# Product Family Strategy and Platform Design Optimzation

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## 1 Abstract

Numerous manufacturing industries are seeking ways to reduce manufacturing costs and development times of product families through implementation of platform strategies. Deploying several variants from a single product platform can yield considerable savings in time, cost and maximize profits. It is, however, generally accepted that product platforms impose design and component reuse constraints that can lead to a compromise in performance, relative to a set of individually tailored products. Currently, a number of methodologies to determine an optimum product platform architecture have been developed. These methodologies are helpful in determining the components that should be common between products and therefore represent the constituent elements of a product platform. However, a company producing a large number of products also has to determine the total number of platforms to deploy along with the most appropriate leveraging strategy with respect to the target market segments. It appears that little research has been done on systematically determining the optimum number of product platforms to maximize overall product family profitability. In this paper, a methodology is presented to determine the optimum number of platforms to maximize overall profit for a product family given a set of simplifying assumptions. The methodology is based on a careful analysis of the target market segments, the identification of the performance vs. price position of the segment leaders and a bi-level design optimization scheme to simultaneously optimize platform and variant designs. The usefulness of the methodology is demonstrated for a hypothetical set of automotive vehicle platforms that attempt to serve seven different vehicle market segments. It is found that the use of three distinct platforms will maximize overall profit by pursuing primarily a horizontal leveraging

strategy in this example.

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## Nomenclature

| | |
|---|---|
| $\mathbf{A}_{\mathcal{CP}}$ | Product components to variant assignment matrix |
| $\mathbf{A}_{\mathcal{PM}}$ | Variant to market segment assignment matrix |
| $\mathbf{A}_{\Pi\mathcal{P}}$ | Platform to variant assignment matrix |
| $\mathbf{A}_{\mathcal{X}\Pi}$ | Design variable to platform assignment matrix |
| $\mathcal{C}_c$ | Set of product components |
| $\mathcal{J}_{\mathcal{M}}, \mathcal{J}_{\mathcal{P}}$ | Set of objective functions |
| $\mathcal{M}$ | Set of market segments |
| $\mathcal{P}$ | Set of product variants offered |
| $\Omega$ | Objective preference weight matrix |
| $\Pi$ | Set of product platforms |
| $\mathcal{X}_{\Pi}, \mathcal{X}_{\mathcal{P}}$ | Set of design vectors $\mathbf{x}$ |
| $\mathbf{J}$ | Product objective vector |
| $\mathbf{x}_{\pi}, \mathbf{x}_{\mathcal{P}}$ | Design vectors |
| D | Weighted performance objective distance |
| $\hat{J}$ | Normalized aggregate objective function value |
| $C_{\mathcal{P}}$ | Total variable cost of product family |
| $C_{\pi}$ | Cost of a product platform |
| $C_{\text{Comp}}$ | Cost of a product component |
| $C_{\text{Cap}}$ | Capital investment |
| K | Number of product components |
| M | Number of market segment |
| N | Number of product platform |
| n,r | Number of product design variables |
| P | Price |
| $\hat{P}$ | Normalized price |
| Q | Number of objective functions |
| SV | Sales volume |
| $TFU_c$ | Theoretical first unit cost of product component |
| $TFU_{\pi}$ | Theoretical first unit cost of product platform |
| $U_c$ | Component usage |
| V | Number of product variants |

## Introduction

Modern manufacturing industries are concentrating their efforts on maximizing profits by seeking ways to reduce development and manufacturing costs, while at the same time offering a set of competitive products in many diverse market segments. One way of achieving this objective is to implement a product platform strategy. By implementing a product platform strategy, manufacturers are able to reduce overall production costs and development time, while satisfying diverse customer demands. A platform strategy is essentially an effective and deliberate program of component reuse which takes advantage of the economies of scale across the product family, while minimizing the negative impact of reuse on individual product variant distinctiveness and performance.

