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Flexible Product Platforms: Framework and Case Study

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Abstract Mass customization and market uncertainty require increased functional and physical bandwidth in product platforms. This paper presents a flexible platform design process in response to such future uncertainty. The process consists of seven iterative steps and is applied to an automotive body-in-white (BIW) where 10 out of 21 components are identified as potential candidates for embedding flexibility. The paper shows how to systematically pinpoint and value flexible elements in platforms. This allows increased product family profit despite uncertain variant demand, and specification changes. We show how embedding flexibility suppresses change propagation and lowers switch costs, despite an increase of 34% in initial investment for equipment and tooling. Monte Carlo simulation results of 12 future scenarios reveal that as the degree of uncertainty increases, the value of embedding flexibility also increases. The findings suggest that if length and styling changes occur every four years or faster, the flexible BIW platform will be superior.

Keywords Product Family, Product Platform, Change Propagation · Flexibility

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1 Introduction

Mass customization emerged as a paradigm in the late 1980s (Pine 1993). Mass customization focuses on serving the needs of individual customers through high product variety while achieving economies of scale through high volume production that uses flexible manufacturing processes. This paradigm was the result of emergent global markets that created new market segments reflecting age, gender, ethnicity and lifestyle. The resulting increase in product variety demanded a corresponding decrease in development time (Sanderson and Uzumeri 1997). Manufacturers were forced to seek more efficient and flexible product design and manufacturing strategies to respond to pressures that included regional policies and regulations, demand for more product variety, rising costs for raw materials, labor costs, and manufacturing resources, and faster evolution of new technologies.

Two of the more successful strategies were the lean manufacturing strategy (Womack et al. 1991) and the product platform strategy (Meyer and Lehnerd 1997; Bremmer 1999). The lean manufacturing strategy attempts to reduce manufacturing costs by 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. Both strategies have received significant attention in the literature, but opportunities for further research still abound. This is mainly so because new situations arise that are not handled by the traditional approaches. Lean supply chains have been shown to be excessively vulnerable due to unexpected disruptions (terrorism, natural disasters). Product platforms often turn out to be overly constraining in a dynamic market environment.

Figure 1 illustrates this last point by showing the percent change in aggregate demand for various types of automobiles in the United States from 2003 to 2004. While small sports utility vehicles (SUV) and crossover wagons gained in popularity, traditional large cars (sedans) and pickup trucks suffered significant losses. These market dynamics are caused by a multitude of factors such as the price of fuel, changing demographics, government regulations for safety, emissions and fuel economy, international competition and shifting customer preferences in terms of styling and favored functional attributes.

When new products are designed in response to or anticipation of such changes, the manufacturing firm has essentially two alternatives: design a full up new product or derive a product by modifying an existing product to suit the changed requirements. If these modifications are done in a systematic way with sharing

Type of Model	2004 unit sales	% change from 2003
Small SUV	269,851	18.5
Sport wagon/crossover	1,734,622	13
Large pickup trucks	2,456,656	7.8
Large van	344,693	6.6
Luxury cars	1,496,753	4.4
Minivan	1,110,817	3.4
Midsize SUV	1,742,463	0.7
Luxury SUV	237,065	-0.6
Midsize car	3,500,065	-1.1
Small car	2,194,148	-1.8
Large SUV	759,157	-6.1
Small pickup truck	653,823	-10.6
Large car	306,257	-25

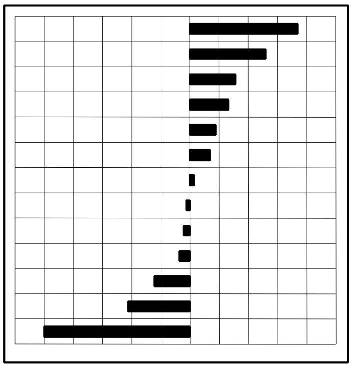


Fig. 1 Changes in aggregate unit sales from 2003 to 2004 for U.S. car and truck market (Simmons 2005)

of common elements across multiple variants we call this a platform strategy. Figure 2 shows an example of a new vehicle derived from an existing platform. The exploded view highlights new and unique components (dark gray), carryover-modified (light grey) and carryover-common (medium grey) components. Only the last category of elements is reused without modifications.

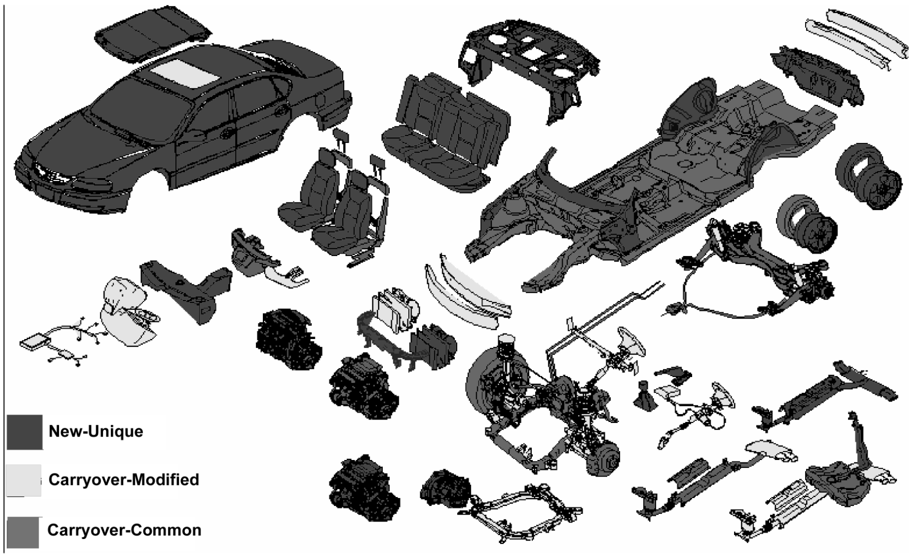


Fig. 2 Decomposition of new automotive product (courtesy: General Motors, 2004)

The tension between wanting to reuse as much as possible from previous products, i.e. having the platform comprise a large percentage of the product, and the desire for innovation and new styling requiring many new and unique components is well documented in practice and in the academic literature (Simpson 2005).

Reusing the common platform frequently will facilitate learning curves and economies of scale in manufacturing. Creating many new and unique components on the other hand can lead to fresh products and potentially higher sales, but also causes a “mushrooming” of the firm’s Bill of Materials (BOM).

What has not received a lot of attention is the second category of components in Figure 2. The components labeled as “carryover-modified” are those that are very similar to existing components, but not exactly the same. These components are generated by redesign of existing components, and such redesigns are most often done in an expensive reactive mode. The degree of change varies, but oftentimes these components require substantial redesign as well as tooling and equipment changes in manufacturing. The purpose of this paper is to develop and demonstrate a systematic design process for treating such elements as “flexible elements” and to consider them as part of an expanded product platform. The hypothesis is that if the right subset of elements is designed with flexibility, that a platform will be more nimble in the future, therefore avoiding expensive redesigns and manufacturing switch costs. We strive to (1) demonstrate how to select flexible elements by projecting exogenous uncertainty into the platform and (2) to quantify both the additional upfront investment required to achieve this flexibility as well as the downstream benefits resulting from the investment. Our assertion is that some firms are better than others at anticipating trends on short time scales of 2-3 years, or even at setting trends or influencing future preferences, but that no firm has the ability to predict the future with certainty on time scales of 10-15 years corresponding to typical lifetimes of complex product platforms. This is where flexible product platforms can add strategic value.

After a brief literature review in Section 2, we present a general flexible product platform design process in Section 3. This flexible platform design process takes exogenous uncertainties into account and incorporates the concept of flexible elements. Flexibility is defined as “the property of a system that is capable of undergoing specified classes of changes with relative ease (Moses 2002).” In Section 4 we demonstrate the process in a real world case study where three car variants are to be built from a common, but flexible platform. We will show that while the original purpose of product platforms was to create a flexible infrastructure for a family of products, designers and manufacturers still need to know how to identify the places to embed flexibility. How much flexibility is needed? How much will flexibility cost? What are the future benefits of flexibility?

2 Previous Work

The state of the art in product family and platform design research has been recently summarized and broadly reviewed by Simpson, Siddique and Jiao (2005). Instead of repeating such a review here, we will focus our discussion on five papers that are most closely related to product platform design under uncertainty. They are papers published by Simpson et al. (2001), Martin and Ishii (2002), Li and Azarm (2002), and Gonzalez-Zugasti, Otto et al. (2000, 2001).

Simpson et al. (2001) proposed the Product Platform Concept Exploration Method (PPCEM). In the paper, the authors state that PPCEM 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 and validation, 4) product platform specifications aggregation, and 5) product platform and family development. The method is demonstrated through a universal motor case study, in which a family of ten motors is designed by varying the stack length.

Martin and Ishii (2002) proposed another platform design method, called the Design for Variety (DFV) method, to develop modularized product platforms (2002). The authors used the Generational Variety Index (GVI) and Coupling Index (CI) to design platforms 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 the other." The method is demonstrated through a water cooler example, in which the GVI and CI for seven major components are calculated. Then, for components with high GVI and CI, flexible designs are generated to reduce GVI and CI, thus lowering future redesign (switch) cost.

Li and Azarm (2002) developed a design process for a 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 optimized and evaluated using a Multi-Objective Genetic Algorithm (Narayanan and Azarm 1999), due to the combinatorial nature of the formulated optimization problem. In the end, the best product line (family) is chosen using a selection rule, which takes into account the designer's utility of the product line balance. The proposed design process was demonstrated through a case study in which a cordless screw driver family is designed. Of the three major components (motor, gear, battery), the motor was designated as the platform component a *priori*. Through optimization of the other components, the authors identified best designs for several different uncertain scenarios.

Finally, Gonzalez-Zugasti, Otto and Baker introduced a quantitative method to design product platforms (Gonzalez-Zugasti et al. 2000) and a framework to assess value of the product platform-based family using the real options approach (Gonzalez-Zugasti et al. 2001). In the first paper, the proposed method was implemented for an interplanetary spacecraft family in which three candidate platform designs based on various telecommunications technologies and bandwidths (X-band, Ka-band, optical) were optimized for mass, cost, and launch margin, given a pre-determined set of future NASA missions. In the second paper, the interplanetary spacecraft family was evaluated under uncertain future mission requirements and platform development investments were valued using the real options approach.

This previous research covers several areas of product platform design which inspired our work. However, of all previously published methods, none deal with a complete end-to-end design process in which the uncertainty is systematically mapped to product attributes, design variables, physical components, flexible designs, and 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 they offered 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 consequences and subsequent uncertainty analysis were not developed. Work by Simpson et al. deals with scalable ("flexible") universal motors, but only optimizes them for current needs. Finally, most of the previous work deals with rather simple examples, thus not fully capturing the intricacy of designing complex products. The main difficulty in going from simple to complex products is that the product architecture is not trivial and that the effects of change propagation (Eckert et al. 2004) must be captured. The research discussed in this paper contributes to the product platform design process, when future uncertainty is taken into account. In the next section, the steps and logic of the flexible platform design process are presented.

3 Design Process Formulation

3.1 Overview

Figure 3 outlines the framework for designing flexible product platforms. This process is to be applied during the early stages of product platform development in order to establish a system-level platform definition. This process precedes the actual product development process in which individual product variants are designed in detail. The process in Figure 3 resulted from numerous discussions and iterations with car designers and vehicle architects at a large automotive manufacturer. However, we believe the process to be general enough to be applied to other types of physical products.

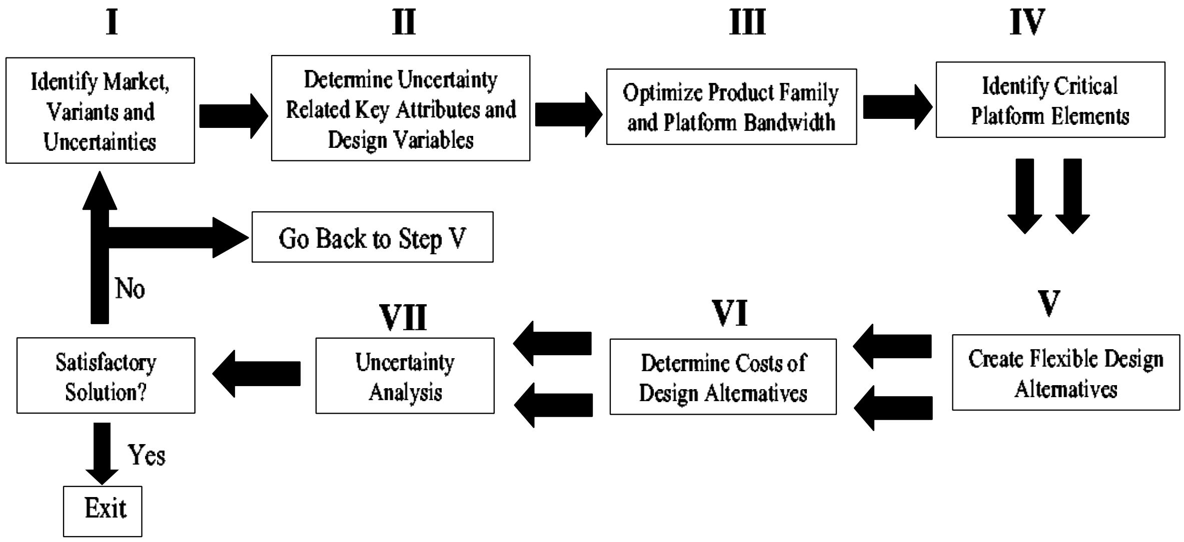


Fig. 3 Flexible Product Platform Design Process. Multiple arrows indicate that several alternatives could be carried along.

