively shown that, as the degree of uncertainty increases, the value of flexibility increases. Finally, it is shown that a critical subset of product platform, if made flexible, can make entire platform flexible to specified future uncertainties.

6.2 Contributions

The research presented in this thesis contributes to the field of product platform design methodology, and by extension, engineering systems research. Figure 6-1 graphically shows contribution of this research. Four claims are made as research contributions. They are: 1) development of general design process for incorporating and evaluating flexibility in product platforms; 2) bandwidth optimization framework for product family revenue optimization; 3) formalization of change propagation analysis through development of quantitative metric and general guideline; and 4) introducing a thought process to incorporate flexibility in platform elements design.

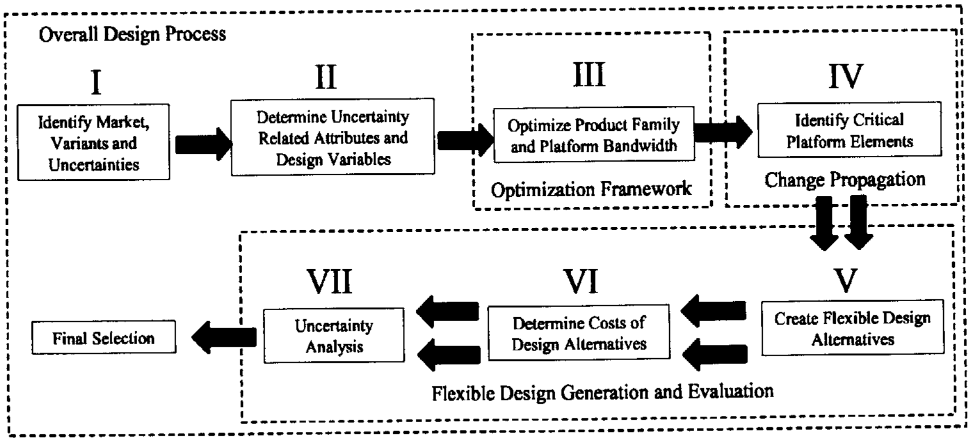


Figure 6-1: Research Contributions

6.2.1 Overall Design Process for Flexible Product Platforms

The comprehensive design process introduced in this thesis offers an end-to-end process to design flexible product platforms, accounting for future uncertainties. Through integration of traditional product platform based family design methodology, change propagation analysis, flexible elements design principles, and future uncertainty analysis, it is now possible to incorporate flexibility in critical subset of the product platform for future uncertainties and evaluate the benefit to make profitable decision. As shown in Figure 1-7, this research filled the gap not covered by previous research in academia.

6.2.2 Product Platform Bandwidth Optimization Framework

The developed optimization framework performs bandwidth optimization of vehicle variants to maximize product family revenue, subject to technical feasibility constraints. It establishes desirable bandwidth for functional attributes and system-level design variable. In traditional platform design methods, one forces a pre-defined set of design variables to be common among variants. In this framework, system-level design variables were allowed to vary to find optimum positions.

6.2.3 Formalization of Change Propagation

Introduced by Eckert et. al. [23], change propagation in complex systems is a very important issue. In this research, a new index for measuring the change propagation (CPI) is introduced. Using CPI, relevant switch costs for system elements, and the generalizable guideline proposed (see Section 3.6), system architects are able to formally identify critical elements that propagate change to other system elements, or elements that require high switch costs.

6.2.4 Flexible Platform Elements Design

Improving on the work published by Martin and Ishii [48], general guideline for flexible platform design is established in this research (see Section 3.7) and is demonstrated through a single platform element design example. What differentiates this work from previous research is the addition of uncertainty analysis to evaluate incorporated flexibility in a single platform element and in a product platform. This can provide decision makers with more lucid insight into the cost-benefit tradeoff of flexibility under various circumstances. Other useful guideline for flexible platform is also published by Rajan et. al. [64].

6.3 Future Work

Recommendations are made to improve the process presented in this thesis. Many questions and issues which were raised in the course of research, but were not addressed in the thesis. These issues can lead to future research topics.

One of the most important future contributions can be made in the field of uncertainty management, if aforementioned design framework can be applied to other complex systems. Once the proposed process can be demonstrated through several examples, it can become a generalizable system design framework.

Another area of promising future research is model validation. In Chapter 5, several attribute translation models and the market simulation model are used to obtain the optimization results. However, if the uncertainty in the model framework is greater than the objective sensitivity itself, it would invalidate the sensitivity analysis results, thus making downstream results less credible. Active research is being done in the area of meta-modeling, where modeling methodologies for high precision approximation response surface model of detailed simulation model is being introduced. In complex engineering system simulations, capturing such fidelity, while reducing the computation time, is becoming increasingly important.

Change propagation analysis needs much work in the future. Eckert et. al. [23] have studied change propagation in complex system design, but their focus is more towards management related change. In this thesis, an attempt was made to analyze technical change propagation to identify critical elements that can potentially be made flexible. A good theoretical formulation and representation of change propagation is a very promising future research topic.

One of the limitations of this research is that the number of product variants is decided beforehand, and the bandwidth of the product platform is established through the revenue optimization. In future research, these can be treated as uncertain factors which influence the flexible platform design. How does flexibility in the product platform add value if additional product variants are added to the product family that were not in the original mix? What would happen if one of the product variants must be added with its system-level design variable values that are outside of the established bandwidth? How can product platforms be designed differently if such bandwidth requirements become uncertain in the future? These are all valid and important questions, that can be researched in the future.

Finally, one must consider the management of platform portfolio. Product platforms cannot be stretched indefinitely without compromising individual product variant's performance. This raises an important research topic of *multiple platform* strategy. Some of the fundamental questions asked are:

- Given a number product variants, what is the best number of platforms to derive from?
- What is the optimal assignment of the product variants to the set of platforms, given a set of target market segments and competitors?
- What criteria should be used to decide on platform extent?
- Given above conditions, how to incorporate flexibility in each platform, and how much?

Work done by de Weck et. al. [21] investigated this issue through development of "sweet spot analysis" for product platform portfolio profit optimization. Work by Seepersad et. al. [72, 73] attempted to find the optimal platform extent through utilization of compromise Decision Support Problem and linear physical programming. They demonstrated the method using a family of eight absorption chillers. Aforementioned research provide some insights into issues previously listed, but it still remains a rarely researched field, waiting to be explored. It is author's hope that, with knowledge from previous literature, combined with knowledge gained from this thesis, system architects can design "optimum" product platform portfolio, with "optimum" degree of incorporated flexibility, which can respond to "right" set of uncertainties that may be different for each market segment.

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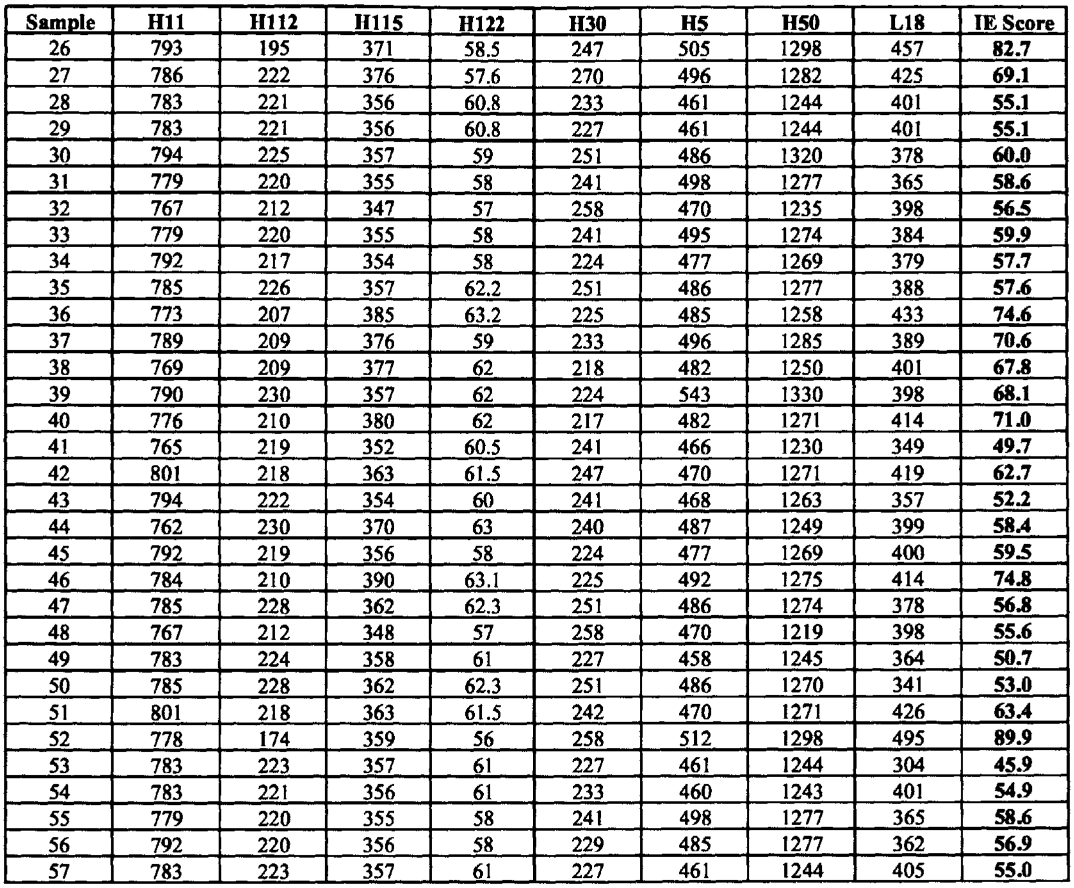
Appendix A

Sample Data Used for Principal Component Analysis (IE & RM)

Sample	H11	H112	H115	H122	H30	H5	H50	L18	IE Score
1	780	204	364	60.9	261	510	1282	407	**73.0**
2	792	211	379	59.2	242	507	1298	413	**75.2**
3	780	206	365	60.9	261	514	1283	407	**73.0**
4	771	178	358	62	254	516	1287	499	**88.8**
5	801	216	360	61.5	247	467	1268	419	**62.2**
6	784	222	361	62	244	472	1256	426	**60.6**
7	783	207	365	60.4	261	496	1282	401	**69.7**
8	765	211	360	63.1	250	486	1251	463	**69.7**
9	801	216	360	61.5	242	467	1268	426	**62.9**
10	770	207	345	63	210	432	1202	391	**50.4**
11	790	216	370	60	272	511	1301	421	**72.7**
12	789	213	369	60	272	511	1300	421	**73.6**
13	779	220	355	57.7	240	493	1272	384	**59.5**
14	773	213	385	63.2	225	484	1257	433	**72.2**
15	784	209	375	59	233	491	1275	389	**69.0**
16	762	194	363	63	240	480	1203	399	**66.3**
17	783	214	373	62.1	278	529	1297	508	**83.8**
18	782	195	363	59.9	221	524	1306	432	**81.5**
19	788	211	363	55.6	221	517	1305	392	**71.1**
20	784	212	391	63.1	225	491	1275	414	**74.2**
21	779	222	355	57.9	241	498	1273	365	**57.6**
22	792	222	356	57.9	229	485	1276	362	**56.1**
23	783	223	356	60.8	227	461	1244	405	**54.7**
24	770	207	345	63	210	432	1202	391	**50.4**
25	783	214	352	62	227	457	1240	419	**57.7**