Because of its advantages, product platform strategies are aggressively implemented by various product manufacturers. Volkswagen is the recognized global leader in platform strategy for passenger cars, and currently produces over four million vehicles from just four platforms.[?] Boeing is developing the platform based Blended Wing Body (BWB) aircraft family consists of a tanker, commercial aircraft and bomber. Hewlett-Packard implemented platform strategies on its DeskJet products.[?] The overall objective is to maximize the product variants to platform ratio $V/N$, while maximizing the performances of each product variant. $V$ is the number of product variants in the product family $\mathcal{P}$ (sometimes called portfolio), and $N$ is the number of platforms in the set $\Pi$. Example of this trend is shown by analyzing the $V/N$ ratio for four leading automotive manufacturers in Figure 1.

**Previous Research**

Many product platform strategies are developed by various scholars throughout academia. Simpson et al.[?] proposed the Product Platform Concept Exploration Method (PPCEM) to define the market segment and product platform specification for a vertically scalable product family. Simpson and D'Souza[?] proposed a multiobjective two level genetic algorithm optimization method to optimize product family and individual product variants using the Product Family Penalty Function, which was developed by Messac et al.[?] Martin and Ishii[?] proposed a method to develop decoupled product platform architecture using the General Variety Index (GVI) and the Coupling Index (CI) to create robust product platform. Fellini et al.[?] developed a method for making commonality decisions for product platforms while controlling individual performance losses. Also, a new methodology for selecting the product platform with information from individual product variant optimization using the Sharing Penalty Vector (SPV) was introduced by Fellini et al.[?] for family products with mild variation. Gonzalez-Zugasti et al.[?] proposed a methodology to design product platforms and variants which take technical performance requirements and product family costs into consideration.

Until now, most product platform strategies were focused on selecting common components and architectures for a single platform to achieve commonality goals, while maintaining performance thresholds of product variants. It is observed that there is no clear and rigorous methodology to determine the optimum number of platforms to cover wide market segments. In this paper, an optimization methodology to determine the optimum number of platforms is proposed.

In the following section, various platform strategies are presented. In proceeding sections, a new two level optimization methodology for the product family is proposed in detail. The methodology identifies the leader for each market segment, calculates the weighted distance of each of the competitors from the market leader, obtains sales volumes for each product variant, and finally, determines the optimum number of platforms and leveraging strategy that produces the largest net profit. The proposed methodology is implemented to automotive product family to determine the optimum number of vehicle platforms. The results and analysis are presented, and conclusions are drawn.

## Platform and Platform Strategy

There are many definitions of the term *platform*. Ulrich and Eppinger[?] define platform as a collection of assets, including component designs, shared by multiple products. Simpson and Souza[?] define platform as a group of related products that share common components and/or subsystems. Figure 2 illustrates three different products, each assembled with different combinations of elements A, B, C, D and E.

It is apparent that three products in Figure 2 share elements A, B, and C together, while elements D and E are shared among one or two products. Based on set theory, it can be concluded that this product family shares a common platform that contains elements A, B and C. However, if we analyze the Design Structure Matrices (DSM) of these products, it can be concluded that only element A constitutes the platform.

Many well known products are developed on platforms. Products based on platforms include airplanes, computers, power tools and automobiles. In the automotive industry, Volkswagen, along with its partners Skoda, Seat and Audi, produces the Beetle, the Golf, the Bora, the Octavia, the Toledo and the A3 from a single platform, which share common components such as engine, transmission, brakes, seat, axles, etc. Boeing is currently in the process of developing the Blended Wing Body (BWB) aircrafts, which will share identical wings, cockpit, and center body elements among its product family. Today's personal computers are made of a motherboard with standardized interfaces for CPU, hard drive, ethernet cards and other components, which enable rapid implementation of next generation technologies. In general, platforms are categorized into three classes. They are modular platforms, scalable platforms and generational platforms.

**Modular (Functional) Platforms:** A modular platform is a platform that allows creation of functionally different product variants. A good example is the Blended Wing Body aircrafts from Boeing. Using a common platform, the firm is able to create different airplane variants, which can be a tanker, commercial airplane, global transport, and bomber.

**Scalable Platforms:** A scalable platform allows creation of functionally identical products of various capacities. A camera film is a good example. Using a film casing and the film itself as platform elements, products with a differing exposures and film qualities can be manufactured and offered to suit various consumer needs.