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). Subsequently, functional product attributes impacted by uncertainty and related system-level design variables are identified (Step II). The identified set of design variables for each product variant in the family is optimized to yield maximum product family revenue (Step III). In this way the required bandwidth for key product design variables in the product family is determined. Given the requirement to achieve bandwidth for uncertainty-related design variables, a critical set of physical elements, affected by the design variable change, is determined via change propagation analysis (Step IV). Using the identified physical elements and given bandwidth requirements, flexible platform design alternatives are generated (Step V). Initial investment, variable costs, and switch costs for the design alternatives are calculated in Step VI. The final step in the framework consists of uncertainty analysis (Step VII), wherein the benefit of each design alternative is estimated under future scenarios with varying degrees of uncertainty. Finally, the best flexible platform design alternative is selected, or one enters a loop back to Step I or Step V if a satisfactory solution has not been found. For each of the steps in the platform design process a variety of methods and tools may be used, see Table 1:

Table 1 Methodologies and Tools for Individual Design Steps

Design Step	Available Methodologies and Tools
Step I	Clustering Analysis (Jajuga et. al 2002), Conjoint Analysis (1992)
Step II	Principal Components Analysis (Dunteman 1999), QFD (Hauser 1988), Response Surfaces (Myers 2002)
Step III	Gradient-based Optimization (Arora 1989), Heuristic Optimization (Goldberg 1989, Kirckpatrick et al. 1983)
Step IV	Change Propagation Analysis (Eckert et al. 2004), Engineering Expertise (Bahl and Beitz 1996), QFD
Step V	Brainstorming (Pahl and Beitz 1996), Concept Screening and Scoring Matrix (Ulrich and Eppinger 1999)
Step VI	Parametric Cost Modeling (Kirchain 2004)
Step VII	Decision Trees (Clemen 1996), NPV Analysis (de Neufville et al. 2004), Real Options (Trigeorgis 1996)

The sections that follow present the generic mathematical formulation and give explanations for each step of the design framework.

3.2 Step I: Identify Market, Variants, and Uncertainties

The first step of the process is to identify target market segments $\mathscr{M} = [M_1, M_2, ...]$, desired product variants $\mathscr{P} = \left[p_1, p_2, ..., p_{n_p}\right]$ assigned to those segments, and a set of uncertainties $\mathscr{U} = [u_1, u_2, ...]$ that are related to $\mathscr{M}$ and $\mathscr{P}$. It is assumed that all product variants in a product family set $\mathscr{P}$ will be derived from a common product platform. A graphical representation of the assignment of the set of variants $\mathscr{P}$ to the set of market segments $\mathscr{M}$ and is shown in Figure 4.

A set of market segments $\mathscr{M}$ for a specific type of product is typically defined through clustering analysis (Jajuga et al. 2002). Figure 4(a) shows how small, medium and large sedans as well as vans cluster in terms of passenger volume [cft] versus price [2002 $]. We can see that products in the same market segment are grouped together in terms of similar product attributes.

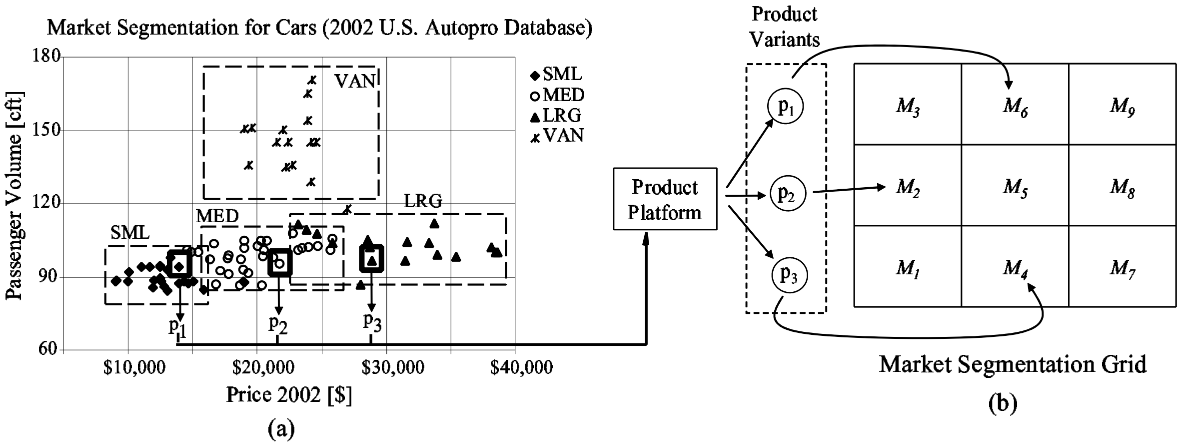


Fig. 4 (a) Market Segmentation based on Clustering; (b) Placement of Platform-derived Product Variants in Market Segments

Once the set of market segments $\mathscr{M}$ is defined, a set of product variants $\mathscr{P}$ can be positioned in the individual market segments. Figure 4(a) assumes that three variants: p_1 a small sedan, p_2 a mid-size sedan and p_3 a large sedan are built from the same platform and differentiated via price and other attributes not shown on the chart. A product provides value to customers by offering attributes such as passenger volume, acceleration, fuel economy and so forth. An individual product variant can therefore be expressed as a vector of specific product attributes ($\mathbf{J}_A$) and price (P), i.e. let $p_i = [\mathbf{J}_{A,i}\ P_i]^T$. Therefore, the product variant set (family) $\mathscr{P}$ can be expressed as a matrix of specific product attributes' values and prices, as shown in Equation (1):

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

The last item to be defined in this step is a set of critical uncertainties $\mathscr{U}$ that might impact the design of the product platform. Specifically, in this paper we acknowledge that customer preferences, regulations, fuel prices, overall economic conditions and new technologies are dynamic quantities that change over time. Figure 1 demonstrated that demand can change significantly for different market segments from year to year, whereby such fluctuations can be amplified for individual product variants. To illustrate this point, Table 2 summarizes how various quantities have evolved dynamically in the sports utility vehicle (SUV) market in North America in the period from 1999-2003.

Table 2 Dynamic evolution of SUV market in North America. 1999-2003 (Autopro 2003) averages: D=demand, FE=combined fuel economy (city & highway), HT= height, WB= wheelbase, HP = horsepower, P=price

Year	D [units]	FE [mpg]	HT [in]	WB [in]	HP [hp]	P [$]
1999	2,780,568	17.9	69.4	107.5	196.9	28,794
2000	3,221,683	17.9	69.8	107.6	200.3	30,164
2001	3,835,129	18.4	69.6	107.5	199.2	29,928
2002	3,728,810	18.6	70.5	108.4	204.7	31,529
2003	4,169,317	18.8	70.8	109.5	214.9	31,567
5y Avg	Δ D/y	Δ FE/y	Δ HT/y	Δ WB/y	Δ HP/y	Δ P/y
%/y	+10.0	+1.0	+0.4	+0.4	+1.8	+1.9

The data suggests that the aggregate SUV market has grown at an average rate of 10% per year and that these types of vehicles have grown larger, more powerful and yet slightly more fuel efficient over the same 5 year period. Recently however, the SUV market has softened significantly due to concerns over high gasoline prices. So, a 2005 or 2010 prediction based on a linear extrapolation of the 1999-2003 trend would have been wrong and misleading. Moreover, the data shows that exogenous uncertainties and future trends cannot be ignored in engineering design of product platforms that have long lifecycles. The main issue addressed by the flexible platform design process (Fig. 3) is that product platforms often have a lifecycle that exceeds that of the variants built from it and that market and technological trends are difficult or impossible to predict accurately over such planning horizons. A platform must be designed not only to accommodate several product variants at its point of inception, but also be flexible in regard to future uncertainties.

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

In the previous step, we identified market segments $\mathscr{M}$, product variants $\mathscr{P}$, and uncertainties $\mathscr{U}$. Each market segment M_j can be expressed as a range of customer-preferred attribute values and price, within which a specific product variant's $\mathbf{J}_{A,i}$ and price P_i must fall (see dashed boxes in Fig. 4(a)) :

$$M_j = \left\{ \begin{array}{l} \mathbf{J}_{A,j} : \left(\mathbf{J}_{A,j}\right)_{\min} \leq \mathbf{J}_{A,i} \leq \left(\mathbf{J}_{A,j}\right)_{\max} \\ \mathrm{P}_j : \left(\mathrm{P}_j\right)_{\min} \leq \mathrm{P}_i \leq \left(\mathrm{P}_j\right)_{\max} \end{array} \right\} \tag{2}$$

Depending on the number and position of competing products and the firms own current product attribute values in a specific market segment M_j, the firm needs to set their i^{th} product's $\mathbf{J}_{A,i}$ and P_i values within the established range of M_j in order to gain market share and a competitive position. $\mathbf{J}_A$ is a function of a system-level design variable vector $\mathbf{X}_A$. Examples of system-level design variables $x_{A,i} \in \mathbf{X}_A$ are height, wheelbase and engine horsepower rating (see Table 2) in automobiles. These are design variables because customers don't value these variables directly and designers can choose their instantiations freely (within bounds). The term "system-level" implies that these variables are not directly associated with individual components such as the ones shown in Figure 2, but instead they describe the product at an aggregate level. We write:

$$\mathscr{P} = \begin{bmatrix} \mathbf{J}_{A,1}(\mathbf{X}_{A,1}) & \mathbf{J}_{A,2}(\mathbf{X}_{A,2}) & \dots \\ \mathrm{P}_1 & \mathrm{P}_2 & \dots \end{bmatrix} \tag{3}$$

Even though there can be many different product attributes within $\mathbf{J}_A$, the ones that are of special interest are product attributes that are related to the set of uncertainties, $\mathscr{U}$. A product attribute vector, related to a set of uncertainties $\mathscr{U}$, can be expressed as $\mathbf{J}_{\mathscr{U}}$, where $\mathbf{J}_{\mathscr{U}} \subseteq \mathbf{J}_A$. These attributes are significantly affected by the uncertainties identified in Step I and must be mapped to system-level design variables.

The next step is to establish the relationship between the uncertainty-specific product attributes $\mathbf{J}_{\mathscr{U}}$ and the related system-level design vector $\mathbf{X}_{\mathscr{U}}$, where $\mathbf{X}_{\mathscr{U}} \subseteq \mathbf{X}_A$. This is expressed as

$$\mathbf{J}_{\mathscr{U}} = f(\mathbf{X}_{\mathscr{U}}) \tag{4}$$

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

3.4 Step III: Optimize Product Family and Platform Bandwidth

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

$$\begin{aligned} &\text{maximize} \sum_{\text{i}=1}^{n_p} R_{p_i}\left(\mathbf{J}_{u,i}\left(\mathbf{X}_{u,i}\right), P_i\right) \\ &\text{s.t. } \mathrm{h}\left(\mathbf{J}_{u,i}, \mathbf{X}_{u,i}\right) = 0 \\ &\text{s.t. } \mathrm{g}\left(\mathbf{J}_{u,i}, \mathbf{X}_{u,i}\right) < 0 \end{aligned} \tag{5}$$

where R_{p_i} is the total revenue generated by the i^{th} product variant, and h and g are inequality and equality constraints that must be satisfied. Individual product variant revenue R_{p_i} is further explained in Equation (6):

$$R_{p_i} = ms_{i,j}\left(\mathbf{J}_{u,i}\left(\mathbf{X}_{u,i}\right), \mathrm{P}_i\right) \mathrm{P}_i \mathrm{D}_{T,j} \tag{6}$$

where $ms_{i,j}$ is the market share for the i^{th} product variant in its assigned market segment M_j, and $D_{T,j}$ is the total current demand existing in the market segment M_j. Market share is a function of product attribute values $\mathbf{J}_A$ and variant price P. However, in this step, only attributes related to $\mathbf{J}_{\mathscr{U}}$ and price P will be perturbed while other attributes will be fixed to a specific value for each product variant i (thus Equation (6)).