Figure A-1: Sample Data (1 - 25) Used for *IE* Attribute Calculation (Dimension Units in mm, $H122$ in Degrees)



Sample	**H11**	**H112**	**H115**	**H122**	**H30**	**H5**	**H50**	**L18**	**IE Score**
26	793	195	371	58.5	247	505	1298	457	**82.7**
27	786	222	376	57.6	270	496	1282	425	**69.1**
28	783	221	356	60.8	233	461	1244	401	**55.1**
29	783	221	356	60.8	227	461	1244	401	**55.1**
30	794	225	357	59	251	486	1320	378	**60.0**
31	779	220	355	58	241	498	1277	365	**58.6**
32	767	212	347	57	258	470	1235	398	**56.5**
33	779	220	355	58	241	495	1274	384	**59.9**
34	792	217	354	58	224	477	1269	379	**57.7**
35	785	226	357	62.2	251	486	1277	388	**57.6**
36	773	207	385	63.2	225	485	1258	433	**74.6**
37	789	209	376	59	233	496	1285	389	**70.6**
38	769	209	377	62	218	482	1250	401	**67.8**
39	790	230	357	62	224	543	1330	398	**68.1**
40	776	210	380	62	217	482	1271	414	**71.0**
41	765	219	352	60.5	241	466	1230	349	**49.7**
42	801	218	363	61.5	247	470	1271	419	**62.7**
43	794	222	354	60	241	468	1263	357	**52.2**
44	762	230	370	63	240	487	1249	399	**58.4**
45	792	219	356	58	224	477	1269	400	**59.5**
46	784	210	390	63.1	225	492	1275	414	**74.8**
47	785	228	362	62.3	251	486	1274	378	**56.8**
48	767	212	348	57	258	470	1219	398	**55.6**
49	783	224	358	61	227	458	1245	364	**50.7**
50	785	228	362	62.3	251	486	1270	341	**53.0**
51	801	218	363	61.5	242	470	1271	426	**63.4**
52	778	174	359	56	258	512	1298	495	**89.9**
53	783	223	357	61	227	461	1244	304	**45.9**
54	783	221	356	61	233	460	1243	401	**54.9**
55	779	220	355	58	241	498	1277	365	**58.6**
56	792	220	356	58	229	485	1277	362	**56.9**
57	783	223	357	61	227	461	1244	405	**55.0**

Figure A-2: Sample Data (26 - 57) Used for *IE* Attribute Calculation (Dimension Units in mm, $H122$ in Degrees)

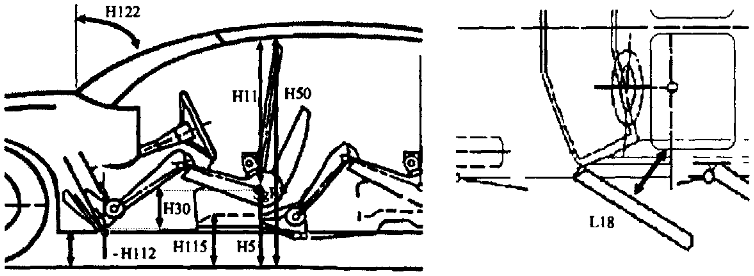
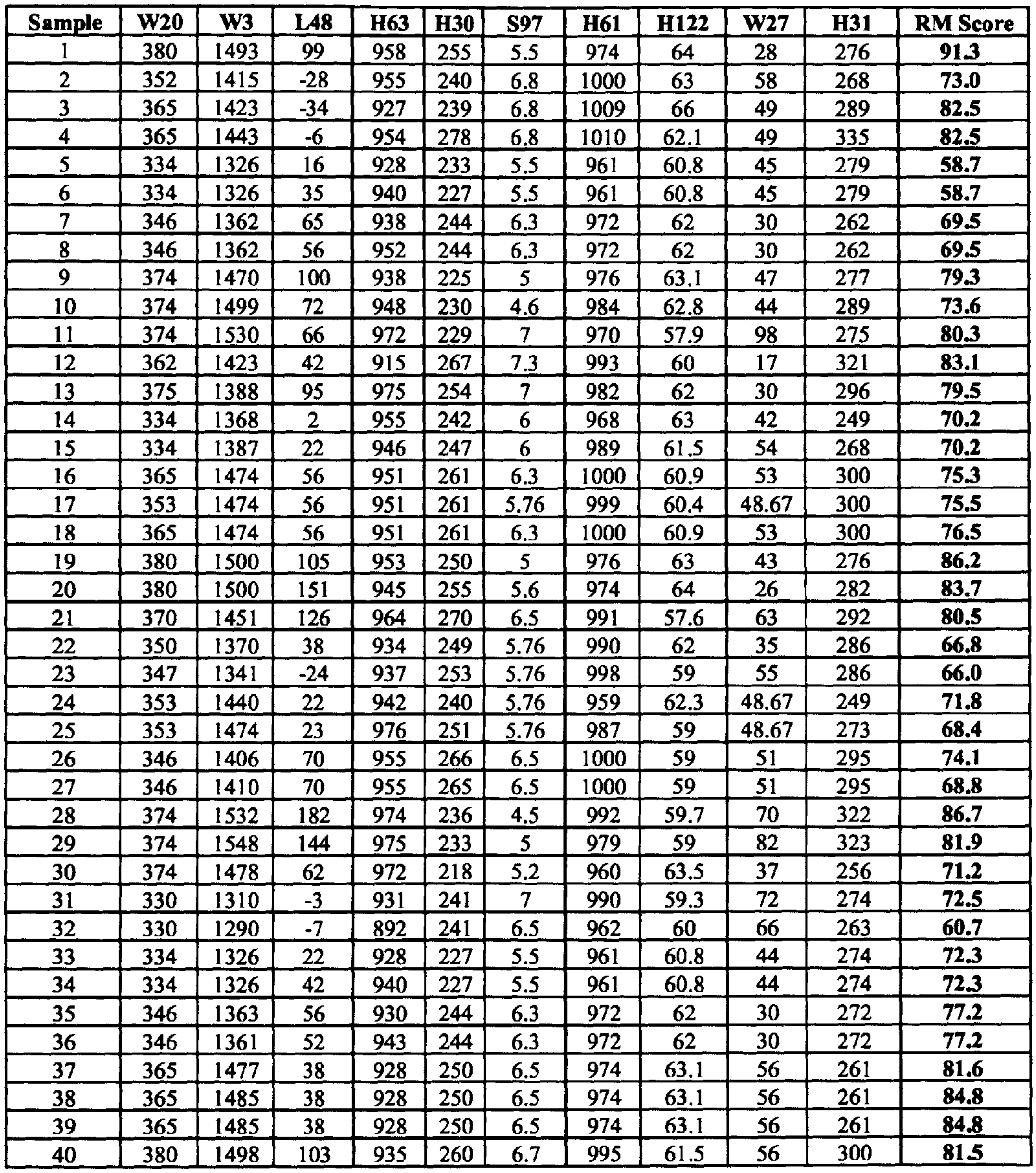


Figure A-3: Key Dimensions for *IE*



Sample	**W20**	**W3**	**L48**	**H63**	**H30**	**S97**	**H61**	**H122**	**W27**	**H31**	**RM Score**
1	380	1493	99	958	255	5.5	974	64	28	276	**91.3**
2	352	1415	-28	955	240	6.8	1000	63	58	268	**73.0**
3	365	1423	-34	927	239	6.8	1009	66	49	289	**82.5**
4	365	1443	-6	954	278	6.8	1010	62.1	49	335	**82.5**
5	334	1326	16	928	233	5.5	961	60.8	45	279	**58.7**
6	334	1326	35	940	227	5.5	961	60.8	45	279	**58.7**
7	346	1362	65	938	244	6.3	972	62	30	262	**69.5**
8	346	1362	56	952	244	6.3	972	62	30	262	**69.5**
9	374	1470	100	938	225	5	976	63.1	47	277	**79.3**
10	374	1499	72	948	230	4.6	984	62.8	44	289	**73.6**
11	374	1530	66	972	229	7	970	57.9	98	275	**80.3**
12	362	1423	42	915	267	7.3	993	60	17	321	**83.1**
13	375	1388	95	975	254	7	982	62	30	296	**79.5**
14	334	1368	2	955	242	6	968	63	42	249	**70.2**
15	334	1387	22	946	247	6	989	61.5	54	268	**70.2**
16	365	1474	56	951	261	6.3	1000	60.9	53	300	**75.3**
17	353	1474	56	951	261	5.76	999	60.4	48.67	300	**75.5**
18	365	1474	56	951	261	6.3	1000	60.9	53	300	**76.5**
19	380	1500	105	953	250	5	976	63	43	276	**86.2**
20	380	1500	151	945	255	5.6	974	64	26	282	**83.7**
21	370	1451	126	964	270	6.5	991	57.6	63	292	**80.5**
22	350	1370	38	934	249	5.76	990	62	35	286	**66.8**
23	347	1341	-24	937	253	5.76	998	59	55	286	**66.0**
24	353	1440	22	942	240	5.76	959	62.3	48.67	249	**71.8**
25	353	1474	23	976	251	5.76	987	59	48.67	273	**68.4**
26	346	1406	70	955	266	6.5	1000	59	51	295	**74.1**
27	346	1410	70	955	265	6.5	1000	59	51	295	**68.8**
28	374	1532	182	974	236	4.5	992	59.7	70	322	**86.7**
29	374	1548	144	975	233	5	979	59	82	323	**81.9**
30	374	1478	62	972	218	5.2	960	63.5	37	256	**71.2**
31	330	1310	-3	931	241	7	990	59.3	72	274	**72.5**
32	330	1290	-7	892	241	6.5	962	60	66	263	**60.7**
33	334	1326	22	928	227	5.5	961	60.8	44	274	**72.3**
34	334	1326	42	940	227	5.5	961	60.8	44	274	**72.3**
35	346	1363	56	930	244	6.3	972	62	30	272	**77.2**
36	346	1361	52	943	244	6.3	972	62	30	272	**77.2**
37	365	1477	38	928	250	6.5	974	63.1	56	261	**81.6**
38	365	1485	38	928	250	6.5	974	63.1	56	261	**84.8**
39	365	1485	38	928	250	6.5	974	63.1	56	261	**84.8**
40	380	1498	103	935	260	6.7	995	61.5	56	300	**81.5**

Figure A-4: Sample Data (1 - 40) Used for *RM* Attribute Calculation (Dimension Units in mm, $S97$ in Degrees)