**Generational Platforms:** A generational platform is a platform that can be used as a lever for rapid next generation development. A good example of generational platforms is a personal computer, which has standardized interfaces for components with short development cycles. This allows the quick and easy implementation of new technologies, without changing the base platform.

Although product platforms can help reduce cost and development time, they must be implemented effectively. Based on empirical evidence, platforms should be implemented when the family of products can be described by one or more of following criteria:

- the product family is a system with a common basic sets of attributes.;
- the product family has a long life cycle and distributed ownership;
- the product family has highly interconnected systems with a need for future growth and a constant update of technologies;
- the product family must adapt to rapidly changing environments, trends and "fast clock speed" technologies;
- the product family has stable core functionality but has variability in secondary functions and/or external styling;
- the product family interfaces with an intricate peripheral customized architecture.

In some cases, using the product platform may not be appropriate. Products with the following characteristics are not suitable for platform implementation:

- the product is intended for a single use or has short life cycles without need for product variety;

- the product is insensitive to change over time;
- the product has only a single function;
- the product consists of fixed packaging and/or design;
- the product is sold in a slowly changing markets;
- the product is placed in an ultra-high performance market, where no performance compromises can be tolerated;

Once the decision to implement platforms is made, there are different strategies for the product implementation. Figure 3 illustrates various platform strategies that are implemented throughout various industries. With a single platform, the firm can cover different market segments using different approaches. Some of the most widely practiced platform strategies are *No Leveraging, Vertical Leveraging, Horizontal Leveraging*, and the *Beachhead Strategy.*

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

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

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

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

Implementing a platform strategy has many advantages. It increases standard parts,[?] reduces product design lead times,[?] makes coverage of market niches easier,[?] reduces design risk and cost, allows faster response to changing market needs, and makes standardization of manufacturing processes and tooling easier.

However, platform strategy has shortcomings that are rarely discussed in the literature. By implementing platforms, undesirable functions can be introduced to the system, causing unexpected technical difficulties to the platform based product family. Audi retrofitted a tail spoiler to its TT sports roadster to fix the rear wheel pressure problem. The cause of the problem was traced to the utilization of a common platform for this particular vehicle, which in turn, had unexpected side effects. Cannibalization of common platform based high end products by low end products is a weakness for the vertical leveraging strategy. Another disadvantage of an aggressive platform strategy is a performance compromise. If the degree of commonality is too high, each variant from product platform might not be competitive in their respective market segment due to inferior performance (with respective to the market leader) caused by sharing constraints.

## Platform Strategy Formulation

### General Overview

Product platform strategy is a powerful concept that is widely implemented throughout many industries. Figure 4 shows an overview of general corporate strategy for product development.

A typical product family development plan consists of the marketing plan, designing plan, and manufacturing plan. The marketing plan identifies potential niche markets and products that could generate corporate profit. The product design plan outlines target specification values for product variant in each market segment, and the efficient platform strategy to design the product family. The manufacturing plan outlines detailed product family production plan that could achieve low cost, high facility reuse and utilization. All three plans are subjects of interesting research. In this study, the product design plan, particulary the product platform strategy, was discussed in detail.

In general, the product platform strategy can be expressed as

$$\mathcal{X}_\pi, \mathcal{C}_\pi \rightarrow \Pi \rightarrow \mathcal{P} \rightarrow \mathcal{M} \tag{1}$$

where the chosen platform design variable set $\mathcal{X}_\pi$ and platform component set $\mathcal{C}_\pi$ is mapped to the product platform set $\Pi$, which then maps to the product family set $\mathcal{P}$. The product family set $\mathcal{P}$ is then mapped to the market segment set $\mathcal{M}$. In the past, many methods have been developed to assign proper design variables and components to product platforms. These methods are mentioned in the introduction. This study focuses on product design plan, with emphasis mapping $\Pi$ to $\mathcal{P}$, and $\mathcal{P}$ to $\mathcal{M}$.

**Two Level Design Optimization**

The product design plan is divided into product family level design plan and product variant design plan. During the product family design stage, decision makers choose and optimize product family variables such as the market segment, the overall product family architecture, the product platform architecture, the number of platforms, and the platform placement in appropriate market segments.