Estimating a reliable market share for given values of $\mathbf{J}_{A,i}$ and P_i is, in itself, a large research field. It can be accomplished through conjoint analysis (1992), in which companies estimate customers' preference sensitivities for particular products by systematically changing the product's attribute values. Once the maximum revenue generating solution for Equation (5) is obtained through optimization, the values of $\mathbf{X}_{\mathscr{U},i}$ and $\mathbf{J}_{\mathscr{U},i}$ for each product variant are determined, thus defining the bandwidth of the product platform in both the system-level design variable space and the customer-preferred attribute space. Figure 5 shows bandwidths of a hypothetical product platform in design variable and attribute space (grey shaded area).

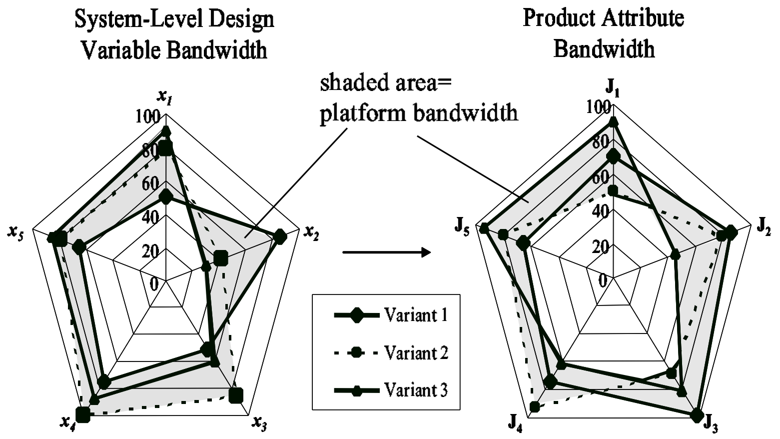
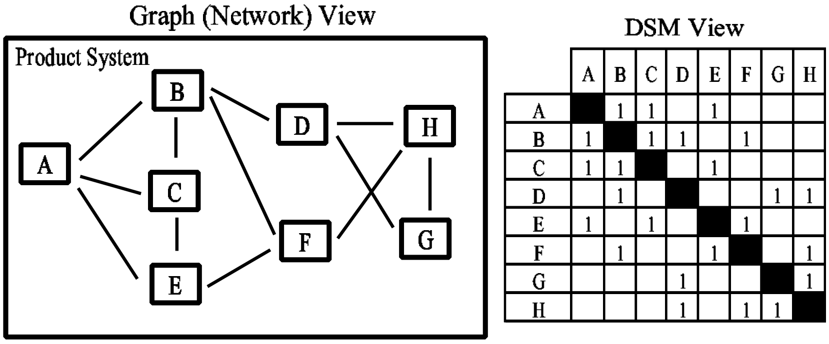


Fig. 5 Platform Bandwidth in Design Variable and Product Attribute Space

3.5 Step IV: Identify Critical Elements for Flexibility

After establishing the platform bandwidth, each $x_i \subseteq \mathbf{X}_{\mathscr{U}}$, must be mapped to a set of specific physical elements. This is an important prelude to identifying critical platform elements that must be flexible enough to achieve the desired design variable bandwidth, as dictated by the result of variant optimization in Step III. This step will be explained using a generic example.



	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	■

Fig. 6 Graph and DSM Representation of a Generic System

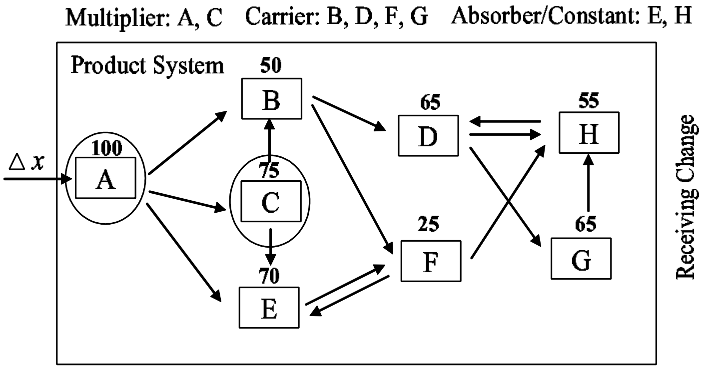
Figure 6 shows both a graph (network) and Design Structure Matrix (DSM) representation of a generic product system. Within the system, there are eight physical elements (A – H) connected to each other. Elements can be connected physically (e.g. welded together), or through information (e.g. signals), energy (e.g. electrical power) or fluid flow. The DSM represents the system using a matrix format with 1’s indicating connectivity between elements, see Eppinger et al. (1998). This is useful because (1) when a system-level design variable is required to be flexible, the designer needs to identify system elements affected by such change; and (2) when the identified elements are changing, the system designer must observe the change propagation to other elements (which may not be directly related to $\mathbf{X}_{\mathscr{U}}$) to estimate the effects of change.

Next, for every x_i in $\mathbf{X}_{\mathscr{U}}$ that must be flexible in terms of variable range (Fig. 5), the designer must observe how a change in Δx propagates throughout the system. We refer to Eckert et al.’s (2004) seminal work on change propagation in this context. The questions then arise: what are reasons that initiate such changes, and how does element flexibility help to accommodate such changes? We propose that there are four sources of changes for product platforms:

1. Non-zero bandwidth of design variables is required by the revenue optimization (Step III, Fig. 5).

2. Product family revenue or market share might be very sensitive to some design variables and might benefit from flexibility in the future, even if the initially required bandwidth is zero or very small.
3. Changes might be required in response to changes in other coupled elements of the system through change propagation.
4. Unknown additional product variants might be added in the future, possibly within the pre-established platform bandwidth, but potentially also outside the bandwidth.

Figure 7 shows how a hypothetical change Δx can propagate through the system. This figure represents the final system configuration after the change (due to Δx) has been implemented, showing the direction of change propagation.



Propagating Change

Receiving Change

	A	B	C	D	E	F	G	H	ΔE_{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
ΔE_{out}	3	2	2	2	1	2	1	1	
CPI	**3**	**0**	**1**	**0**	**-1**	**0**	**0**	**-2**	
Class	**M**	**C**	**M**	**C**	**A**	**C**	**C**	**A**	

Fig. 7 Change Propagation Due to Δx

The terms *multiplier, carrier, absorber*, and *constant* have been defined by Eckert et al. (2004) to classify elements that react to changes. We find this nomenclature compelling and adopt it here. *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 7, 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?

Once each element's reaction to change can be measured quantitatively, then the system architect or designer can identify, for a given design change, critical elements for embedding flexibility. To measure the degree of change propagation for a single element, we introduce a new metric. For a single element i, the Change Propagation Index (CPI) measures the degree of physical change propagation caused by this element when the change is imposed on the element. Equation (7) is shown below:

$$CPI_i = \sum_{j=1}^{n_{out}} \Delta E_{out,j} - \sum_{k=1}^{n_{in}} \Delta E_{in,k} \tag{7}$$

In Equation (7), 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} element 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 the i^{th} element. CPI helps classify elements and measures physical change propagation to other elements.

However, simply measuring the degree and number of physical change propagation instances is not enough. One must consider the economic impact caused by Δx on the system via its affected elements. For each element changed, the change-related investment cost (switch cost K_{switch}) needs to be identified. This provides the system architect with two quantitative measures for each element and each type of change Δx: one indicating the degree of physical change propagation (CPI), and the other indicating the economic consequence of such change (K_{switch}).

In Figure 7, the final state of change propagation is shown for a system after it has been altered due to the design variable change Δx. This final state can be expressed in matrix form shown in Figure 7 (right side). The column sum indicates the total number of changes going outward from a specific element ($\sum \Delta E_{out}$). The row sum 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 the CPI value for each specific element. Depending on the value of the CPI, an element can be classified according to the terms previously defined. A positive CPI indicates that the element is a *multiplier* (class **M**); a zero CPI indicates that the element is a *carrier* (class **Ca**); a negative number indicates that the element is either an *absorber* (class **A**) or a *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 (2002).

The numbers added on top of each component in Figure 7 (left) show the relevant switch cost, K_{switch} (hypothetical) due to 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 engineering cost of design changes and additional fabrication and assembly tooling and equipment investment to implement the changes. Based on the CPI and switch cost incurred for each element, the following recommendations can be made for selecting critical elements and designing them to be flexible:

1. Multiplier elements are prime candidates for incorporating flexibility. These are elements that, as more changes are added, make the system harder to change.
2. One must investigate elements connected to multiplier elements to understand the nature of change. These elements might require flexibility (a "*buffer*" to absorb the change, as Eckert (2004) calls them) to reduce or even eliminate change propagation.
3. Carrier elements must be examined as well. For example, a carrier element might receive changes from five elements and send out five changes, making it more expensive than a multiplier element that receives change from only one element and sends it out to two elements.
4. 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 unattractive to change the system.
5. Suppression of physical change 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 result in more change propagation. All these factors must be weighed to reach a decision for incorporating flexibility.

Efforts 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 that they can be changed with significantly lower switch cost. One practical example comes from the automotive industry. When engineers design a front motor compartment (see Section 4), they may have the 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 a 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.

3.6 Step V: Create Flexible Design Alternatives

With target elements for embedding flexibility identified in Step IV, the system designer must consider changing the elements so that they propagate a smaller degree of change and/or require lower switch cost than for the inflexible design. This is accomplished by embedding flexibility into key elements - the ones that have the greatest impact. According to Hull (1993) and de Neufville (2004), such flexibility is a *real option*, in which we can either avoid downside risks or exploit upside opportunities.” However, this flexibility will often incur additional upfront investment and might result in additional system complexity. This raises important questions: How much flexibility is needed? How should it be embedded into these elements?

To answer the first question, we examine the platform bandwidth obtained by the revenue optimization in Step III (Fig. 5). The upper and lower limit values of $\mathbf{X}_A$, established through Equation (5), set the range within which the platform must be flexible. Additionally, sensitive system design variables in $\mathbf{X}_{\mathscr{U}}$ need to be examined (see case study below).

Addressing the second question the system architect must consider several factors related to the identified elements such as the demand distribution among variants, the types of physical changes required and the frequency with which those changes are expected in terms of future product releases.

Embedded flexibility should be biased towards a particular p_i in $\mathscr{P}$ to yield favorable overall cost expenditure to amortize investments in flexible parts and tooling. After considering all factors discussed, the product architect can generate a set of different platform design alternatives. One of the challenges in this step is the non-uniqueness of the design space. For a given requirement of achieving platform bandwidth, multiple flexible designs can be generated (Pahl and Beitz (1996)). This point is illustrated in Figure 8 where three levers of different length A,B, and C must be produced (top). Rather than producing three distinct levers each requiring dedicated tooling we may conceive a number of flexible design alternatives to generate levers of varying lengths without impact on tooling. One flexible concept (Figure 8, bottom left) decomposes the lever into two overlapping parts whereby the length can be adjusted by lining up pre-drilled holes with a rivet. The second alternative uses a wingnut and slot to adjust lever length continuously between a lower and upper bound. Alternatively, one can think about various ways in which the levers A,B and C could be produced using flexible tooling. In complex products (see Section 4) a combination of flexibility in the elements themselves and in the manufacturing processes is often considered.

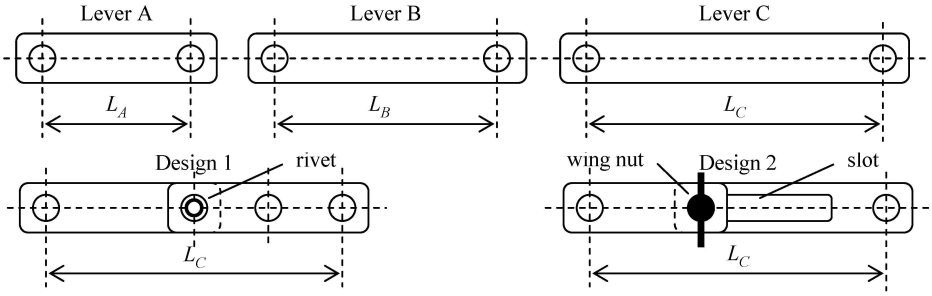


Fig. 8 Three distinct lever variants: A,B and C (top); flexible realization alternatives (bottom)

After flexible elements have been generated, the system is divided into two portions: (1) the product platform that consists of common elements, and flexible elements that, with minor modifications, can be used for multiple product variants, and (2) the unique portion of the product that is customized for each variant.