Sample	**W20**	**W3**	**L48**	**H63**	**H30**	**S97**	**H61**	**H122**	**W27**	**H31**	**RM Score**
41	380	1498	105	935	250	5	974	63	43	276	**86.1**
42	380	1495	100	951	255	5.6	974	64	26	276	**87.4**
43	365	1472	50	951	261	6.5	999	60.4	33	300	**77.8**
44	374	1502	100	969	240	6.5	960	61	41	309	**73.0**
45	374	1502	106	961	240	5.6	986	57.7	76	280	**77.5**
46	367	1413	28	914	237	3.7	959	60.1	31	302	**85.8**
47	359	1466	51	950	221	5.76	990	61.1	48.67	305	**90.8**
48	353	1483	34	949	251	6	975	60	68	286	**69.9**
49	346	1409	70	955	266	6.5	1000	59	51	300	**76.4**
50	378	1497	77	952	221	5.5	967	63.3	52	247	**73.5**
51	350	1370	38	934	249	5.76	990	62	35	286	**66.5**
52	343	1357	11	934	232	7.4	993	62.5	41	293	**76.6**
53	374	1499	69	972	241	6	983	58	84	275	**71.1**
54	374	1503	156	965	242	5.8	1011	59.2	77	311	**86.6**
55	353	1474	56	951	261	5.76	999	60.4	48.67	300	**82.1**
56	365	1474	56	951	261	6.3	1000	60.9	53	300	**78.8**
57	374	1469	83	919	225	4.8	970	63.2	54	268	**80.5**
58	370	1457	115	930	268	5.8	1000	63.7	61	302	**67.7**
59	340	1357	-74	906	210	5.3	978	63	45	257	**71.2**
60	340	1357	-74	906	210	5.3	978	63	45	257	**68.9**
61	363	1415	52	967	272	8	999	60	82	286	**79.1**
62	340	1378	-10	965	227	6	998	62	50	277	**69.9**
63	374	1501	94	965	240	5.7	969	61.5	29	277	**77.1**
64	374	1496	114	972	218	5	966	62	36	262	**77.2**
65	334	1327	-26	928	227	5.5	961	60.8	44	274	**48.3**
66	334	1327	-5	940	227	5.5	961	60.8	44	274	**48.3**
67	334	1374	2	929	242	6	956	63	35	249	**68.4**
68	334	1387	23	946	242	6	989	61.5	54	263	**68.4**
69	370	1457	115	920	268	5.8	996	63.7	61	301	**70.3**
70	394	1576	146	966	220	6	992	56.2	80	304	**88.6**
71	394	1538	151	953	221	5	996	59.9	73	304	**72.0**
72	380	1500	105	953	250	5	976	63	43	276	**88.0**
73	364	1445	95	956	269	9.5	1016	62.7	43	322	**85.0**
74	353	1425	38	960	208	4	1008	61	94	302	**92.4**
75	334	1336	23	945	248	7.5	1011	59.5	48	288	**68.2**
76	347	1349	-51	942	253	7	993	59	55	286	**61.8**
77	342	1364	-10	978	281	7	998	60.8	52	345	**80.7**
78	370	1483	106	963	280	7.3	983	60	72	343	**91.9**
79	353	1425	38	930	208	4	978	61	94	302	**92.4**
80	364	1445	95	925	266	9.5	1002	62.5	43	308	**85.0**

Figure A-5: Sample Data (41 - 80) Used for *RM* Attribute Calculation (Dimension Units in mm, *S*97 in Degrees)

Sample	**W20**	**W3**	**L48**	**H63**	**H30**	**S97**	**H61**	**H122**	**W27**	**H31**	**RM Score**
81	374	1499	72	948	230	4.6	984	63	44	289	**73.6**
82	346	1363	56	930	244	6.3	972	62	30	272	**75.1**
83	365	1485	38	928	250	6.5	974	63.1	56	261	**81.6**
84	374	1502	72	949	230	6	985	62.8	43	292	**73.5**
85	365	1472	50	951	261	6.5	999	60.4	33	300	**77.8**
86	380	1498	103	935	260	6.7	995	61.5	56	300	**81.5**
87	346	1409	70	955	267	6.5	1000	59	51	300	**74.7**
88	365	1481	51	927	247	6	967	63.5	62	253	**77.7**
89	374	1532	182	974	236	4.5	992	59.7	70	322	**86.7**
90	374	1478	62	972	218	5.2	960	63.5	37	256	**70.5**
91	374	1501	94	965	240	5.7	969	61.5	29	277	**74.3**
92	374	1502	100	965	240	6.5	989	61	41	309	**73.0**
93	365	1474	56	951	261	6.3	1000	60.9	53	300	**75.6**
94	370	1465	72	952	213	5.93	1025	60.3	68	299	**72.3**

Figure A-6: Sample Data (81 - 94) Used for *RM* Attribute Calculation (Dimension Units in mm, *S*97 in Degrees)

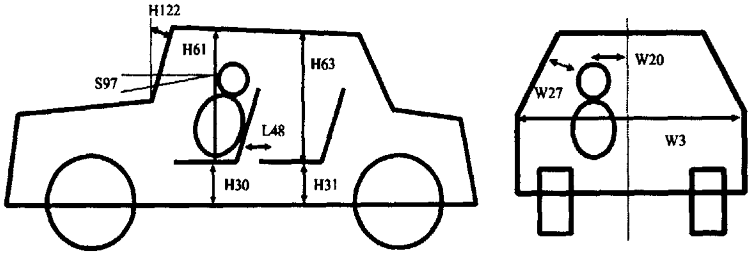


Figure A-7: Key Dimensions for *RM*

Appendix B

Vehicle Platform Optimization and Sensitivity Analysis Results

Table B.1: Lower and Upper Bounds $\mathbf{X}_{\mathcal{U}_{\text{veh}}}$ ($H5$ left out at the request of the company)

Independent Design Variables	Units	Lower Bound	Upper Bound
$H5$ (p_1)	mm	5**	6**
$H5$ (p_2)	mm	5**	6**
$H5$ (p_3)	mm	5**	6**
$H50$ (p_1)	mm	1392	1448
$H50$ (p_2)	mm	1392	1448
$H50$ (p_3)	mm	1392	1448
$L48$ (p_1)	mm	55	130
$L48$ (p_2)	mm	55	130
$L48$ (p_3)	mm	130	180
P_w (p_1)	\$	25000	29000
P_w (p_2)	\$	29000	33000
P_w (p_3)	\$	45000	60000
$W20$ (p_1)	mm	390	410
$W20$ (p_2)	mm	390	410
$W20$ (p_3)	mm	390	410
$W3$ (p_1)	mm	1498	1532
$W3$ (p_2)	mm	1498	1532
$W3$ (p_3)	mm	1498	1532

Table B.2: Values of Constants for Each p

Design Variables	Units	Value
$H112$ (p_1)	mm	220
$H112$ (p_2)	mm	220
$H112$ (p_3)	mm	220
$H115$ (p_1)	mm	385
$H115$ (p_2)	mm	385
$H115$ (p_3)	mm	385
$H122$ (p_1)	degree	61.5
$H122$ (p_2)	degree	61.0
$H122$ (p_3)	degree	59.7
$L18$ (p_1)	mm	389
$L18$ (p_2)	mm	389
$L18$ (p_3)	mm	389
$W27$ (p_1)	mm	55
$W27$ (p_2)	mm	41
$W27$ (p_3)	mm	70

Table B.3: Lower and Upper Bounds of Vehicle Attributes $\mathbf{J}_{\mathcal{U}_{\text{veh}}}$

Vehicle Attributes	Units	Lower Bound	Upper Bound
AC_{50-70} (p_1)	Second	3.72	3.82
AC_{50-70} (p_2)	Second	3.72	3.82
AC_{50-70} (p_3)	Second	3.71	3.77
FE (p_1)	mpg	20	27
FE (p_2)	mpg	20	27
FE (p_3)	mpg	18	25
IE (p_1)	% of Customers Satisfied	65	90
IE (p_2)	% of Customers Satisfied	65	90
IE (p_3)	% of Customers Satisfied	65	90
RM (p_1)	% of Customers Satisfied	70	90
RM (p_2)	% of Customers Satisfied	70	90
RM (p_3)	% of Customers Satisfied	70	90