After the product family architecture variables are decided, individual product variants are optimized with respect to their specific market segment. Each product variant is optimized within the constraint of the platform the variant is based on. Once the product variant is optimized, the total revenue and the profit of the product family is calculated. The optimization process switches back and forth between the upper (family) level and the lower (variant) level to see if a new assignment $\mathbf{A}_{\Pi\mathcal{M}}$ and platform design variable set $\mathcal{X}_\Pi$ yields better overall profit. The optimization process continuously iterates until the product family with the best aggregate product variant performance and profits are found. This optimization process is represented in Figure 5.

Proposed two level optimization is implemented with certain limitations. It is assumed that on the product family optimization, the contending market segments and the product platform architecture (component to platform assignment) are already decided, leaving the number of product platforms as the only family level variable. By optimizing the number of product platforms from $N = 1, 2, \ldots, V$, the best product variant to platform assignment and the product platform to market segment assignment are determined. In order to generate accurate two level optimization simulation, appropriate product platform model, product variant model, and market segment model are needed.

**Product Platform Model**

A product platform is a set of design variables or components that are commonly shared across the product family (See Figure 2). A typical product platform consists of components or design variables that have finite range of flexibility, imposing constraint on the individual product variant optimization. Mathematically, a product platform can be represented as a set of design variable, $\mathcal{X}_\Pi$, that is common across the platform sharing variants in the product family set, $\mathcal{P}$. The design variable assignment matrix $\mathbf{A}_{\mathcal{X}\Pi}$ that assigns a set of design variables $\mathcal{X}_\Pi$ to a set of product platform $\Pi$ can be generated:

$$\mathbf{A}_{\mathcal{X}_\Pi\Pi} = \begin{bmatrix} a_{\mathcal{X}_\Pi\Pi,11} & \cdots & a_{\mathcal{X}_\Pi\Pi,1N} \\ \cdots & \cdots & \cdots \\ a_{\mathcal{X}_\Pi\Pi,R1} & \cdots & a_{\mathcal{X}_\Pi\Pi,RN} \end{bmatrix} \tag{2}$$

where the rows of the $\mathbf{A}_{\mathcal{X}_\Pi \Pi}$ represent available design variables and the columns represent available product platforms. If $i^{th}$ design variable is part of $j^{th}$ platform, a 1 is placed in that cell. It is entirely possible that each platform has different design variables set from the other platforms.

**Product Variant Model**

The individual product variant can be represented by a set of variant design variables, $\mathcal{X}_\mathcal{P}$, and a set of variant objective functions, $\mathcal{J}_\mathcal{P}$:

$$\begin{aligned} \mathcal{X}_\mathcal{P} &= \{\mathbf{x}_{p_1}, \mathbf{x}_{p_2} ..., \mathbf{x}_{p_V}\} \\ \mathcal{J}_\mathcal{P} &= \{\mathbf{J}_{p_1}, \mathbf{J}_{p_2} ..., \mathbf{J}_{p_V}\} \end{aligned} \tag{3}$$

where $\mathbf{x}_p$ is the design vector unique to the specific product variant and $\mathbf{J}_p$ is the individual product variant objective functions vector. Design vectors $\mathbf{x}_p$ can be changed freely on the individual product variant level to optimize product variant objective $\mathbf{J}_p$ for their respective market segments. However, the bandwidth of $\mathbf{x}_p$ may be limited due to constraints imposed by the product platform design vector $\mathbf{x}_\pi$. One of the key process in the product family level optimization is to choose the set of platform design variables, $\mathcal{X}_\Pi$, that has has high sensitivity effect on $\mathcal{J}_\mathcal{P}$ with minimal perturbation.

**Market Segment Model**

A market segment model can be generated using the sales volume($SV$), the price($P$) and the performance vector($\mathbf{J}_p$) of each competing product. An example plot of sales volume vs. price for the U.S. Sports Utility Vehicles(SUV) in year 2001 is shown in Figure 6.