3.7 Step VI: Determine Costs of Design Alternatives

At the end of Step V, one or more flexible product platforms are defined. At a minimum we need to be able to compare two platform alternatives (rigid, flexible), but could include platforms with varying degrees of flexibility. To determine whether the generated platform design alternatives are flexible to change, accurate cost estimates for each alternative need to be generated. Costs are divided into the following categories:

1. Initial investment cost K_{init}, which includes fabrication and assembly equipment and corresponding tooling investments;
2. Variable cost C_{total}, which is the unit cost of each product multiplied by the number of products produced;
3. Switch related capital investment cost K_{switch}, which consist of investment costs caused by design changes.

To verify that the 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 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 (the option) is truly needed and can be amortized over the course of the product platform life cycle. With upfront investment cost, variable cost, and switch cost identified, the benefits of each design alternative must then be evaluated through uncertainty analysis.

3.8 Step VII: Uncertainty Analysis

Once all costs are identified, design alternatives must be evaluated under scenarios with varying degrees 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 net present value can be generically stated as:

$$E\left[NPV\right]_i = f\left(R_{T,i}, K_{\mathrm{init,i}}, C_{\mathrm{total,i}}, K_{\mathrm{switch,i}}, \mathscr{U}\right) \tag{8}$$

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 $K_{\mathrm{init,i}}$, the total variable cost $C_{\mathrm{total,i}}$, and the switch cost $K_{\mathrm{switch,i}}$ incurred due to $\mathscr{U}$, as defined in Step I. After evaluating the proposed platform design alternatives under several scenarios, the system architects can select the most beneficial platform design for a given uncertainty set $\mathscr{U}$. In the next section, the flexible platform process is demonstrated through a case study in which a vehicle platform is designed with flexibility to respond to future uncertainties in demand, length and styling.

4 Case Study: Automotive Vehicle Platform

4.1 Background

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. All three variants are mid-size to large passenger sedans in different market segments (Fig. 4) and have different requirements in terms of styling, production volume, and system-level design variables. Two variants will have a short wheelbase and one variant will be a stretched vehicle (long wheelbase). The new platform must be flexible enough to accommodate the initial vehicle variant specifications, as well as uncertain changes in the future. To achieve these objectives, we identify a critical subset of vehicle elements, incorporate flexibility into these platform elements, and then evaluate the flexible design under various uncertain scenarios. This case study investigates in detail the Body in White (BIW), an important vehicle structural sub-system. At the end, the final common, flexible and unique BIW platform elements are defined along with recommendations on when to implement a flexible BIW platform.

4.2 Step I: Identify Market, Variants, and Uncertainties

4.2.1 Market Segments

For this case study, the vehicle sedan market segment is divided into smaller segments according to vehicle size and price (see Fig. 4), ranging from low-end economy sedans to upper-end ultra luxury sedans.

4.2.2 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. We define the vehicle family $\mathscr{P}_{\text{veh}}$ as: $\mathscr{P}_{\text{veh}} = [p_1, p_2, p_3]$ where each p_i in set $\mathscr{P}_{\text{veh}}$ is described by specific values of $\mathbf{J}_A$ and P, according to Equation (1). Detailed explanations of $\mathbf{J}_A$ and P for this automotive market are presented in the next section. The three variants are positioned in the following market segments:

Table 3 Market Segment Designation for each Vehicle Variant p_i

Variant	Vehicle Market Segment
p_1	Mid Size Sedan
p_2	Large Sedan
p_3	Large Luxury Sedan

4.2.3 Uncertainties

In this case study, the following set of uncertainties $\mathscr{U}_{\text{veh}}$ is defined:

$$\mathscr{U}_{\text{veh}} = \left[D_{\mathscr{P}_{\text{veh}}}(t) \;\; S_{\mathscr{P}_{\text{veh}}}(t) \right]. \tag{9}$$

$D_{\mathscr{P}_{\text{veh}}}$ is the future demand of the vehicle family as a function of time t, and $S_{\mathscr{P}_{\text{veh}}}$ is a discrete sequence of required styling changes of the vehicle family as a function of time t. Note that the three variants are currently produced on different platforms and that their initial demand is known: $D_{\mathscr{P}_{\text{veh}}}(t=0) = [280,000 \; 125,000 \; 60,000]$.

4.3 Step II: Determine Critical Key Attributes and Design Variables

4.3.1 Key Attributes

For automobiles, the customer-preferred attributes set $\mathbf{J}_A$ has several attributes (Cook 1997). Some of these attributes are fuel economy, acceleration, reliability, towing capacity, and workmanship quality, to name a few. Some attributes are related directly to vehicle performance, while others are perceived by customers, i.e. they are subjectively scored. This later category is referred to as ‘soft’ attributes by Cook (1997). From these attributes, four attributes related to the uncertainties $\mathscr{U}_{\text{veh}}$, were identified as part of the case. They are

$$\mathbf{J}_{\mathscr{U}_{\text{veh}}} = [RM, \text{IE}, \text{FE}, \text{AC}_{50-70}] \tag{10}$$

RM is customer-perceived vehicle roominess, IE is the ease of front ingress/egress, FE is fuel economy, and AC_{50-70} is the acceleration time interval from 50 to 70 mph. RM and IE are scores between 0 and 100 and represent the percentage of customers who are either “very satisfied” or “satisfied” with a specific vehicle. These scores are derived from past data obtained through a market survey of customers who owned their vehicle for six months or less. RM and IE are selected as 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 and key dimensions. Since styling cannot be easily quantified, RM and IE are used as constraint attributes that must maintain a certain score level during future styling changes.

Another uncertainty addressed is vehicle family demand. For individual vehicle variants, demand is determined by the values of vehicle attributes such as – FE, AC_{50-70}, RM, and IE – among others (see Equation 6). The reason for selecting these attributes are that: (1) these four attributes are among the most important attributes for market segments where $\mathscr{P}_{\text{veh}}$ is targeted; and (2) FE and AC_{50-70} are vehicle performance attributes affected by the vehicle size, and thus are coupled with RM and IE. Other attribute values, not included in $\mathbf{J}_{\mathscr{U}_{\text{veh}}}$, are treated as constants in the case study.

4.3.2 Design Variables for Key Attributes

Once the set of uncertain attributes $\mathbf{J}_{\mathscr{U}_{\text{veh}}}$ is identified, the next step is to establish the mapping relationship between the attribute space and the system-level design variable space, as described by the system-level design variable set $\mathbf{X}_{\mathscr{U}_{\text{veh}}}$. 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, the two attributes *RM* and *IE* are customer perceived attributes, and so establishing the analytical relationship between the two spaces is not trivial. In order to translate customer judgments in terms of *RM* and *IE* into the vehicle-level design variables, various vehicle dimensions were decomposed into uncorrelated factors by applying principal component analysis (PCA) (Dunteman 1989). Then, the perceived customer preferences for vehicle *RM* and *IE* from a marketing survey were regressed onto those uncorrelated BIW dimensions. Shown in Figure 9 are relevant system level design variables, identified for each attribute. Dimensions in the figure are designated using standard SAE nomenclature (SAE 2001).

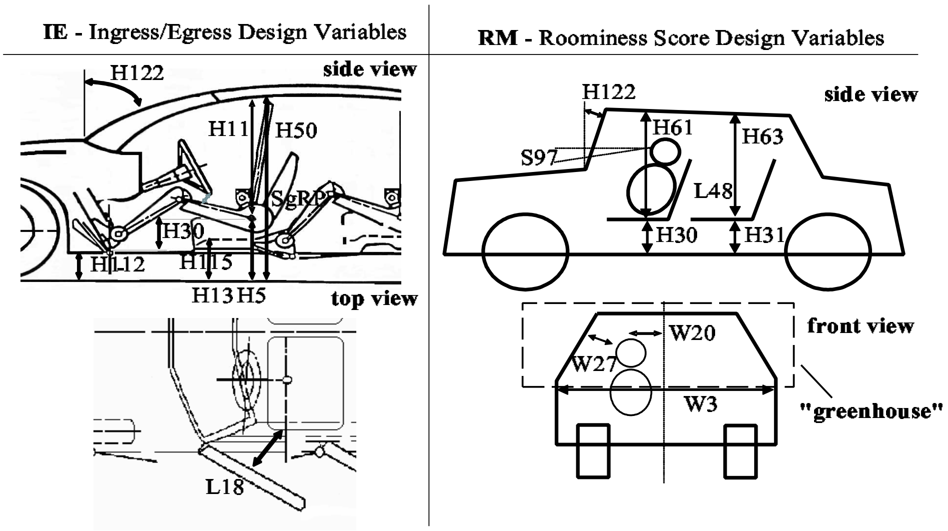


Fig. 9 System Level Design Variables for *IE* and *RM*

We assume that there exists a set of design variables that influence people's perception of vehicle roominess (*RM*) and ease of front ingress/egress (*IE*) more than others. The first step is to gather relevant data for different vehicles. *RM* scores and dimensions for 94 vehicles, produced between 1997 to 2001, were collected for the analysis. For *IE* scores and dimensions, 57 vehicles, produced between 1995 to 2000, were used (Suh 2005). For a single vehicle we collected the following data set:

$$\begin{aligned} \mathbf{X}_{RM,i} &= [H30, H31, H61, H63, H122, L48, S97, W3, W20, W27] \\ \mathbf{X}_{IE,i} &= [H5, H11, H30, H50, H112, H115, H122, L18] \end{aligned} \tag{11}$$

These two data sets are first standardized:

$$\mathbf{X}_s = \frac{\mathbf{X} - \overline{\mathbf{X}}}{\Sigma_X} \tag{12}$$

where $\overline{\mathbf{X}}$ is the mean of the sample data and Σ_X is the diagonal matrix of standard deviations. Using the collected standardized data, we identified the principal components through singular value decomposition:

$$[\mathbf{U}, \mathbf{S}, \mathbf{V}] = svd(\mathbf{X}_s) \text{ where } \mathbf{X}_s = \mathbf{U}\mathbf{S}\mathbf{V}^T \tag{13}$$

The principal component matrix **V** is obtained and we retain the first four principal components. Moreover, let **T** be the attribute score matrix. With matrix **T** known for both the *RM* and *IE* customer-preferred attributes, RM and IE values for a vehicle are calculated by multiplying the singular value matrix **S** to the transpose of the score matrix T.

$$\begin{aligned} RM &= S_{RM}\mathbf{T}_{RM}^T \\ IE &= S_{IE}\mathbf{T}_{IE}^T \end{aligned} \tag{14}$$

S_{RM} and S_{IE} are the singular value matrix for *RM* and *IE*, respectively. Using the analysis, *RM* and *IE* scores can be estimated as functions of the design variables in Equation 11.

The following design variables are selected as a result of the PCA as independent design variables for each p_i in $\mathscr{P}_{\text{veh}}$, and they will be used for optimization in Step III:

$$\mathbf{X}_{\mathscr{U}_{\text{veh}},i} = [L48_i, \mathrm{W3_i}, \mathrm{W20_i}, \mathrm{H5_i}, \mathrm{H50_i}] \tag{15}$$

- $L48$: Second row knee clearance relates to *RM* and wheelbase differentiation.
- $W3$: PCA determined that $W3$ is one of the most sensitive dimensions that affects *RM*.
- $W20$: Head to centerline width affects *RM* strongly.
- $H5$: Distance from ground to seat is important for ease of *IE*.
- $H50$: Overall BIW height dimension affects both *RM* and *IE*.

From the dimensions shown in Figure 9, several dependent variables are expressed as functions of independent design variables defined in Equation (15). The 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 $H122$. The constants $L18$, $H112$, and $H115$ are the same for all vehicle variants. The variables $W27$ and $H122$ are variant-unique for styling differentiation of the “greenhouse”, i.e. the part of the vehicle above the belt line, see Fig. 9 lower right. This will be discussed shortly.