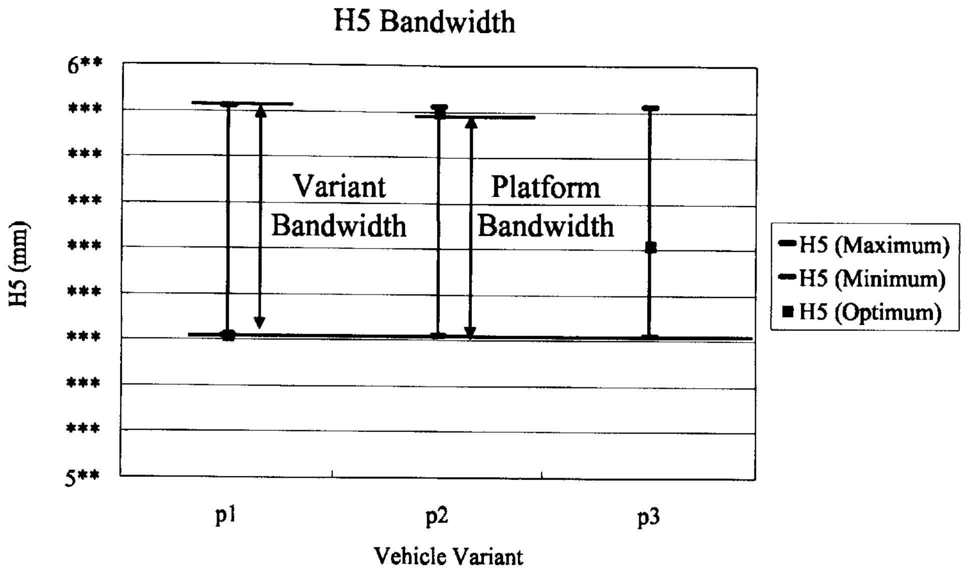


Figure B-1: Bandwidth of $H5$

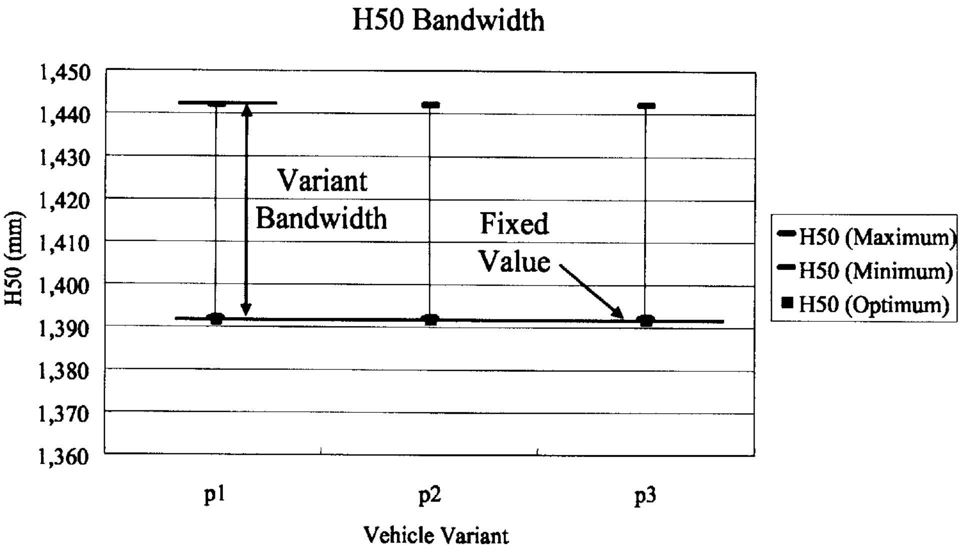


Figure B-2: Bandwidth of $H50$

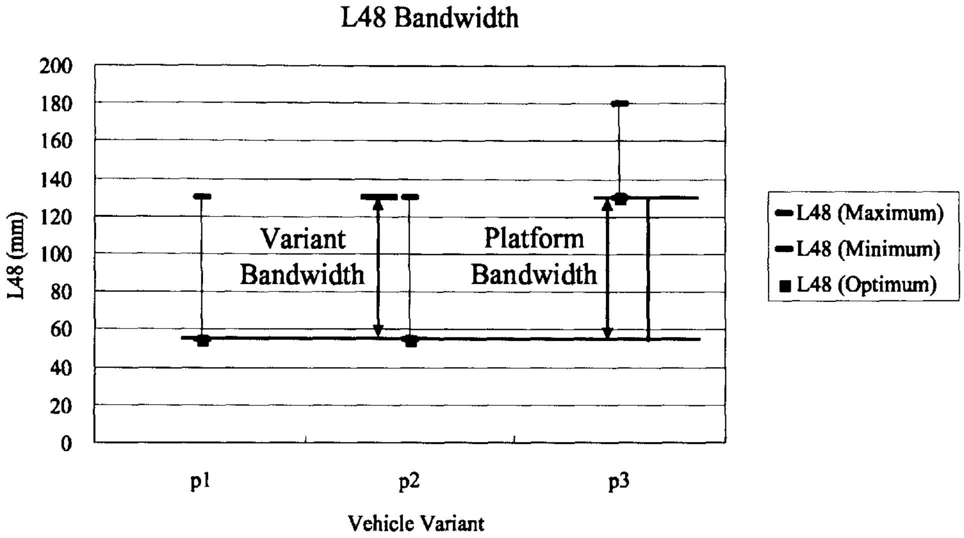


Figure B-3: Bandwidth of $L48$

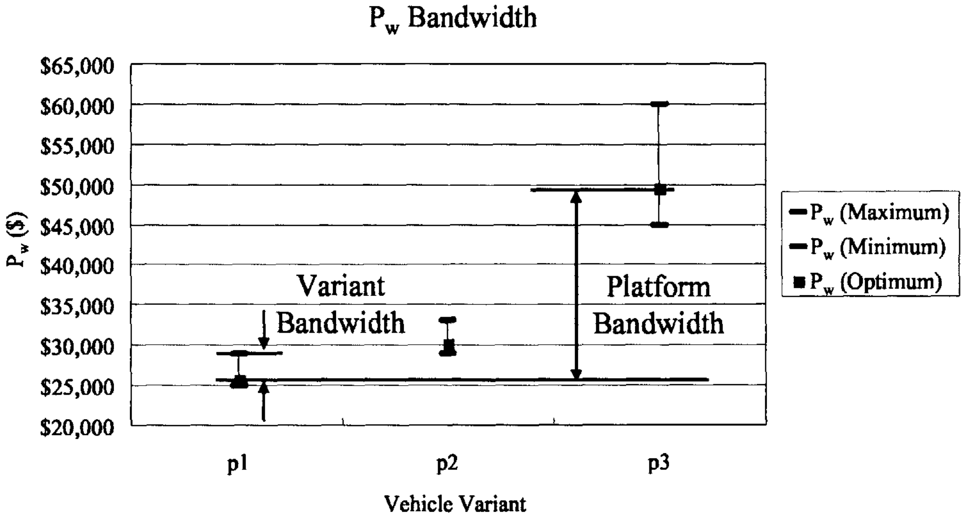


Figure B-4: Bandwidth of P_w

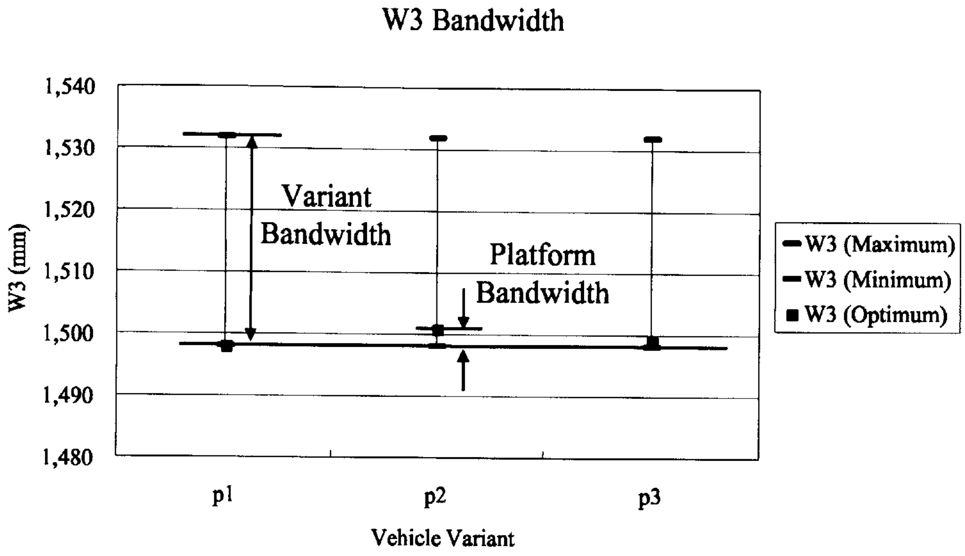


Figure B-5: Bandwidth of $W3$

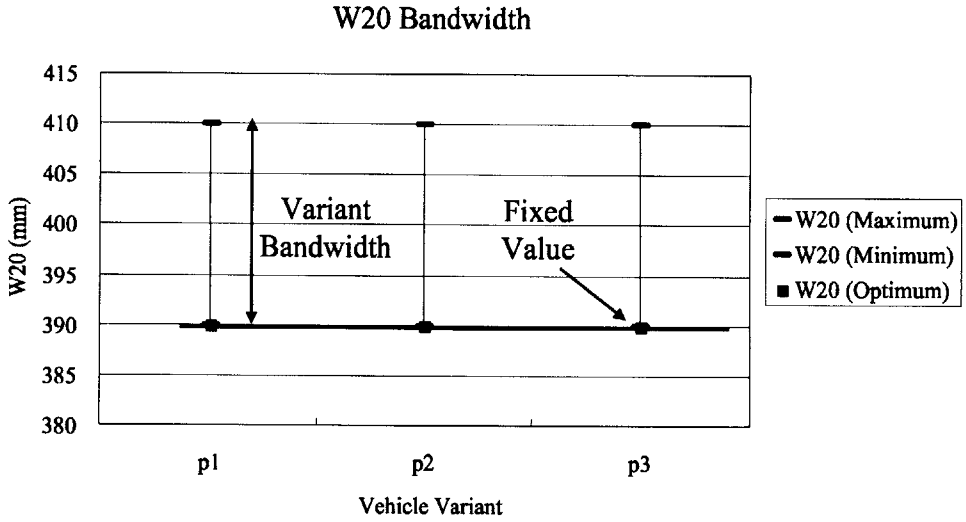


Figure B-6: Bandwidth of $W20$

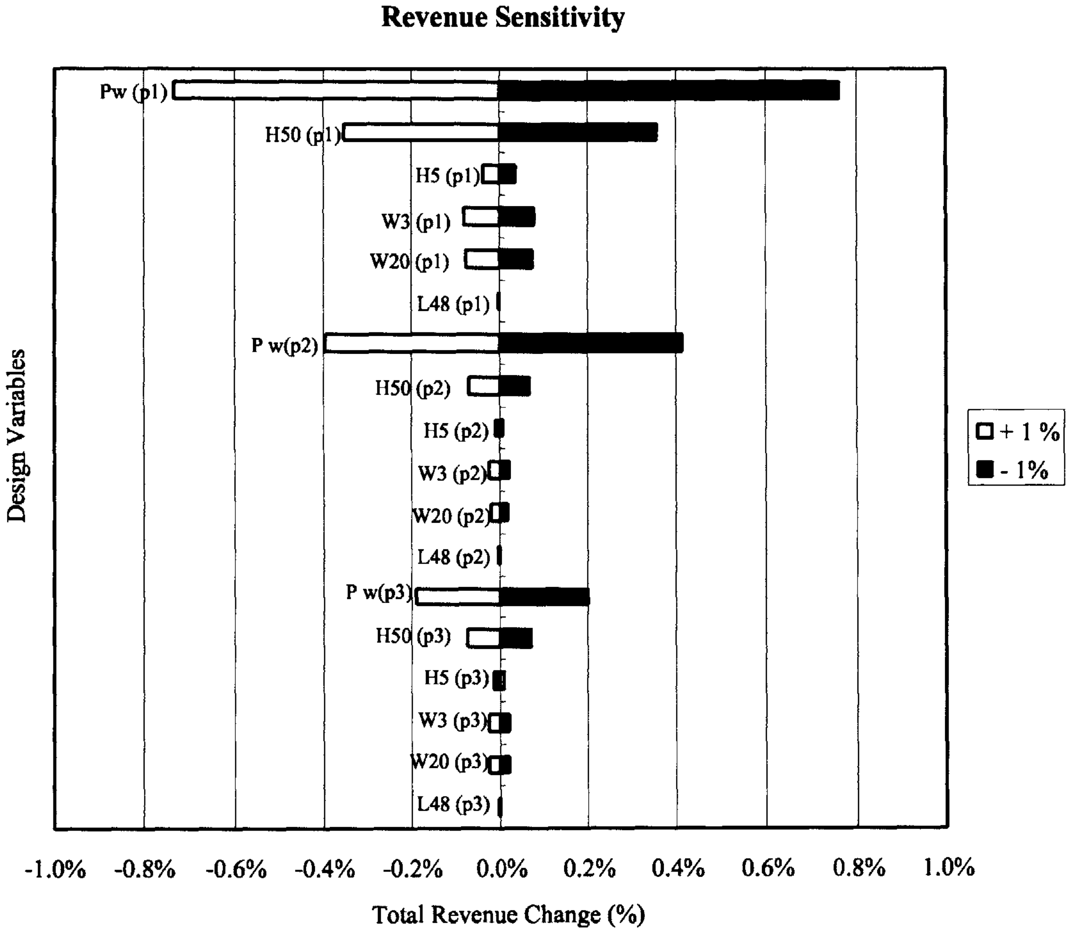


Figure B-7: Total Revenue Sensitivity With Respect to $\mathbf{X}_{\mathcal{U}_{\text{veh}}}$

Appendix C

BIW Change Propagation Analysis

This appendix presents change propagation analysis results for the inflexible and flexible BIW design. Details of each design are described in Chapter 5. Ten components are identified as critical components that are affected by pre-specified uncertainties and attributes. Figure C-1 shows two BIW design alternatives. The inflexible BIW design utilizes customized uni-piece components for each vehicle variant, and the flexible BIW design decomposed critical BIW components, so that certain parts can be used in all variants with small switch costs.