It is noticeable that this market segment features a clear leader in terms of sales volume. This situation can be found in many different products and market segments. This gives rise to the hypothesis of a “sweet spot”. The hypothesis states that there is a most desirable location in the price-performance space of each market segment that will maximize the sales volume. The ”sweet spot” hypothesis forms the basis for sales volume based revenue calculation in this study. In Figure 7, using the weighted distance function $D$ (derived in later section), relative positions for all competing products in the compact automotive vehicle market segment are plotted.

It is interesting to observe that with the market leader positioned at (1,1), the competitor’s positions are placed in four different quadrants. The first quadrant is populated with over-performing, over-priced vehicles. Vehicles in the second quadrant are noncompetitive, since they are overpriced, with less performance than the market leader. The third quadrant is populated with vehicles that are less expensive and inferior in performance. The fourth quadrant contains possible contenders for this market segment, offering better performance at the lower price than the market leader.

Performing the regression analysis using the relative positions of all competitors, the estimated sales volume for each competitor can be calculated. Relevant equations for sales volume calculation are introduced in the next section. Figure 8 shows the plot of sales volume for a medium size automotive vehicle market segment as the function of absolute weighted distance $D_{ij}$ of each product:
where $D_{ij}$ is the weighted distance of $i^{th}$ variant in $j^{th}$ market segment, and is a function of the normalized price $\hat{P}$ and the normalized aggregated product variant performance $\hat{J}$.

**Assignment Matrix**

One of the key tasks in creating product family architecture is to assign product platforms to market segments. This assignment is captured with platform assignment matrix $\mathbf{A}_{\Pi\mathcal{M}}$:

$$\mathbf{A}_{\Pi\mathcal{M}} = \begin{bmatrix} a_{\Pi\mathcal{M},11} & \cdots & a_{\Pi\mathcal{M},1M} \\ \cdots & \cdots & \cdots \\ a_{\Pi\mathcal{M},N1} & \cdots & a_{\Pi\mathcal{M},NM} \end{bmatrix} \tag{4}$$

where $a_{\Pi\mathcal{M},ij} \in \{1,0\}$ and $\sum_{i=1}^{N} a_{\Pi\mathcal{M},ij} = 1$. The rows of the platform assignment matrix correspond to the product platforms, and the columns correspond to the market segments. If the $i^{th}$ platform is used in $j^{th}$ market segment a 1 is placed in the $i^{th}$ row and $j^{th}$ column of $\mathbf{A}_{\Pi\mathcal{M}}$.

Next key task in the product family optimization is the assignment of the product variants to market segments. It is expressed in matrix form in Equation (5):

$$\mathbf{A}_{\mathcal{P}\mathcal{M}} = \begin{bmatrix} a_{\mathcal{P}\mathcal{M},11} & \cdots & a_{\mathcal{P}\mathcal{M},1M} \\ \cdots & \cdots & \cdots \\ a_{\mathcal{P}\mathcal{M},V1} & \cdots & a_{\mathcal{P}\mathcal{M},VM} \end{bmatrix} \tag{5}$$

where rows represent the product variants available and columns represent the available market segments. If the $i^{th}$ variant is in the $j^{th}$ market segment a 1 is placed in the $i^{th}$ row and $j^{th}$ column of $\mathbf{A}_{\mathcal{P}\mathcal{M}}$.

Multiplying two matrices $\mathbf{A}_{\Pi\mathcal{M}}$ and $\mathbf{A}_{\mathcal{P}\mathcal{M}}^{\mathrm{T}}$, the platform to product variant assignment matrix, $\mathbf{A}_{\Pi\mathcal{P}}$, is generated.

$$\mathbf{A}_{\Pi\mathcal{P}} = \mathbf{A}_{\Pi\mathcal{M}}\mathbf{A}_{\mathcal{P}\mathcal{M}}^{\mathrm{T}} \tag{6}$$