4.4 Step III: Optimize Product Family and Platform Bandwidth

4.4.1 Product Family Optimization

The ultimate goal of the product platform is to maximize profit of the product family built from it through product variety increase and cost reduction. To begin the process of maximizing profit, the first task is to position each vehicle variant in $\mathscr{P}_{\text{veh}}$ within the corresponding vehicle market segment to generate maximum revenue as a product family. Using relationships defined in the previous section, the revenue maximization problem for the vehicle variant set $\mathscr{P}_{\text{veh}}$ can be formulated as shown in Equation (16).

$$\begin{aligned} &\text{maximize} \sum_{i=1}^{3} R_{p_i}; R_{p_i} = ms_i \left(\mathbf{J}_{\mathscr{U}_{\text{veh}},i}, P_{p_i}\right) P_{p_i} D_T \\ &\text{w.r.t.} \left\{\mathbf{X}_{\mathscr{U}_{\text{veh}},i}, P_{p_i}\right\} \\ &\text{s.t.} \, \mathrm{h}\left(\mathbf{J}_{\mathscr{U}_{\text{veh}},i}, \mathbf{X}_{\mathscr{U}_{\text{veh}},i}\right) = 0, \; \mathrm{g}\left(\mathbf{J}_{\mathscr{U}_{\text{veh}},i}, \mathbf{X}_{\mathscr{U}_{\text{veh}},i}\right) < 0 \end{aligned} \tag{16}$$

In the equation, the individual vehicle market share ms_i is a critical value that is difficult to estimate. In our case study this information was obtained through a market simulation software for the North American automotive market for the 2002 model year, as a function of aforementioned vehicle attributes. Published methods of demand prediction could also be used, see Cook (1997). The market simulation model is integrated into the platform bandwidth optimization framework with an Excel-based attribute translator model and commercial optimization software (iSIGHT). Figure 10 shows the simulation and optimization framework for product family revenue optimization in step III. Coupling equations capture the effect of RM and IE on fuel economy FE and acceleration AC (Suh 2005). Generally, an increase in vehicle dimensions leads to poorer fuel economy due to increased drag as well as longer 50-70 [mph] acceleration times due to larger structural mass.

Once all optimized attribute values and design variable values $\mathbf{X}_{\mathscr{U}_{\text{veh}}}$ are determined, the vehicle platform bandwidth of the product family $\mathscr{P}_{\text{veh}}$ is determined, both in the design space and attribute space. Tables 4 and 5 list optimized values (normalized) of $\mathbf{X}_{\mathscr{U}_{\text{veh}}}$ and $\mathbf{J}_{\mathscr{U}_{\text{veh}}}$. They are normalized with respect to the maximum value of each variable among the three vehicle variants.

For some design variables, values for all vehicle variants are either the same or very close, indicating that a very small or no bandwidth is required for those design variables. Three independent variables - $H5$, $L48$, and $\mathrm{P_w}$ - require significant bandwidths. Variable $\mathrm{P_w}$ (weighted price across trim levels) is the domain of the marketing or planning departments, and will be used during the uncertainty analysis phase (Step VII) to

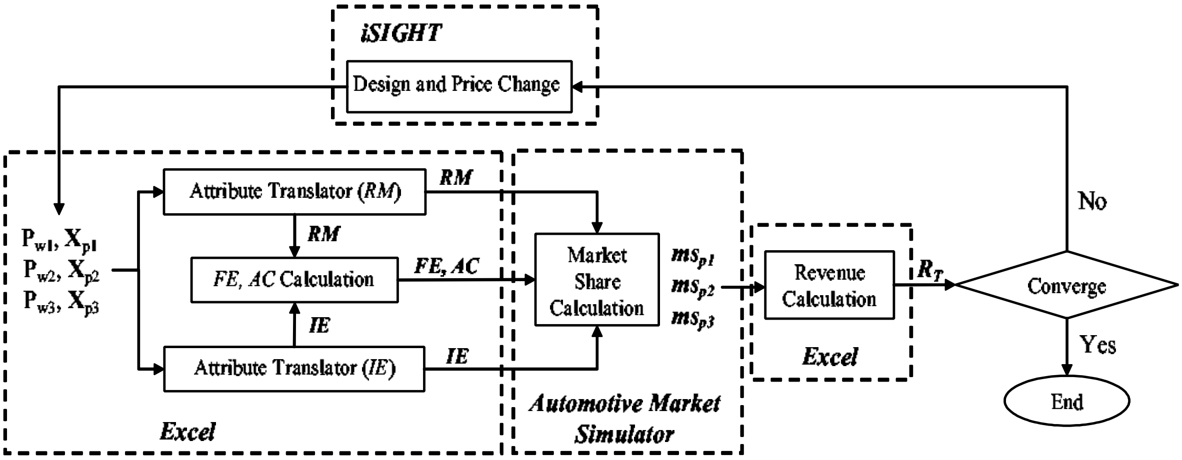


Fig. 10 Revenue Optimization Framework for Vehicle Family $\mathscr{P}_{\mathrm{veh}}$

Table 4 Optimized $\mathbf{X}_{\mathscr{U}_{\mathrm{veh}}}$ for $\mathscr{P}_{\mathrm{veh}}$ (Normalized)

Variants	$L48$	$W20$	$W3$	$H5$	$H50$	P_w
p_1	0.42	1.00	1.00	0.92	1.00	0.52
p_2	0.42	1.00	1.00	1.00	1.00	0.61
p_3	1.00	1.00	1.00	0.95	1.00	1.00

Table 5 Optimized $\mathbf{J}_{\mathscr{U}_{\mathrm{veh}}}$ for $\mathscr{P}_{\mathrm{veh}}$ (Normalized)

Variants	IE	RM	AC_{50-70}	FE
p_1	0.95	0.97	0.89	1.00
p_2	1.00	0.99	0.99	0.99
p_3	0.97	1.00	1.00	0.91

calculate the overall product family profit. The next task is to perform a sensitivity analysis of the optimum solution, which will identify additional design variables that might benefit from flexibility, even if their initial bandwidth required is small. Bandwidth can be graphically shown using polar plots as in Figure 5.

4.4.2 Sensitivity Analysis

The normalized sensitivity of variant p_1's revenue with respect to the product design variable set $\mathbf{X}_{\mathscr{U}_{\mathrm{veh}}}$ is shown in Figure 11.

The chart shows the percent change in the revenue of vehicle variant p_1 as a function of percent change in each design variable. First, and foremost, note that with the exception of $L48$, the design variables have

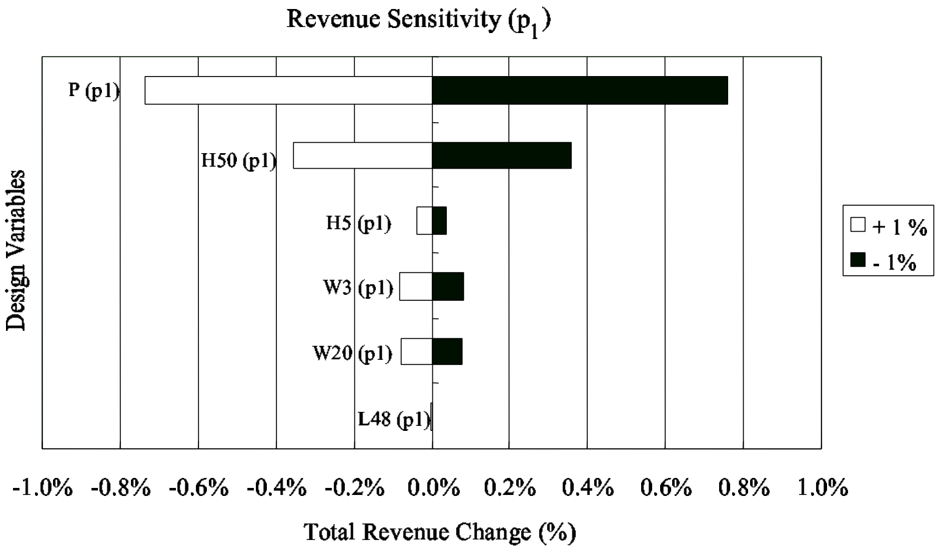


Fig. 11 Revenue Sensitivity Chart (p_1)

negative sensitivity value. This means that when these design variable values increase, revenue decreases. The reason for this phenomenon is that as vehicle size increases to improve IE and RM, it degrades FE and AC_{50-70} values, resulting in decreased market share and variant revenue.

Analysis results show that the vehicle price P is the most sensitive parameter, representing in effect the price elasticity of demand. The most sensitive geometrical design variable is $H50$, the upper body opening to ground dimension. It has a significant effect on total revenue, especially for p_1. $H50$ is a highly sensitive design variable since it affects several vehicle attributes, which in turn affect the total revenue generated. However, referring back to Table 4, for $H50$ the values for all three vehicle variants were the same, so no differentiation is required a priori. We also observed that the optimized values of $H50$ are all located at the lower bound of the design variable value, indicating that it is an active constraint. This is due to the effect of $H50$ on FE and AC_{50-70}. If $H50$ decreases, it negatively affects RM and IE. However, FE and AC_{50-70} would improve (due to vehicle size reduction), resulting in overall revenue increase of the vehicle variants up to a point where losses in RM and IE became too large. Even though this particular dimension does not require any differentiation currently, incorporating flexibility for this particular dimension may be advantageous in the future. The reason is that when the customers' preferences change in the future (e.g., they want roomier cars, or cars with better ingress/egress features, or fuel prices dictate more fuel efficiency), the firm can respond to this uncertainty with greater ease.

4.5 Step IV: Identify Critical Elements

4.5.1 Selecting Flexibility Drivers

In Section 4.4, the bandwidths for the vehicle platform in the attribute and design variable space were established through vehicle family revenue optimization. Figure 12 shows the independent design variables $(L48, \mathrm{W3}, \mathrm{W20}, \mathrm{H5}, \mathrm{H50})$ and differentiating constants ($H122$, $W27$). The figure shows two variants, say p_1 and p_2 that feature differences in these values, which are most pronounced in the geometry of the body (“greenhouse”) above the belt line and the difference in wheelbase.

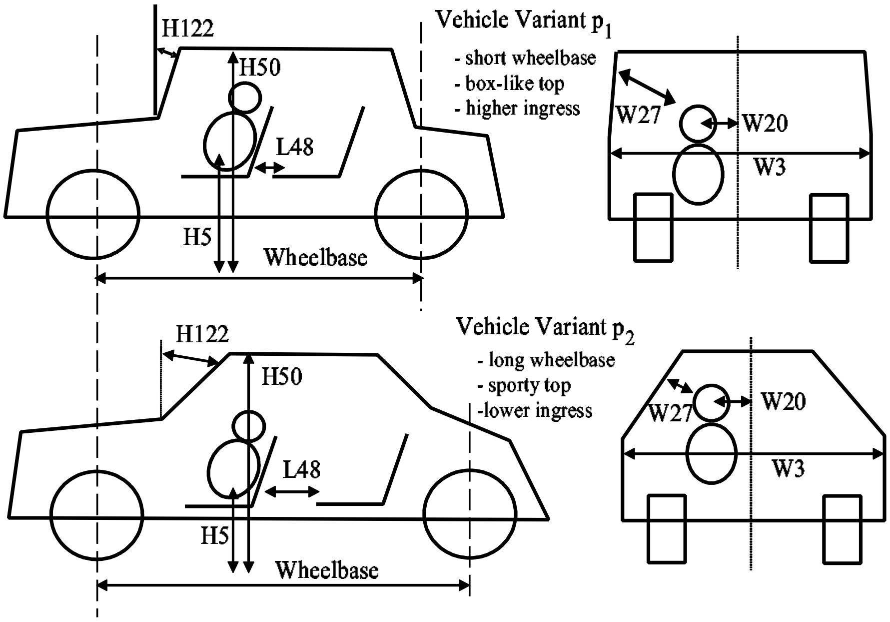


Fig. 12 Design Variables Requiring Flexible Bandwidth

As stated earlier, vehicle variants in $\mathscr{P}_{\text{veh}}$ have two different wheelbases. This difference in wheelbase is reflected in the initial lower and upper bounds of $L48$ within which $L48$ was optimized for each variant in the previous step. $W27$ and $H122$ require differentiation to achieve styling distinction of individual variants in the vehicle family. The upper variant in Fig. 12 shows a short wheelbase sedan with a box-like greenhouse and higher (easier) ingress/egress, while the second variant features a longer wheelbase, sportier look and lower ingress/egress point. $H50$ was shown to be a very sensitive dimension, and if made flexible, can potentially add value under future uncertainty. $H5$ is a design variable related to interior seating, so adjustments to

$H5$ could potentially be achieved without significant BIW modifications. For $W3$ and $W20$, results of the optimization yielded values that are either the same or are very close. These values can be achieved through the differentiation of interior trim and might not necessitate BIW changes either.

To this end, we select the four design variables $L48$, $W27$, $H122$, and $H50$ as those that are the primary drivers of flexibility in the BIW. Some of the flexibility is dictated by the initial bandwidth between variants, while for $H50$ the need for flexibility arises out of sensitivity to potential future requirements. Once BIW related design variables and their bandwidths are chosen, change propagation analysis for these variables needs to be performed to identify physical BIW elements that would be impacted by a required change.