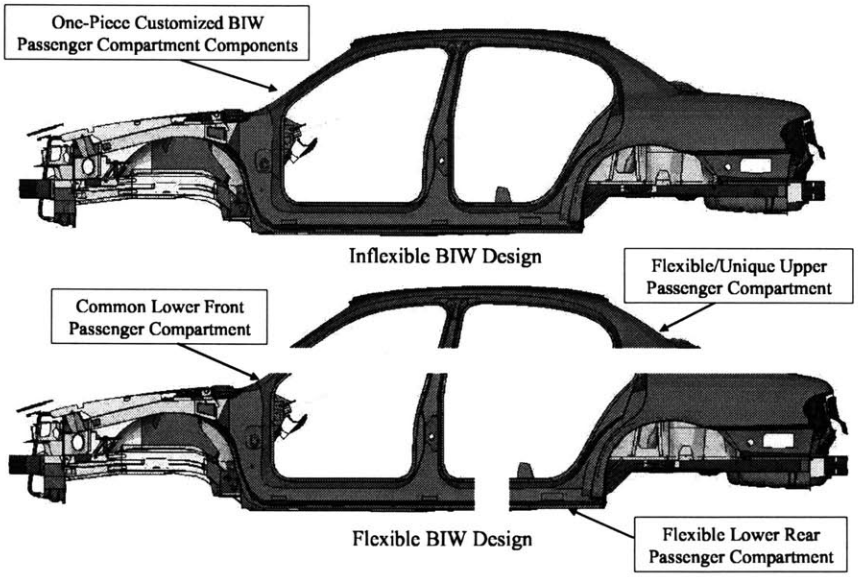


Figure C-1: BIW Design Alternatives

Table C.1 lists initial investment costs for each component, both in inflexible BIW and flexible BIW design. Initial investment cost consists of blanking tool, stamping tool, and welding fixture tool costs. Costs are normalized with respect to the initial investment cost of the body outer panel (inflexible BIW design). For body outer panel, body inner panel, and rocker inner panel, right side (RH) and left side (LH) components have same amount of investment cost.

Table C.1: Initial Investment Costs for Critical BIW Components

Component Name	Initial Investment Cost (Inflexible BIW Design)	Initial Investment Cost (Flexible BIW Design)
Body Outer Panel	100.0	-
Body Outer Panel - Lower	-	73.5
Body Outer Panel - Upper	-	87.3
Body Inner Panel	134.3	-
Body Inner Panel - Lower Front	-	82.9
Body Inner Panel - Lower Rear	-	76.5
Body Inner Panel - Upper	-	76.6
Rocker Inner Panel	45.9	53.4
Floor Pan	120.5	206.5
Roof Panel	39.9	39.9
Front Roof Support	3.5	3.9
Rear Roof Support	3.5	3.8

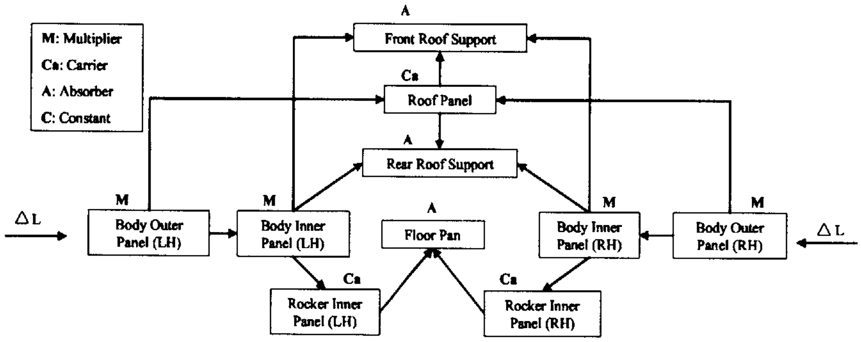


Figure C-2: Lengthwise Change Propagation Effect on Inflexible BIW

As expected, flexible components require more upfront initial investment cost. However when the situation requires designers to change vehicle length or styling, there are significant differences in switch related investment costs between the inflexible and flexible BIW design. Figure C-2 and C-3 show the change propagation

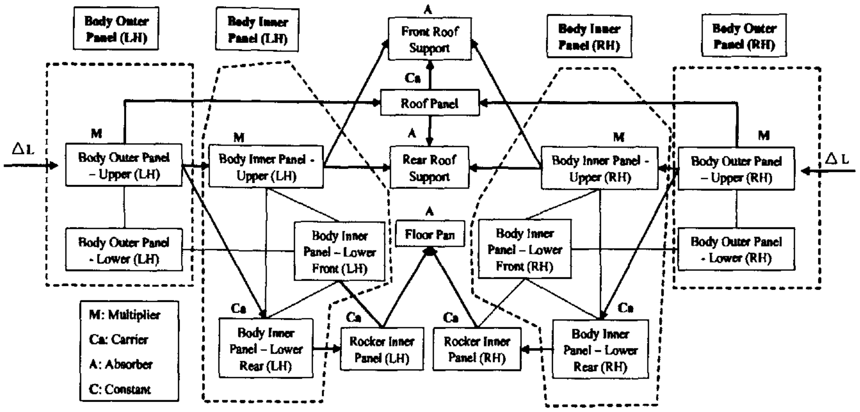


Figure C-3: Lengthwise Change Propagation Effect on Flexible BIW

Table C.2: Switch Costs for Critical BIW Components (Length Change)

Component Name	Component Class	Switch Cost (Inflexible BIW)	Switch Cost (Flexible BIW)
Body Outer Panel	Multiplier	100.0	-
Body Outer Panel - Lower	-	-	-
Body Outer Panel - Upper	Multiplier	-	45.1
Body Inner Panel	Multiplier	134.3	-
Body Inner Panel - Lower Front	-	-	-
Body Inner Panel - Lower Rear	Carrier	-	2.9
Body Inner Panel - Upper	Multiplier	-	35.9
Rocker Inner Panel	Carrier	45.9	4.0
Floor Pan	Absorber	120.5	3.9
Roof Panel	Carrier	39.9	39.9
Front Roof Support	Absorber	3.5	1.6
Rear Roof Support	Absorber	3.5	1.6

within the system when the BIW's length changes for both inflexible and flexible BIW designs, along with classification of each component. For the flexible BIW in Figure C-3, dashed boundaries represent inflexible BIW design's component equivalent.

Table C.2 lists change related switch costs for critical components. Again, costs are normalized with respect to the initial investment cost for body outer panel (inflexible BIW). From the component classification and switch cost observation, several comments can be made. For the body outer panel, lower component is entirely eliminated from the change propagation path. The upper body outer panel still propagates change, but its switch cost is much cheaper than its inflexible counterpart. Similar comments can be made for the body inner panel. Lower front component is eliminated, since it is a common component for all three vehicle variants. Lower rear body inner panel is a carrier that sends out change to the rocker inner panel. However, its switch cost is very small. Upper body inner panel, a unique component for each vehicle variant, is still a multiplier, but with lower switch cost than its inflexible counterpart.

Another change propagation analysis is performed for the case when the styling changes above the vehicle belt line only, without changing the vehicle length. As it is stated in Chapter 5, attributes (*IE* and *RM*) related variables $H50$, $H122$, and $W27$ need to be either differentiated, or must remain fixed for each vehicle variant. Figure C-4 and C-5 show the change propagation within the system when the BIW's style changes for both inflexible and flexible BIW designs, along with classification of each component. For the flexible BIW in Figure C-5, dashed boundaries represent inflexible BIW design's component equivalent.

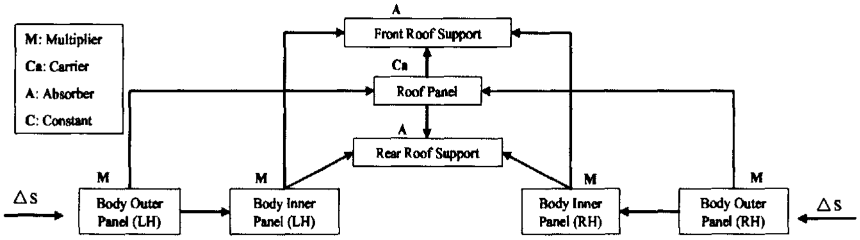


Figure C-4: Styling Change Propagation Effect on Inflexible BIW

Table C.3 lists change related switch costs for seven critical components affected by styling change above the vehicle belt line. Again, costs are normalized with respect to the initial investment cost for the body outer panel (inflexible BIW). The result shows that there are less number of changing components than when the length changed, and the flexible components in the flexible BIW design incurred lower switch cost when subject to change. It is clear that the flexible BIW design is indeed more flexible to specified changes than the inflexible BIW design. However, the flexibility is achieved at a price: higher initial upfront investment cost. The question of "which

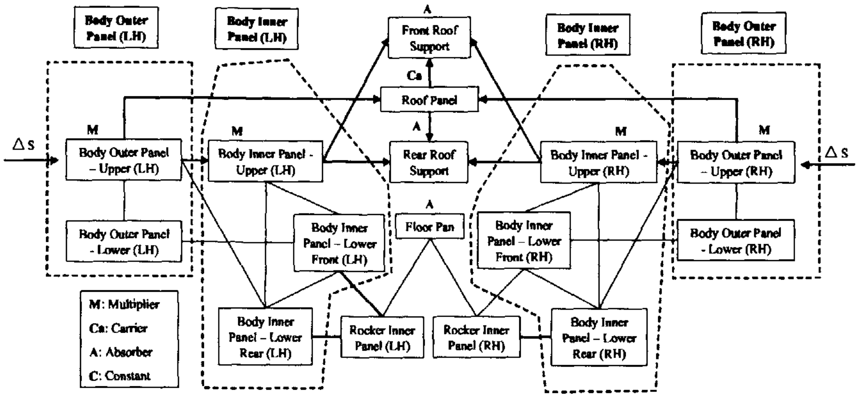


Figure C-5: Styling Change Propagation Effect on Flexible BIW

Table C.3: Switch Costs for Critical BIW Components (Styling Change)

Component Name	Component Class	Switch Cost (Inflexible BIW)	Switch Cost (Flexible BIW)
Body Outer Panel	Multiplier	100.0	-
Body Outer Panel - Lower	-	-	-
Body Outer Panel - Upper	Multiplier	-	45.1
Body Inner Panel	Multiplier	134.3	-
Body Inner Panel - Lower Front	-	-	-
Body Inner Panel - Lower Rear	-	-	-
Body Inner Panel - Upper	Multiplier	-	35.9
Rocker Inner Panel	-	-	-
Floor Pan	-	-	-
Roof Panel	Carrier	39.9	39.9
Front Roof Support	Absorber	3.5	1.6
Rear Roof Support	Absorber	3.5	1.6

design is more advantageous?" can only be answered through the future uncertainty analysis, presented in Chapter 5.

Appendix D

Expected Profit (in NPV) for Uncertainty Scenarios I - VI

In this appendix, the expected BIW manufacturing costs and expected profit (in terms of NPV) for uncertainty scenarios I - VI, presented in Chapter 5, are listed. All costs are normalized with respect to the initial investment cost of the inflexible BIW design (same for all scenarios).

Table D.1: Expected Annual Production Volume for Each p

Year	p_1	p_2	p_3
1	280,000	125,000	60,000
2	297,639	124,581	56,775
3	316,390	124,164	53,724
4	336,322	123,748	50,837
5	357,509	123,334	48,105
6	380,032	122,920	45,520
7	403,973	122,509	43,073
8	429,422	122,098	40,758
9	456,475	121,689	38,568
10	485,232	121,282	36,495
11	515,000	120,875	34,534
12	548,295	120,471	32,678
13	582,836	120,067	30,922
14	619,554	119,665	29,260
15	658,854	119,264	27,687

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.25	2,577.49	2,547.24	2,267.03
3	0.00	0.00	0.00	31.13	2,631.92	2,600.79	2,183.67
4	0.00	0.00	0.00	32.10	2,693.21	2,661.12	2,107.85
5	0.00	10.58	0.00	33.15	2,761.64	2,717.91	2,030.98
6	0.00	0.00	0.00	34.29	2,837.47	2,803.18	1,976.13
7	0.00	0.00	0.00	35.53	2,921.01	2,885.48	1,919.01
8	0.00	0.00	0.00	36.87	3,012.60	2,975.74	1,867.01
9	0.00	0.00	0.00	38.31	3,112.61	3,074.29	1,819.67
10	0.00	10.58	0.00	39.87	3,221.42	3,170.97	1,770.65
11	0.00	0.00	0.00	41.55	3,339.48	3,297.93	1,737.31
12	0.00	0.00	0.00	43.35	3,467.23	3,423.89	1,701.57
13	0.00	0.00	0.00	45.28	3,605.19	3,559.91	1,669.03
14	0.00	0.00	0.00	47.35	3,753.88	3,706.53	1,639.40
15	0.00	0.00	0.00	49.56	3,913.87	3,864.30	1,612.44
Scenario I NPV (Inflexible BIW)							**28,560.47**

Figure D-1: $E[NPV]$ for Scenario I, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	0.00	30.79	2,577.49	2,546.70	2,266.55
3	0.00	0.00	0.00	31.73	2,631.92	2,600.19	2,183.17
4	0.00	0.00	0.00	32.76	2,693.21	2,660.45	2,107.33
5	0.00	17.99	0.00	33.87	2,761.64	2,709.77	2,024.90
6	0.00	0.00	0.00	35.08	2,837.47	2,802.38	1,975.57
7	0.00	0.00	0.00	36.39	2,921.01	2,884.61	1,918.43
8	0.00	0.00	0.00	37.81	3,012.60	2,974.80	1,866.42
9	0.00	0.00	0.00	39.33	3,112.61	3,073.28	1,819.07
10	0.00	17.99	0.00	40.97	3,221.42	3,162.47	1,765.90
11	0.00	0.00	0.00	42.73	3,339.48	3,296.75	1,736.69
12	0.00	0.00	0.00	44.62	3,467.23	3,422.61	1,700.93
13	0.00	0.00	0.00	46.64	3,605.19	3,558.55	1,668.39
14	0.00	0.00	0.00	48.81	3,753.88	3,705.06	1,638.75
15	0.00	0.00	0.00	51.13	3,913.87	3,862.73	1,611.78
Scenario I NPV (Flexible BIW)							**28,507.99**

Figure D-2: $E[NPV]$ for Scenario I, Flexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.21	2,577.49	2,547.28	2,267.07
3	0.00	0.00	0.00	31.05	2,631.92	2,600.87	2,183.74
4	0.00	0.00	0.00	31.97	2,693.21	2,661.24	2,107.95
5	0.00	10.58	0.00	32.98	2,761.64	2,718.07	2,031.10
6	0.00	0.00	0.00	34.08	2,837.47	2,803.39	1,976.28
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	0.00	36.56	3,012.60	2,976.05	1,867.21
9	0.00	0.00	0.00	37.95	3,112.61	3,074.66	1,819.89
10	0.00	10.58	0.00	39.45	3,221.42	3,171.39	1,770.89
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	0.00	42.80	3,467.23	3,424.43	1,701.84
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	0.00	46.66	3,753.88	3,707.21	1,639.70
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario II NPV (Inflexible BIW)							**28,563.21**

Figure D-3: $E[NPV]$ for Scenario II, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	0.00	30.75	2,577.49	2,546.74	2,266.59
3	0.00	0.00	0.00	31.65	2,631.92	2,600.27	2,183.24
4	0.00	0.00	0.00	32.63	2,693.21	2,660.58	2,107.43
5	0.00	17.99	0.00	33.70	2,761.64	2,709.95	2,025.03
6	0.00	0.00	0.00	34.87	2,837.47	2,802.60	1,975.72
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	0.00	37.49	3,012.60	2,975.12	1,866.63
9	0.00	0.00	0.00	38.95	3,112.61	3,073.66	1,819.29
10	0.00	17.99	0.00	40.53	3,221.42	3,162.90	1,766.15
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	0.00	44.05	3,467.23	3,423.18	1,701.22
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	0.00	48.11	3,753.88	3,705.77	1,639.07
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario II NPV (Flexible BIW)							**28,510.81**

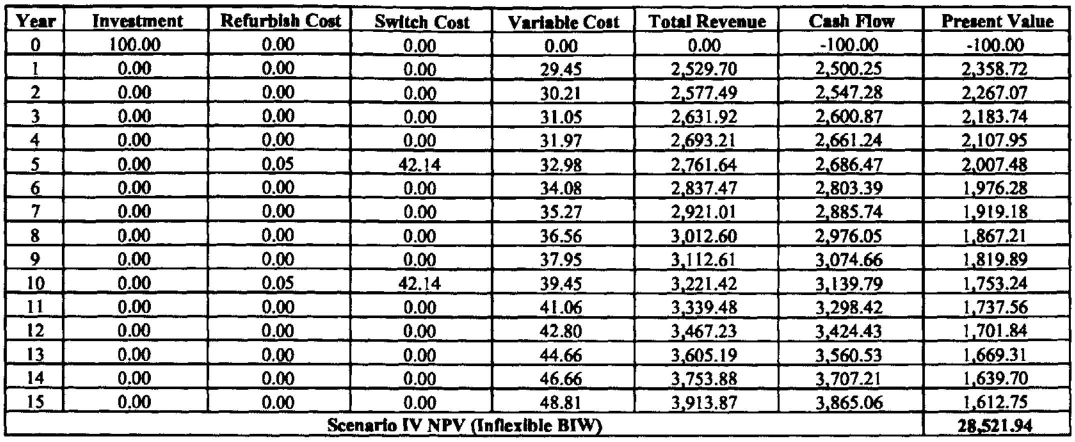
Figure D-4: $E[NPV]$ for Scenario II, Flexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.21	2,577.49	2,547.28	2,267.07
3	0.00	0.00	0.00	31.05	2,631.92	2,600.87	2,183.74
4	0.00	0.00	0.00	31.97	2,693.21	2,661.24	2,107.95
5	0.00	2.58	31.99	32.98	2,761.64	2,694.08	2,013.17
6	0.00	0.00	0.00	34.08	2,837.47	2,803.39	1,976.28
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	0.00	36.56	3,012.60	2,976.05	1,867.21
9	0.00	0.00	0.00	37.95	3,112.61	3,074.66	1,819.89
10	0.00	2.58	31.99	39.45	3,221.42	3,147.40	1,757.49
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	0.00	42.80	3,467.23	3,424.43	1,701.84
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	0.00	46.66	3,753.88	3,707.21	1,639.70
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario III NPV (Inflexible BIW)							**28,531.88**

Figure D-5: $E[NPV]$ for Scenario III, Inflexible BIW Design

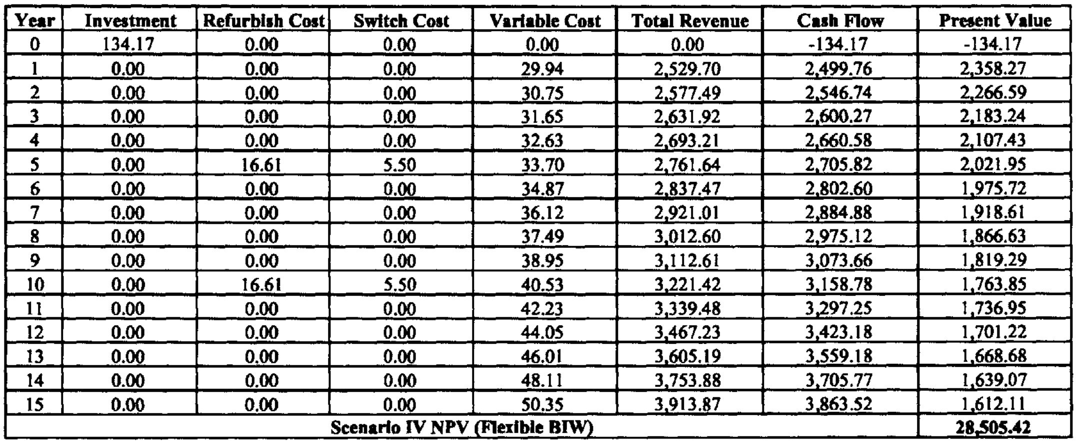
Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	0.00	30.75	2,577.49	2,546.74	2,266.59
3	0.00	0.00	0.00	31.65	2,631.92	2,600.27	2,183.24
4	0.00	0.00	0.00	32.63	2,693.21	2,660.58	2,107.43
5	0.00	16.65	5.35	33.70	2,761.64	2,705.93	2,022.03
6	0.00	0.00	0.00	34.87	2,837.47	2,802.60	1,975.72
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	0.00	37.49	3,012.60	2,975.12	1,866.63
9	0.00	0.00	0.00	38.95	3,112.61	3,073.66	1,819.29
10	0.00	16.65	5.35	40.53	3,221.42	3,158.89	1,763.91
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	0.00	44.05	3,467.23	3,423.18	1,701.22
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	0.00	48.11	3,753.88	3,705.77	1,639.07
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario III NPV (Flexible BIW)							**28,505.57**