4.5.2 Bounding the Physical Domain

The challenge of this step is the non-uniqueness of achieving flexibility in the domain of physical elements (recall the simple lever example in Fig. 8). The identified design variables can be mapped to the physical elements space in many ways, generating many non-unique solutions. To address this problem, the system architect must decompose the physical system to bound the element space, thus constraining the physical space under consideration.

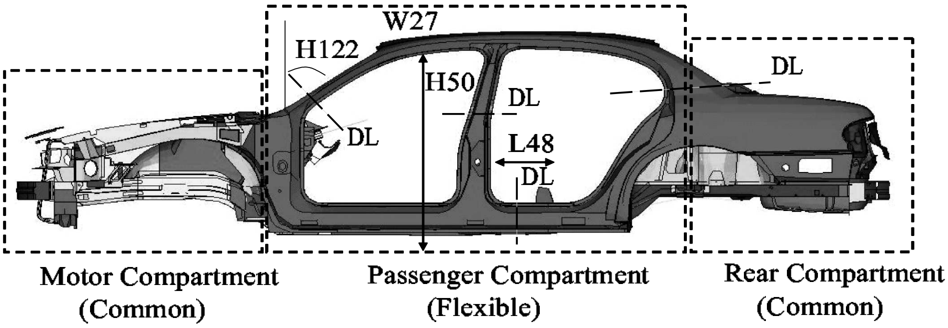


Fig. 13 Body in White (BIW) of a Passenger Sedan

The BIW of a passenger car is shown in Figure 13 with a high level system decomposition (motor compartment, passenger compartment, and cargo compartment). Since the key customer-preferred attributes, *RM* and IE, 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. 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. In this study, the BIW is decomposed down to its individual component level, at which individual components are end-items supplied to the BIW assembly line directly. The architecture of the steel body is a Body Frame Integral (BFI) structure with 21 components that are spot welded together. These components are part of the passenger and cargo compartments (but do not include motor compartment components). Next, the connective relationship between individual components needs to be established and expressed in design structure matrix (DSM) format. This structure is shown in Figure 14.

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		■

Fig. 14 Design Structure Matrix of BIW Components

To achieve flexibility in the variables $L48,\mathrm{W27},\mathrm{H50},\mathrm{andH122}$, the product designer must (1) identify components that need to change, and (2) determine how such changes propagate through the BIW. To analyze change propagation more easily, a network representation is constructed (see Figure 15) based on the DSM.

The links represent physical connections, where each component is connected to another by spot welding. There are four system-level design variables, x_i, mentioned in Section 4.4, that require differentiation for each vehicle variant. Additionally, styling uncertainty is a key factor that causes body-in-white changes to occur. For each specified design variable change,Δx_i, one must identify multipliers and carriers that send out changes to other components when they themselves are changed. Once these components are identified, the system architect can (re-)design them to reduce the degree of change propagation or switch costs by incorporating

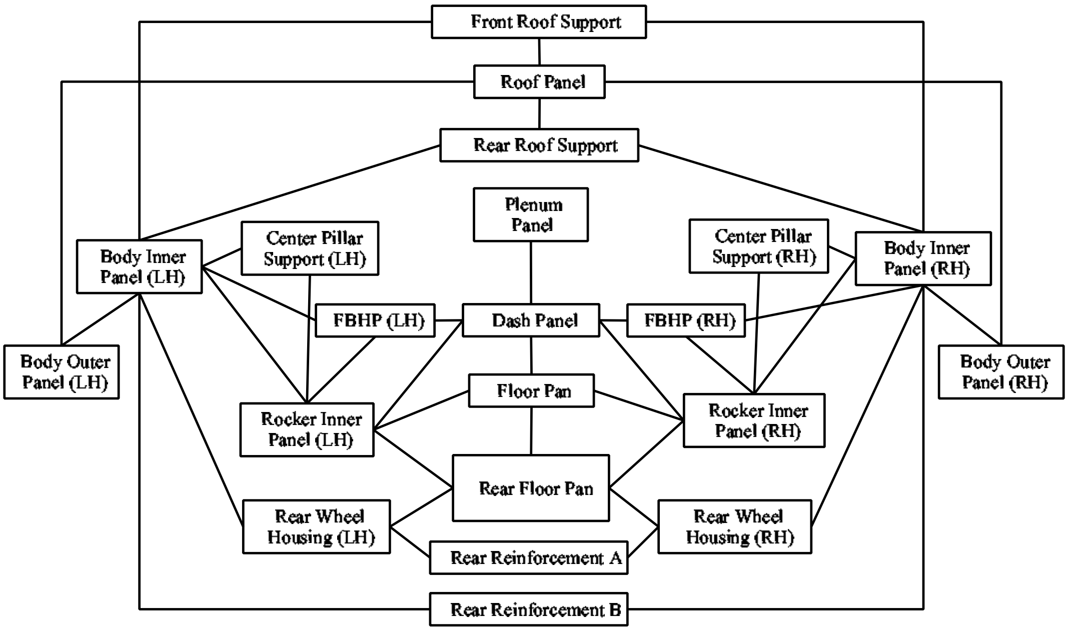


Fig. 15 Network Representation of BIW

flexibility into the multiplier/carrier components directly, or into components to which the multiplier/carrier component is propagating changes.

4.5.3 Change Propagation Analysis: Lengthwise and Styling

As a result of the revenue optimization in Step III, it was determined that the vehicle platform must achieve bandwidth for length, represented by $L48$. Such BIW changes are required because of varying needs for RM, IE or styling as shown in Figure 12. We need to investigate cases in which length and styling requirements change in the future within the optimized $L48$ 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 vehicle styling. The change propagates throughout the BIW, and the final change propagation state is shown in the change propagation DSM in Figure 16. This matrix and method of quantifying change propagation was explained in Section 3.5.

The change propagation DSM 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. Ten components are affected by the lengthwise direction change, initiated by a change in $L48$. We refer to the change as ΔL. Once these components are identified, then the switch costs for making such a change need to be calculated.

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	

Fig. 16 Change Propagation DSM for BIW Length Change

Switch related investment costs for all components are calculated using a process based cost model (Kirchain 2004). The investment cost consists of blanking tool investment, stamping tool investment, and welding tool investment cost. Table 6 lists the initial investment cost and BIW length related switch costs for the ten identified components. The assumption is that these BIW components are customized for each vehicle variant. This corresponds to the components designated as "carryover-modified" in Figure 2. Costs in Table 6 are normalized with respect to the initial investment cost of the body outer panel.

Table 6 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 17 summarizes all change propagation related information into a graphical network format. Above the name of a particular component, its component class (for this particular change) and related switch cost are displayed. Change propagation paths are shown as darkened arrows, changed components are highlighted.

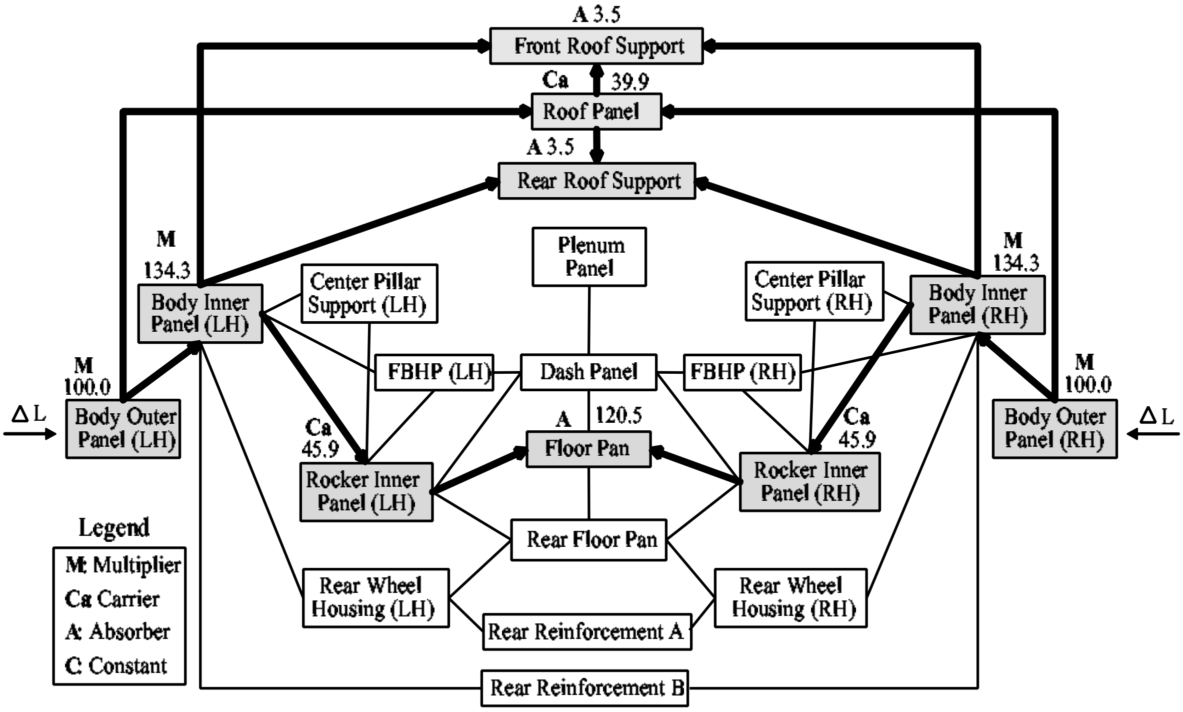


Fig. 17 Change Propagation for BIW Length and Styling Change

Once all critical BIW components and relevant switch costs are identified, this information is used to generate flexible BIW design alternatives in Step V. A 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 number of BIW components may be affected. However, as the magnitude of length change increases beyond a certain threshold (e.g. 1 inch), significant structural changes may be required, resulting in a greater degree of change propagation and the possible addition of extra components to accommodate the change.

4.5.4 Change Propagation Analysis: Styling Only

There are three dimensions that affect styling of the “greenhouse”. They are $H50$, $H122$, and $W27$. As seen in Figure 12, vehicle styling can be differentiated by changing the vehicle body segment above the belt line (the horizontal line running between the door and the window), thus not affecting the vehicle length. The values of $H122$ and $W27$ are unique for each vehicle variant, requiring differentiation in related BIW elements. Change propagation analysis is performed in a manner analogous to the length change to determine components that are affected by differentiating the aforementioned dimensions. We could draw the change DSM and change propagation network again, but for brevity we summarized the information for the affected (seven) components in Table 7. The table lists the *CPI*, component class and 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 7 BIW Styling Change Related Investment Cost for Critical Components (above Belt Line only)

Component Name	CPI	Class	Initial Investment	Switch Cost
Body Outer Panel (RH & LH)	2	M	100.0	100.0
Body Inner Panel (RH & LH)	1	M	134.3	134.3
Roof Panel	0	Ca	39.9	39.9
Front Roof Support	-3	A	3.5	3.5
Rear Roof Support	-3	A	3.5	3.5

From the change propagation analysis, ten components are identified as key components that change as a result of required vehicle differentiation and future changes in styling: body outer panels (LH & RH), body inner panels (LH & RH), rocker inner panels (LH & RH), floor pan, roof panel, front roof support, and rear roof support. Four components - the body outer and inner panels (RH & LH) - are multipliers for both cases (styling change only, length & styling change). Switch costs for these massive components are very high because the components must be completely redesigned and tooling must be reinvested every time the design changes. Based on these facts we decide that the four panels are key components that need to be (re-)designed to incorporate flexibility.

4.6 Step V: Create Flexible Design Alternatives

In Section 4.5, we identified critical BIW components that are affected by the specified uncertainties and attributes through the change propagation analysis. The task is to reduce the magnitude of change propagation through flexible component design and in turn to reduce the economic impact of future changes.

4.6.1 Passenger Compartment Decomposition Strategy

In order to satisfy the required dimensional bandwidth and differentiation in vehicle styling, we propose the following decomposition strategy to make the BIW flexible to change. The passenger compartment is decomposed into three sub-compartments, as shown by the dashed decomposition lines (DL) in Figure 13. The lower front passenger compartment remains 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. Once the system has been decomposed, the system architect must examine each component to incorporate flexibility to achieve the overall decomposition strategy goal. We present the decomposition strategy for two key components, the body outer panel and body inner panel. Components are decomposed so that they would be more economical to change when the design requirements change. It is assumed that the proposed decomposition meets quality, strength and manufacturability criteria.

4.6.2 Single Component Decomposition: Body Outer and Inner Panels

The body outer panel is a critical component that is visible to customers. It probably is the most sensitive component to styling changes. Figure 18 (top) shows how the component can be decomposed.