Figure D-6: $E[NPV]$ for Scenario III, Flexible BIW Design



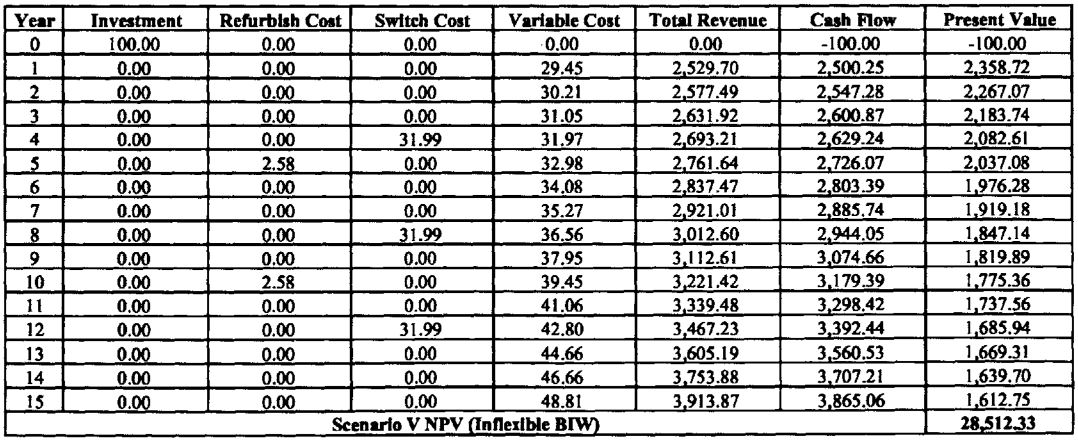
Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.21	2,577.49	2,547.28	2,267.07
3	0.00	0.00	0.00	31.05	2,631.92	2,600.87	2,183.74
4	0.00	0.00	0.00	31.97	2,693.21	2,661.24	2,107.95
5	0.00	0.05	42.14	32.98	2,761.64	2,686.47	2,007.48
6	0.00	0.00	0.00	34.08	2,837.47	2,803.39	1,976.28
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	0.00	36.56	3,012.60	2,976.05	1,867.21
9	0.00	0.00	0.00	37.95	3,112.61	3,074.66	1,819.89
10	0.00	0.05	42.14	39.45	3,221.42	3,139.79	1,753.24
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	0.00	42.80	3,467.23	3,424.43	1,701.84
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	0.00	46.66	3,753.88	3,707.21	1,639.70
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario IV NPV (Inflexible BIW)							**28,521.94**

Figure D-7: $E[NPV]$ for Scenario IV, Inflexible BIW Design



Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	0.00	30.75	2,577.49	2,546.74	2,266.59
3	0.00	0.00	0.00	31.65	2,631.92	2,600.27	2,183.24
4	0.00	0.00	0.00	32.63	2,693.21	2,660.58	2,107.43
5	0.00	16.61	5.50	33.70	2,761.64	2,705.82	2,021.95
6	0.00	0.00	0.00	34.87	2,837.47	2,802.60	1,975.72
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	0.00	37.49	3,012.60	2,975.12	1,866.63
9	0.00	0.00	0.00	38.95	3,112.61	3,073.66	1,819.29
10	0.00	16.61	5.50	40.53	3,221.42	3,158.78	1,763.85
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	0.00	44.05	3,467.23	3,423.18	1,701.22
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	0.00	48.11	3,753.88	3,705.77	1,639.07
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario IV NPV (Flexible BIW)							**28,505.42**

Figure D-8: $E[NPV]$ for Scenario IV, Flexible BIW Design



Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.21	2,577.49	2,547.28	2,267.07
3	0.00	0.00	0.00	31.05	2,631.92	2,600.87	2,183.74
4	0.00	0.00	31.99	31.97	2,693.21	2,629.24	2,082.61
5	0.00	2.58	0.00	32.98	2,761.64	2,726.07	2,037.08
6	0.00	0.00	0.00	34.08	2,837.47	2,803.39	1,976.28
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	31.99	36.56	3,012.60	2,944.05	1,847.14
9	0.00	0.00	0.00	37.95	3,112.61	3,074.66	1,819.89
10	0.00	2.58	0.00	39.45	3,221.42	3,179.39	1,775.36
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	31.99	42.80	3,467.23	3,392.44	1,685.94
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	0.00	46.66	3,753.88	3,707.21	1,639.70
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario V NPV (Inflexible BIW)							**28,512.33**

Figure D-9: $E[NPV]$ for Scenario V, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	0.00	30.75	2,577.49	2,546.74	2,266.59
3	0.00	0.00	0.00	31.65	2,631.92	2,600.27	2,183.24
4	0.00	0.00	5.35	32.63	2,693.21	2,655.23	2,103.19
5	0.00	16.65	0.00	33.70	2,761.64	2,711.28	2,026.03
6	0.00	0.00	0.00	34.87	2,837.47	2,802.60	1,975.72
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	5.35	37.49	3,012.60	2,969.77	1,863.27
9	0.00	0.00	0.00	38.95	3,112.61	3,073.66	1,819.29
10	0.00	16.65	0.00	40.53	3,221.42	3,164.24	1,766.90
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	5.35	44.05	3,467.23	3,417.83	1,698.56
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	0.00	48.11	3,753.88	3,705.77	1,639.07
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario V NPV (Flexible BIW)							**28,502.30**

Figure D-10: $E[NPV]$ for Scenario V, Flexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.21	2,577.49	2,547.28	2,267.07
3	0.00	0.00	31.99	31.05	2,631.92	2,568.87	2,156.88
4	0.00	0.00	0.00	31.97	2,693.21	2,661.24	2,107.95
5	0.00	2.58	0.00	32.98	2,761.64	2,726.07	2,037.08
6	0.00	0.00	31.99	34.08	2,837.47	2,771.40	1,953.72
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	0.00	36.56	3,012.60	2,976.05	1,867.21
9	0.00	0.00	31.99	37.95	3,112.61	3,042.67	1,800.95
10	0.00	2.58	0.00	39.45	3,221.42	3,179.39	1,775.36
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	31.99	42.80	3,467.23	3,392.44	1,685.94
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	0.00	46.66	3,753.88	3,707.21	1,639.70
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario VI NPV (Inflexible BIW)							**28,489.39**

Figure D-11: $E[NPV]$ for Scenario VI, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	0.00	30.75	2,577.49	2,546.74	2,266.59
3	0.00	0.00	5.35	31.65	2,631.92	2,594.92	2,178.75
4	0.00	0.00	0.00	32.63	2,693.21	2,660.58	2,107.43
5	0.00	16.65	0.00	33.70	2,761.64	2,711.28	2,026.03
6	0.00	0.00	5.35	34.87	2,837.47	2,797.25	1,971.95
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	0.00	37.49	3,012.60	2,975.12	1,866.63
9	0.00	0.00	5.35	38.95	3,112.61	3,068.31	1,816.13
10	0.00	16.65	0.00	40.53	3,221.42	3,164.24	1,766.90
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	5.35	44.05	3,467.23	3,417.83	1,698.56
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	0.00	48.11	3,753.88	3,705.77	1,639.07
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario VI NPV (Flexible BIW)							**28,498.47**

Figure D-12: $E[NPV]$ for Scenario VI, Flexible BIW Design

Appendix E

Expected Profit (in NPV) for Uncertainty Scenarios VII - XII

In this appendix, the expected profit (in terms of NPV) for uncertainty scenarios VII - XII, presented in Chapter 5, are listed. All costs are normalized with respect to the initial investment cost of the inflexible BIW design (same for all scenarios).

Table E.1: Expected Annual Production Volume for Each p

Year	p_1	p_2	p_3
1	280,000	125,000	60,000
2	297,639	124,581	56,775
3	316,390	124,164	53,724
4	336,322	123,748	50,837
5	357,509	123,334	48,105
6	380,032	122,920	45,520
7	403,973	122,509	43,073
8	429,422	122,098	40,758
9	456,475	121,689	38,568
10	485,232	121,282	36,495
11	515,000	120,875	34,534
12	548,295	120,471	32,678
13	582,836	120,067	30,922
14	619,554	119,665	29,260
15	658,854	119,264	27,687

Year	**Investment**	**Refurbish Cost**	**Switch Cost**	**Variable Cost**	**Total Revenue**	**Cash Flow**	**Present Value**
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	31.99	30.21	2,577.49	2,515.28	2,238.59
3	0.00	0.00	0.00	31.05	2,631.92	2,600.87	2,183.74
4	0.00	0.00	31.99	31.97	2,693.21	2,629.24	2,082.61
5	0.00	2.58	0.00	32.98	2,761.64	2,726.07	2,037.08
6	0.00	0.00	31.99	34.08	2,837.47	2,771.40	1,953.72
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	31.99	36.56	3,012.60	2,944.05	1,847.14
9	0.00	0.00	0.00	37.95	3,112.61	3,074.66	1,819.89
10	0.00	2.58	31.99	39.45	3,221.42	3,147.40	1,757.49
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	31.99	42.80	3,467.23	3,392.44	1,685.94
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	31.99	46.66	3,753.88	3,675.22	1,625.55
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario VII NPV (Inflexible BIW)							**28,429.29**

Figure E-1: $E[NPV]$ for Scenario VII, Inflexible BIW Design

Year	**Investment**	**Refurbish Cost**	**Switch Cost**	**Variable Cost**	**Total Revenue**	**Cash Flow**	**Present Value**
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	5.35	30.75	2,577.49	2,541.39	2,261.83
3	0.00	0.00	0.00	31.65	2,631.92	2,600.27	2,183.24
4	0.00	0.00	5.35	32.63	2,693.21	2,655.23	2,103.19
5	0.00	16.65	0.00	33.70	2,761.64	2,711.28	2,026.03
6	0.00	0.00	5.35	34.87	2,837.47	2,797.25	1,971.95
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	5.35	37.49	3,012.60	2,969.77	1,863.27
9	0.00	0.00	0.00	38.95	3,112.61	3,073.66	1,819.29
10	0.00	16.65	5.35	40.53	3,221.42	3,158.89	1,763.91
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	5.35	44.05	3,467.23	3,417.83	1,698.56
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	5.35	48.11	3,753.88	3,700.42	1,636.70
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario VII NPV (Flexible BIW)							**28,488.42**

Figure E-2: $E[NPV]$ for Scenario VII, Flexible BIW Design

Year	**Investment**	**Refurbish Cost**	**Switch Cost**	**Variable Cost**	**Total Revenue**	**Cash Flow**	**Present Value**
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	31.99	29.45	2,529.70	2,468.25	2,328.54
2	0.00	0.00	31.99	30.21	2,577.49	2,515.28	2,238.59
3	0.00	0.00	31.99	31.05	2,631.92	2,568.87	2,156.88
4	0.00	0.00	31.99	31.97	2,693.21	2,629.24	2,082.61
5	0.00	2.58	31.99	32.98	2,761.64	2,694.08	2,013.17
6	0.00	0.00	31.99	34.08	2,837.47	2,771.40	1,953.72
7	0.00	0.00	31.99	35.27	2,921.01	2,853.75	1,897.90
8	0.00	0.00	31.99	36.56	3,012.60	2,944.05	1,847.14
9	0.00	0.00	31.99	37.95	3,112.61	3,042.67	1,800.95
10	0.00	2.58	31.99	39.45	3,221.42	3,147.40	1,757.49
11	0.00	0.00	31.99	41.06	3,339.48	3,266.42	1,720.71
12	0.00	0.00	31.99	42.80	3,467.23	3,392.44	1,685.94
13	0.00	0.00	31.99	44.66	3,605.19	3,528.53	1,654.31
14	0.00	0.00	31.99	46.66	3,753.88	3,675.22	1,625.55
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario VIII NPV (Inflexible BIW)							**28,276.26**