The lower body outer panel is made common for all three vehicle variants. The upper body outer panel is customized for each vehicle variant for styling differentiation, as well as for the critical design variables differentiation as shown. Common and unique portions 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. The proposed decomposition will incur extra investment in blanking, stamping, and welding tools, but when the design changes, changes will result in lower switch costs.

The body inner panel 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 18 (bottom). The lower front body inner panel is common for all three vehicle variants, and the upper body inner panel is customized for each variant, similarly 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.

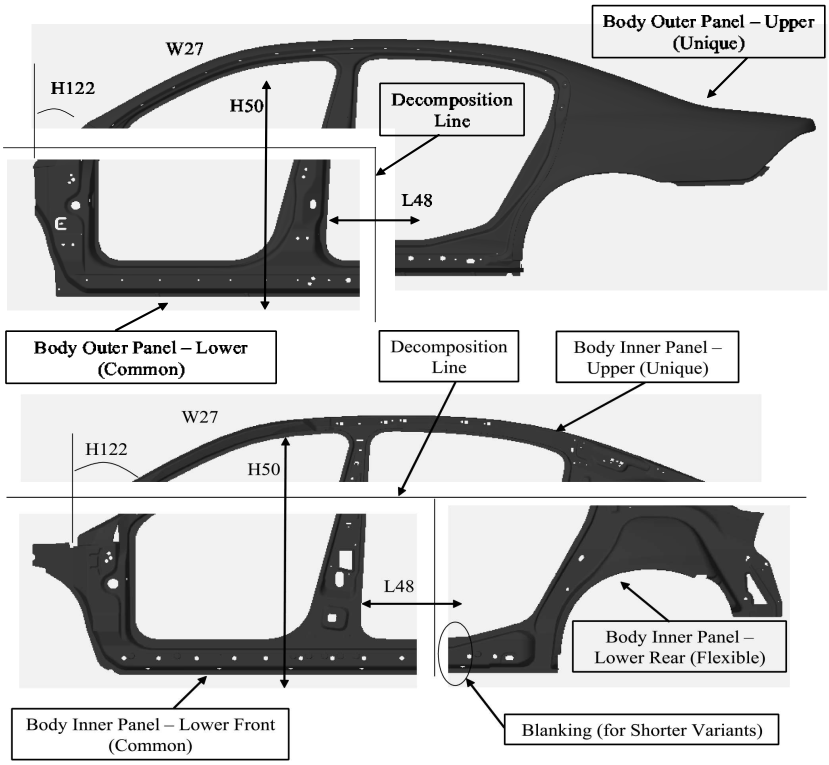


Fig. 18 Body Outer (top) and Inner (bottom) Panel Decomposition for Flexibility

One way to achieve these requirements is to design the flexible piece to meet the long vehicle specification, and to trim the end (where it is welded to the common piece) to produce the short wheel base variant.

4.6.3 Other Components

Of the remaining six components - the 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 changes since it must comply with the styling restrictions imposed by the particular design change. In this case study, flexible designs used for the rocker inner panel, floor pan, and front and rear roof support use the trimming strategy in which these components are designed for longer length specifications, and then trimmed down to meet shorter specifications (Suh et al. 2005).

4.6.4 Flexible Assembly Process

Assembly related investment is perhaps the biggest cost driver during the initial investment phase. In order to accommodate the flexible component designs proposed in the previous section, the BIW assembly line must also be flexible. Shown in Figure 19 is the BIW assembly process (based on the actual process) and the proposed areas to incorporate flexibility.

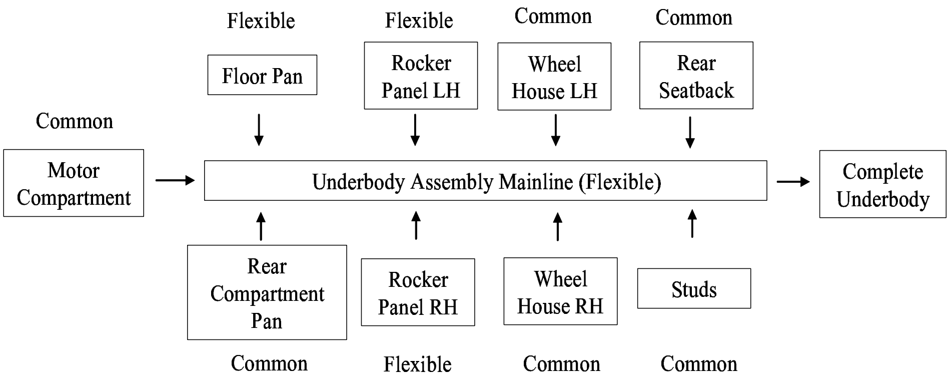


Fig. 19 Flexible BIW Assembly Line

The motor compartment is common for all vehicle variants. However, remaining downstream processes do require flexibility in assembly tooling to accommodate different vehicle variants.

4.6.5 Vehicle Platform Element Selection

As a result of the system decomposition strategy, several components and assembly processes became "flexible" elements, as parts of the vehicle platform. Table 8 shows a 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 as part of the platform.

4.7 Step VI: Determine Costs of Platform Design Alternatives

The next step is to determine the cost of the flexible BIW platform design. For this case study, the process-based cost model developed at MIT (Busch and Field 1988; Han et al. 1993) is used to determine the capital investment cost and the unit cost of each vehicle. As mentioned in the previous section, the architecture of the BIW is Body Frame Integral (BFI), using spot welded steel sheets as its material. Company-specific cost parameters are used for accurate cost calculation.

Table 8 BIW Platform Elements Comparison (Inflexible vs. Flexible)

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

4.7.1 Investment and Unit Cost of Critical BIW Components

In Section 4.6, we generated a flexible BIW design. The costs of the flexible design and the original inflexible design, customized for each vehicle, need to be determined in order to compare benefits and costs under future uncertainty. Table 9 shows, for each vehicle variant, the initial estimated annual production volume, expected volume trend and volatility, maximum expected production volume during the life of the vehicle platform, and the number of required BIW assembly lines per particular vehicle variant.

The number of required assembly lines is based on the maximum expected production volume during the lifetime of each vehicle variant built from the platform (15 years). In each assembly line, a maximum of 225,000 BIW units can be assembled per year. Assembly lines with fixed tooling are dedicated to only one vehicle variant while assembly lines with flexible tooling can accommodate all vehicle variants. The following assumptions are made for determining relevant costs:

- The life of the vehicle platform is 15 years (three cycles of variants).

Table 9 Individual Vehicle Variant Information

Vehicle Variants	p_1	p_2	p_3
Initial Production Volume	280,000	125,000	60,000
Production Volume Trend p.a. (α)	6.11%	-0.34%	-5.52%
Volatility Coefficient p.a. (σ_v)	11.25%	6.62%	13.27%
Maximum Expected (15 years)	650,000	125,000	60,000
BIW Lines Required	3	1	1

- From the analysis in Step IV and V, only ten components require differentiation while the other components remain common. For this study, only costs related to these ten components are calculated.
- Two design alternatives are considered: the inflexible BIW design, in which ten differentiating components are uniquely customized for each vehicle variant and the flexible BIW according to Table 8. 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 19.
- Fabrication and assembly tools are refurbished every five years, at 25% of the new tooling cost.
- Once the initial investment costs and unit costs are determined, they are assumed to be fixed for the remainder of the platform life.

For each design alternative, the initial capital investment cost, refurbishing cost, and switch cost are calculated. As stated in the initial assumption, investment costs for the ten critical components are calculated. Table 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 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

The numbers indicate that the flexible BIW design, with flexible parts fabrication and assembly, requires approximately 34% more upfront investment 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 lines, outperforms the inflexible design in terms of switch cost when the styling and the length of BIW need to be changed (within the pre-defined bandwidth). This shows the costs and benefits of flexible BIW design; extra investment is required initially, but subsequent changes can be accommodated with lower investment costs. It is clear that the flexible BIW design is more expensive to implement initially, but has the potential to perform more economically when the frequency of styling changes increases. Step VII of the flexible platform design process (recall Figure 3) - the uncertainty analysis phase - will help determine those cases in which adding flexibility is worthwhile and those in which it is not.

4.7.2 BIW Unit Costs

The total unit costs of ten BIW components for each vehicle variant were calculated. Total unit costs are calculated as a function of annual production volume, component mass (for fabrication), and the number of spot welding points required (for assembly). Table 11 lists the normalized unit BIW cost (ten components only) of each vehicle variant for two different platform design alternatives being compared. Unit costs are normalized with respect to the unit cost of p_1 for the customized BIW.

Table 11 BIW Unit Cost of Vehicle Variants for Different Platform 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, the unit cost for the flexible BIW design is higher, as expected, due to the high investment cost to amortize, and the additional welding costs for flexible components. However, the unit BIW cost of p_3 for the flexible BIW design is lower than the cost of the inflexible BIW design. This is due to the effect of common component sharing in which the flexible BIW shares more common components with smaller variants, thus lowering the unit cost through economies of scale. Whether or not the additional cost of flexibility is beneficial has not yet been determined.

4.8 Step VII: Uncertainty Analysis

4.8.1 Problem Formulation

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

- All costs are normalized to the initial investment cost of the inflexible BIW design (see Section 4.7).
- The time horizon is 15 years, three cycles of nominal vehicle variant redesigns.
- Fabrication and assembly tools are refurbished every five years unless they are being replaced.
- Geometric Brownian Motion (GBM) is used for future demand prediction (α, σ_V).
- The demand for individual vehicle variants is equal to their production volume.
- The demand for individual vehicle variants cannot exceed the maximum assembly line capacity set by the number of assembly lines designated for each variant (for inflexible BIW platform design).
- Flexible BIW platform manufacturing is also capacity limited, even though the flexible tooling in all assembly lines enables flexible capacity utilization in that case.
- Styling changes and length changes occur within the design variable bandwidths defined from the results of revenue 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 with an annual discount rate of 6%.

Table 9 lists demand forecast-related parameters for each vehicle, where α is the demand trend coefficient, and σ_V is the demand volatility coefficient. These parameters are calculated from actual vehicle sales data (annual) between 1997 and 2003. Within the boundaries of the pre-stated assumptions, expected demand trends, and volatility, the two BIW design alternatives are evaluated and compared under several future scenarios (Table 12).

Scenarios I through IV are scenarios with varying degrees of uncertainty. Uncertainty analysis starts with investigation of scenarios with uncertain production volume. Styling change uncertainty is added to increase

Table 12 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

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

The expected net present value $E[NPV]$ for the total product family is used to measure the economic performance of each platform design alternative. The net present value is obtained by the following equation:

$$NPV = \sum_{t=0}^{15} \frac{CF_t}{(1+r)^t} \tag{17}$$

where

$$CF_t = \sum_{i=1}^{3} (R_{i,t} - C_{\text{total,i,t}}) - K_{\text{Init,t}} - K_{\text{ref,t}} - K_{\text{switch,t}} \tag{18}$$

and

$$R_{i,t} = D_{i,t} \mathrm{P}_{\text{w,i}} \tag{19}$$

$$C_{\text{total,i,t}} = D_{i,t} c_{\text{veh,i}}. \tag{20}$$

NPV is the total sum of time discounted cash flow over a 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 sales of the 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 that occurs at time t; $K_{\text{ref,t}}$ is the refurbishing related investment that occurs at time t; $K_{\text{switch,t}}$ is the switch-related investment that occurs at time t; $D_{i,t}$ is the demand for the i^{th} vehicle variant at time t; $P_{\text{w,i}}$ 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 the BIW will be used as the unit cost c_{veh}.

4.8.2 Scenario I - XII Results

Monte Carlo simulation is conducted to determine the range of future vehicle demand and revenue. For each scenario (with the exception of Scenario I, in which no uncertainty is present), simulation consists of 25,000 runs to represent a full range of outcomes. First, future demand uncertainty is simulated using Geometric Brownian Motion (GBM) and the initial demand, mean trend and volatility from Table 9 are used for the variants in $\mathscr{P}_{\text{veh}}$. Figure 20 shows a particular instantiation of a demand scenario for variant p_2.

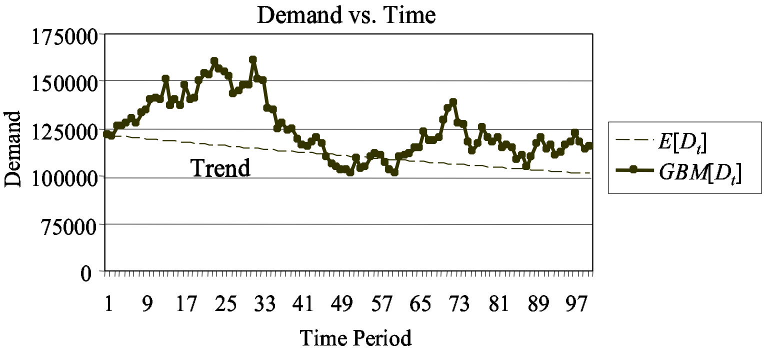


Fig. 20 Geometric Brownian Motion (GBM) Simulation of Future Demand for p_2 (1 out of 25,000 runs).

Depending on the scenario (I-XII) the simulation captures the effects of implementing changes to vehicle variants at varying time intervals. Scenarios III and V-VIII capture demand uncertainty (Fig. 20) plus styling changes above the belt line only (Table 7) at an increasing frequency. In scenario III the styling change is done every five years, while in scenario VIII we assume that the variant redesigns take place every year.

The second group of scenarios assumes that both vehicle length changes and styling changes occur together (Fig. 17). In scenario IV this more invasive change is assumed to occur only every five years. In scenarios IX-XII the change frequency is increased by one year at a time. Under what scenarios will the inflexible or the flexible BIW yield a higher E[NPV]?

To answer this, an NPV analysis is conducted for each change scenario, BIW architecture and demand scenario. Figure 21(a) shows the results of the Monte Carlo simulation for Scenario VI in terms of the expected difference in NPV between the flexible and inflexible BIW, E[ΔNPV]. The distribution of 25,000 runs converges to a probability density function with lower and upper bounds of 5.00 and 14.00 and a mean of E[ΔNPV]=9.1.

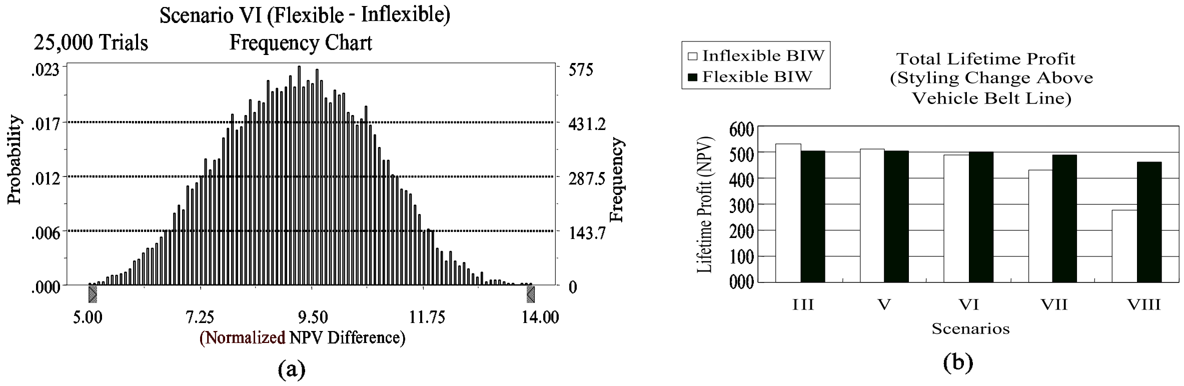


Fig. 21 (a) Monte Carlo Simulation Frequency Histogram (b) Total Profit Comparison (Scenarios III and V-VIII) based on a normalized NPV level of 28,000 for 15 years.

The dark bars in Figure 21(b) show that the flexible BIW outperforms the rigid platform in those cases where a styling change needs to be made every three years or faster. Table 13 summarizes the normalized profit difference for all the scenarios described in Table 12. Table 13 also shows the total expected lifetime profit as *NPV* for each design over the life of the product platform.

Table 13 Normalized Comparison of E[NPV] between Flexible and Inflexible BIW platform for scenarios I-XII. Results are shown with respect to a 15 year lifecycle and an NPV level of 28,000 in normalized units.

scenario	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Flexible BIW	508.0	510.8	505.6	505.4	502.3	498.5	488.4	462.8	502.1	498.1	487.8	461.4
Inflexible BIW	560.5	563.2	531.9	521.9	512.3	489.4	429.3	276.3	495.9	465.6	386.0	183.6
ΔNPV	-52.5	-52.4	-26.3	-16.5	-10.0	9.1	59.1	186.6	6.2	32.6	101.7	277.8

In Scenarios I - IV, the inflexible BIW design performed better than the flexible BIW platform. Even for Scenario IV, where the uncertainty is greatest among the first four scenarios, the inflexible BIW design outperformed the flexible BIW design. Results suggest that under these circumstances, the flexible BIW should not be implemented as the higher investment in flexible elements and assembly equipment is never amortized over the 15 years horizon. However, when the frequency of styling change increases, the results are different.

In Scenarios V - VIII, styling for all vehicle variants is changed more frequently. In these scenarios, styling is changed above the vehicle belt line only (no length change). The rationale for increasing styling change frequency is that there might be a situation in which, to maintain current demand levels under competition, the company must change vehicle styling more frequently to refresh the product family. Mean lifetime NPV for each design alternative is calculated, based on the Monte Carlo simulation described above. Results are shown in the middle of Table 13. 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 frequently, the flexible BIW design outperforms the inflexible BIW design in terms of total profit. This is due to the switch cost incurred every time the vehicle styling changes. Total profit for the flexible BIW design did not decrease as rapidly as that for the inflexible BIW design as changes are made more frequently (see decay of the white bars in Figure 21(b)). This is due to the lower switch cost of the flexible BIW design, making it more robust under increasing uncertainty and market dynamics.

Scenarios IX through XII evaluate situations in which styling changes also require a vehicle length change within the established $L48$ bandwidth from the optimization in Step III. Since there are more components and tooling that require modifications when the vehicle length changes (10 versus 7 components), switch costs for both designs are higher. However, due to its significantly lower switch cost, the flexible BIW has better economic performance once styling and length changes occur every four years (Scenario IX) or faster.

4.8.3 Value of Flexibility for H50 Dimension

During sensitivity analysis in Step III of the process, we determined that product family profit is very sensitive to $H50$, and if rendered flexible, this dimension could influence the total product family revenue. We also found that $H50$ is an active constraint. If the constraint were relaxed, how long would it take to break even? Table 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 platform design.

Table 14 Payback 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 show the superiority of the flexible design when $H50$ is changed. Given the same amount of revenue increase, the flexible design is able to break even within six months while the inflexible design requires approximately two and half years to break even.

4.9 Discussion

Evaluating two different BIW platform designs under scenarios of varying uncertainty produced interesting results. When uncertainty was 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 a certain point, the flexible BIW platform design started to show higher expected NPV. 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 changes in terms of profit, outperforming the inflexible design. The results suggest that, under uncertain styling change frequency and uncertain vehicle family demand, it is beneficial to implement the flexible BIW platform design if styling must change every three years or less, or if styling and length change every four years or less. While the actual particularities of future geometry changes are subject to styling trends and represent exogenous 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 firm's management. Given this situation, Table13 offers decision makers a useful quantitative guideline for making a decision on whether or not flexibility should be embedded into the BIW platform.

5 Summary, Discussion and Future Work

5.1 Summary

This paper introduces an end-to-end design process for flexible product platforms (Fig. 3). The framework is applied to a vehicle platform case study. In the case study, the platform is designed to accommodate three vehicle variants while being flexible to future demand and specification changes.

The process is general and consists of seven steps, using a combination of quantitative analysis and expert engineering knowledge for each step. First, uncertainties are identified (step I) and mapped to quantifiable vehicle attributes (step II), then to critical system-level design variables which require bandwidth and/or are sensitive to the aforementioned attributes (step III). Once the bandwidths for the system-level design variables are determined through product family revenue optimization, critical product platform components are identified using change propagation analysis (step IV). Flexible design alternatives are generated for critical components (step V) in order to reduce change propagation and lower switch costs. The cost of flexible design, both in component fabrication and in the assembly processes, are calculated using a process based cost model (step VI). Uncertainty analysis is performed to determine the economic performance of both the inflexible and flexible platform alternatives (step VII) under a set of uncertain future scenarios.

We believe that step IV, identifying critical platform elements as candidates for embedding flexibility, is the most critical and difficult step. This is were our main contribution lies. Much of the literature on platform design and optimization is satisfied with setting the values of design variables x_i to be common (up to and including step III). If, however the product is complex and the common design variables do not map to the same physical elements for reuse, such purely parametric commonality is of little real benefit. By decomposing the physical product in depth and performing change propagation analysis we reveal those components that act as change multipliers ($CPI > 0$) or whose switch cost is significant. Embedding flexibility in those components requires initial investment in design, tooling and assembly equipment and is akin to taking out a “real option” on the platform design.

A cost comparison in our case study showed that the flexible platform design will cost 34% more to implement initially, but will incur 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 for some variants.

However, other vehicle variants benefited from common component sharing, resulting in lower unit cost relative to the inflexible BIW design based variants.

Additional analysis of the sensitive dimension change ($H50$) showed that the flexible BIW design clearly had a cost advantage when such a situation arose. Such changes might or might not be required depending on which demographic, environmental and economic trends will prevail in the future. Designing vehicles for an aging population with easy ingress/egress might be at odds with the requirements for fuel efficiency and sleek aerodynamic design. It is impossible to forecast with certainty which requirement will dominate in the future, however, designing products and platforms with uncertainty in mind is a strategy to deal with such uncertainty in a rational manner.

5.2 Critical Discussion

The case study demonstrated that a critical subset of flexible BIW platform components allowed the whole BIW to become flexible to respond to the uncertainties defined at the beginning of the design process. Ten out of twentyone BIW components and the flexible assembly process made the BIW flexible to future styling and length changes, while remaining economically robust in terms of total lifetime profit.

Another important outcome of the paper is that the results quantitatively demonstrate the increasing value of flexibility as uncertainty increases. This fact is already well known in options analysis, but the main contribution of the paper lies in a methodology to identify (1) where in a complex, coupled system to embed flexibility and (2) how to value that flexibility in the context of realistic industrial scenarios.

To do so required a number of simplifying assumptions that had a significant impact on the results:

- In step I we chose IE and RM as well as variant demand as the driving uncertainties for which flexibility was embedded. We substantiated this choice by empirical consideration of demand variations across market segments (Fig. 1) as well as historical trends of key product attributes (Table 2). As shown in this paper, flexibility can only be beneficial if the “right” uncertainties were selected in the first place and we acknowledge that the method developed here does not help product platforms deal with wholly unknown uncertainties or provide insurance against all future eventualities.
- In step III we established the “optimal” bandwidth of the product platform across a set of variants p_i. In order to do so required setting lower and upper bounds of the system-level variables. The setting of these

bounds was informed by the minimum and maximum occurrences in the constituent market segments (recall Fig. 4). However, market segment boundaries are always arbitrary and dynamic so that setting different bounds might lead to different platform bandwidths. This relates to the question of platform extent and when it is beneficial to split a single large platform into two or more smaller platforms; a question which has been discussed elsewhere (Seepersad et al. 2001, de Weck 2005).

- A critical analysis of step VI reveals that the BIW only encompasses a relatively small percentage of total vehicle cost (typically $<<$ 20%). So, there remains vast potential for platforming and embedding flexibility in other parts of the system such as the powertrain, and electrical equipment and software. The cost contribution of the latter subsystems has been steadily increasing in recent years.
- Throughout the paper we have tacitely assumed that a basic product platform architecture already exists (see Fig. 15) and that flexibility is achieved by redesigning the basic, rigid platform. There might be other, more efficient ways of deriving a flexible platform architecture *de novo*.
- In the change propagation analysis (Section 4.5) we assumed that the CPI and switch costs were independent of the amount of change (e.g. ΔL48) as long as the change was within the allowed bandwidth. In reality the number of affected components and switch costs will initially not only depend on the type of change, but also on its magnitude.

5.3 Future Work

Throughout this work we assumed that all variants would be built from a single common platform. However, this may not be true in some cases where the differences between variants are too great. In those situations, multiple platforms may be required, see work on this topic by Seepersad et al. (2000, 2001) and more recently by Suh et al. (2003) and de Weck (2005). Future work will include determination of “splitting” criteria which will tell system designers in which cases a platform has been “stretched” too far and should therefore be split into separate platforms. One of the difficulties with this in practice is that the true bandwidth of a platform can often only be established via testing of physical prototypes in the field.

Change propagation analysis was presented for an automotive body-in-white in this paper. While involved in its own right, the change propagation was relatively straightforward, given that only changes in geometry were taken into account. Future work will include analysis of change propagation in complex products were changes can potentially “jump” across subsystem boundaries and are not simply transmitted to directly neighboring components.

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