Figure E-3: $E[NPV]$ for Scenario VIII, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	5.35	29.94	2,529.70	2,494.41	2,353.22
2	0.00	0.00	5.35	30.75	2,577.49	2,541.39	2,261.83
3	0.00	0.00	5.35	31.65	2,631.92	2,594.92	2,178.75
4	0.00	0.00	5.35	32.63	2,693.21	2,655.23	2,103.19
5	0.00	16.65	5.35	33.70	2,761.64	2,705.93	2,022.03
6	0.00	0.00	5.35	34.87	2,837.47	2,797.25	1,971.95
7	0.00	0.00	5.35	36.12	2,921.01	2,879.53	1,915.05
8	0.00	0.00	5.35	37.49	3,012.60	2,969.77	1,863.27
9	0.00	0.00	5.35	38.95	3,112.61	3,068.31	1,816.13
10	0.00	16.65	5.35	40.53	3,221.42	3,158.89	1,763.91
11	0.00	0.00	5.35	42.23	3,339.48	3,291.90	1,734.13
12	0.00	0.00	5.35	44.05	3,467.23	3,417.83	1,698.56
13	0.00	0.00	5.35	46.01	3,605.19	3,553.83	1,666.17
14	0.00	0.00	5.35	48.11	3,753.88	3,700.42	1,636.70
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario VIII NPV (Flexible BIW)							**28,462.83**

Figure E-4: $E[NPV]$ for Scenario VIII, Flexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.21	2,577.49	2,547.28	2,267.07
3	0.00	0.00	0.00	31.05	2,631.92	2,600.87	2,183.74
4	0.00	0.00	42.33	31.97	2,693.21	2,618.91	2,074.42
5	0.00	0.00	0.00	32.98	2,761.64	2,728.66	2,039.01
6	0.00	0.00	0.00	34.08	2,837.47	2,803.39	1,976.28
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	42.33	36.56	3,012.60	2,933.72	1,840.65
9	0.00	0.00	0.00	37.95	3,112.61	3,074.66	1,819.89
10	0.00	0.00	0.00	39.45	3,221.42	3,181.98	1,776.80
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	42.33	42.80	3,467.23	3,382.11	1,680.80
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	0.00	46.66	3,753.88	3,707.21	1,639.70
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario IX NPV (Inflexible BIW)							**28,495.90**

Figure E-5: $E[NPV]$ for Scenario IX, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	0.00	30.75	2,577.49	2,546.74	2,266.59
3	0.00	0.00	0.00	31.65	2,631.92	2,600.27	2,183.24
4	0.00	0.00	5.51	32.63	2,693.21	2,655.07	2,103.07
5	0.00	16.61	0.00	33.70	2,761.64	2,711.32	2,026.06
6	0.00	0.00	0.00	34.87	2,837.47	2,802.60	1,975.72
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	5.51	37.49	3,012.60	2,969.61	1,863.17
9	0.00	0.00	0.00	38.95	3,112.61	3,073.66	1,819.29
10	0.00	16.61	0.00	40.53	3,221.42	3,164.28	1,766.92
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	5.51	44.05	3,467.23	3,417.67	1,698.48
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	0.00	48.11	3,753.88	3,705.77	1,639.07
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario IX NPV (Flexible BIW)							**28,502.05**

Figure E-6: $E[NPV]$ for Scenario IX, Flexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	0.00	30.21	2,577.49	2,547.28	2,267.07
3	0.00	0.00	42.33	31.05	2,631.92	2,558.54	2,148.20
4	0.00	0.00	0.00	31.97	2,693.21	2,661.24	2,107.95
5	0.00	0.00	0.00	32.98	2,761.64	2,728.66	2,039.01
6	0.00	0.00	42.33	34.08	2,837.47	2,761.06	1,946.44
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	0.00	36.56	3,012.60	2,976.05	1,867.21
9	0.00	0.00	42.33	37.95	3,112.61	3,032.33	1,794.83
10	0.00	0.00	0.00	39.45	3,221.42	3,181.98	1,776.80
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	42.33	42.80	3,467.23	3,382.11	1,680.80
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	0.00	46.66	3,753.88	3,707.21	1,639.70
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario X NPV (Inflexible BIW)							**28,465.56**

Figure E-7: $E[NPV]$ for Scenario X, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	0.00	30.75	2,577.49	2,546.74	2,266.59
3	0.00	0.00	5.51	31.65	2,631.92	2,594.76	2,178.61
4	0.00	0.00	0.00	32.63	2,693.21	2,660.58	2,107.43
5	0.00	16.61	0.00	33.70	2,761.64	2,711.32	2,026.06
6	0.00	0.00	5.51	34.87	2,837.47	2,797.10	1,971.84
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	0.00	37.49	3,012.60	2,975.12	1,866.63
9	0.00	0.00	5.51	38.95	3,112.61	3,068.15	1,816.03
10	0.00	16.61	0.00	40.53	3,221.42	3,164.28	1,766.92
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	5.51	44.05	3,467.23	3,417.67	1,698.48
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	0.00	48.11	3,753.88	3,705.77	1,639.07
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario X NPV (Flexible BIW)							**28,498.11**

Figure E-8: $E[NPV]$ for Scenario X, Flexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	0.00	29.45	2,529.70	2,500.25	2,358.72
2	0.00	0.00	42.33	30.21	2,577.49	2,504.95	2,229.40
3	0.00	0.00	0.00	31.05	2,631.92	2,600.87	2,183.74
4	0.00	0.00	42.33	31.97	2,693.21	2,618.91	2,074.42
5	0.00	0.00	0.00	32.98	2,761.64	2,728.66	2,039.01
6	0.00	0.00	42.33	34.08	2,837.47	2,761.06	1,946.44
7	0.00	0.00	0.00	35.27	2,921.01	2,885.74	1,919.18
8	0.00	0.00	42.33	36.56	3,012.60	2,933.72	1,840.65
9	0.00	0.00	0.00	37.95	3,112.61	3,074.66	1,819.89
10	0.00	0.00	42.33	39.45	3,221.42	3,139.65	1,753.16
11	0.00	0.00	0.00	41.06	3,339.48	3,298.42	1,737.56
12	0.00	0.00	42.33	42.80	3,467.23	3,382.11	1,680.80
13	0.00	0.00	0.00	44.66	3,605.19	3,560.53	1,669.31
14	0.00	0.00	42.33	46.66	3,753.88	3,664.89	1,620.98
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario XI NPV (Inflexible BIW)							**28,386.04**

Figure E-9: $E[NPV]$ for Scenario XI, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	0.00	29.94	2,529.70	2,499.76	2,358.27
2	0.00	0.00	5.51	30.75	2,577.49	2,541.23	2,261.69
3	0.00	0.00	0.00	31.65	2,631.92	2,600.27	2,183.24
4	0.00	0.00	5.51	32.63	2,693.21	2,655.07	2,103.07
5	0.00	16.61	0.00	33.70	2,761.64	2,711.32	2,026.06
6	0.00	0.00	5.51	34.87	2,837.47	2,797.10	1,971.84
7	0.00	0.00	0.00	36.12	2,921.01	2,884.88	1,918.61
8	0.00	0.00	5.51	37.49	3,012.60	2,969.61	1,863.17
9	0.00	0.00	0.00	38.95	3,112.61	3,073.66	1,819.29
10	0.00	16.61	5.51	40.53	3,221.42	3,158.77	1,763.84
11	0.00	0.00	0.00	42.23	3,339.48	3,297.25	1,736.95
12	0.00	0.00	5.51	44.05	3,467.23	3,417.67	1,698.48
13	0.00	0.00	0.00	46.01	3,605.19	3,559.18	1,668.68
14	0.00	0.00	5.51	48.11	3,753.88	3,700.27	1,636.63
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario XI NPV (Flexible BIW)							**28,487.76**

Figure E-10: $E[NPV]$ for Scenario XI, Flexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	100.00	0.00	0.00	0.00	0.00	-100.00	-100.00
1	0.00	0.00	42.33	29.45	2,529.70	2,457.92	2,318.79
2	0.00	0.00	42.33	30.21	2,577.49	2,504.95	2,229.40
3	0.00	0.00	42.33	31.05	2,631.92	2,558.54	2,148.20
4	0.00	0.00	42.33	31.97	2,693.21	2,618.91	2,074.42
5	0.00	0.00	42.33	32.98	2,761.64	2,686.33	2,007.38
6	0.00	0.00	42.33	34.08	2,837.47	2,761.06	1,946.44
7	0.00	0.00	42.33	35.27	2,921.01	2,843.41	1,891.03
8	0.00	0.00	42.33	36.56	3,012.60	2,933.72	1,840.65
9	0.00	0.00	42.33	37.95	3,112.61	3,032.33	1,794.83
10	0.00	0.00	42.33	39.45	3,221.42	3,139.65	1,753.16
11	0.00	0.00	42.33	41.06	3,339.48	3,256.09	1,715.27
12	0.00	0.00	42.33	42.80	3,467.23	3,382.11	1,680.80
13	0.00	0.00	42.33	44.66	3,605.19	3,518.20	1,649.47
14	0.00	0.00	42.33	46.66	3,753.88	3,664.89	1,620.98
15	0.00	0.00	0.00	48.81	3,913.87	3,865.06	1,612.75
Scenario XII NPV (Inflexible BIW)							**28,183.59**

Figure E-11: $E[NPV]$ for Scenario XII, Inflexible BIW Design

Year	Investment	Refurbish Cost	Switch Cost	Variable Cost	Total Revenue	Cash Flow	Present Value
0	134.17	0.00	0.00	0.00	0.00	-134.17	-134.17
1	0.00	0.00	5.51	29.94	2,529.70	2,494.26	2,353.07
2	0.00	0.00	5.51	30.75	2,577.49	2,541.23	2,261.69
3	0.00	0.00	5.51	31.65	2,631.92	2,594.76	2,178.61
4	0.00	0.00	5.51	32.63	2,693.21	2,655.07	2,103.07
5	0.00	16.61	5.51	33.70	2,761.64	2,705.82	2,021.94
6	0.00	0.00	5.51	34.87	2,837.47	2,797.10	1,971.84
7	0.00	0.00	5.51	36.12	2,921.01	2,879.38	1,914.95
8	0.00	0.00	5.51	37.49	3,012.60	2,969.61	1,863.17
9	0.00	0.00	5.51	38.95	3,112.61	3,068.15	1,816.03
10	0.00	16.61	5.51	40.53	3,221.42	3,158.77	1,763.84
11	0.00	0.00	5.51	42.23	3,339.48	3,291.74	1,734.05
12	0.00	0.00	5.51	44.05	3,467.23	3,417.67	1,698.48
13	0.00	0.00	5.51	46.01	3,605.19	3,553.68	1,666.10
14	0.00	0.00	5.51	48.11	3,753.88	3,700.27	1,636.63
15	0.00	0.00	0.00	50.35	3,913.87	3,863.52	1,612.11
Scenario XII NPV (Flexible BIW)							**28,461.43**

Figure E-12: $E[NPV]$ for Scenario XII, Flexible BIW Design