### Mathematical Model Formulation

The optimization objective is to maximize the aggregate profit of the entire product family $\mathcal{P}$, where $\mathcal{P}$ is the set of product variants $\{p_1, p_2, ..., p_V\}$. The optimization problem can be stated as:

$$\max_{N,\mathcal{X}_{\Pi},\mathcal{X}_{\mathcal{P}}} \sum_{\mathrm{i}=1}^{V}\sum_{j=1}^{M} SV_{ij}P_{ij} - C_{\mathcal{P}} \tag{7}$$

where $N$ is the number of platforms, $\mathcal{X}_{\Pi}$ is the set of platform design variable vectors, $\mathcal{X}_{\mathcal{P}}$ is the set of product variant design variable vectors, $V$ is the number of product variants, $M$ is the number of market segments, $SV_{ij}$ is the sales volume of the $i^{th}$ variant in $j^{th}$ market segment, $P_{ij}$ is the sales price of the $i^{th}$ variant in $j^{th}$ market segment, and $\mathcal{C}_{\mathcal{P}}$ is the total variable and fixed cost for the product family.

## Proposed Method

### Overview

The purpose of implementing a platform strategy is to reduce development time and cost while maximizing market share and profit. In the past, many scholars proposed the methods for optimizing a single product platform and its variants. However, little work has been done to address the product family level optimization. In the product family level, many heuristic decisions, such as the product platform architecture selection, the number of market segments to compete, the number of product platforms needed, and the assignment of product platforms to appropriate market segments, need to be made. In this study, a two level optimization method (the product family level and the individual product variant level) to find the maximum profit for the product family is proposed.

The proposed methodology is implemented with following assumptions:

- market segments, in which platform based product variants will be placed, are well established, with steady sales volume;
- only a single product per market segment will be placed;
- the methodology assumes that the components that make up a platform have been decided *priori* by one of the existing methodologies search;
- in each market segment, competitors will keep offering the same products as before;
- each market segment operates independent of the other;

- the sales price of the product is equal to the Manufacturer's Suggested Retail Price with no discounts;
- the proposed entry's price is set to the sales price of the marker leader for that particular market segment. Competition occurs over relative performance;
- the sales volume of the product is equal to the number of products produced.

**Proposed Methodology**

*Step 1: Identify market segments and corresponding market leaders*

Define a set of market segments $\mathcal{M}$, where $\mathcal{M} = \{m_1, m_2, ..., m_M\}$. Individual market segments are chosen according to the preference of best profit opportunity for the product family variant and potential for profitable market share. This is a product family level heuristic variable and is usually determined through financial analysis. In this study, the market segment set $\mathcal{M}$ is assumed to be decided and fixed.

Once the market segment set $\mathcal{M}$ is defined, the market leader for each market segment can be identified. In the proposed methodology, the market leader is defined as the product with the largest sales volume.

*Step 2: Establish the design variable set for each market segment*

The second step is to define the product platform design variable set $\mathcal{X}_\Pi$ and the product variant design variable set $\mathcal{X}_\mathcal{P}$ that belongs to each element in the market segment set $\mathcal{M}$:

$$\begin{aligned} \mathcal{X}_\Pi &= \{\mathbf{x}_{\pi_1}, \mathbf{x}_{\pi_2}, ..., \mathbf{x}_{\pi_M}\} \\ \mathcal{X}_\mathcal{P} &= \{\mathbf{x}_{p_1}, \mathbf{x}_{p_2}, ..., \mathbf{x}_{p_M}\} \end{aligned} \tag{8}$$

Set $\mathcal{X}_\Pi$ is a collection of product family level design variables pertaining to the product platform set $\Pi$, and it acts as an imposed constraint for the product variant optimization. Set $\mathcal{X}_\mathcal{P}$ is a collection of design variables that belongs to the product variant set $\mathcal{P}$ and enables product variants to be optimized to its respective market segment. The flexibility range of set $\mathcal{X}_\mathcal{P}$ may be limited by the constraint imposed from the platform design variable set $\mathcal{X}_\Pi$. In this study, set $\mathcal{X}_\Pi$ and $\mathcal{X}_\mathcal{P}$ are known *a priori*.

One of the task of optimizing the product family is the assignment of best product platforms for each individual market segment from the available platform set $\Pi$. The constraint is the number of platforms that are allowed to be used for the entire product family, which ranges from $N = 1...M$. Let

$$\mathbf{x}_{\pi,Optimum,j} = \mathbf{x}_{\pi,Leader,j} \tag{9}$$

where $\mathbf{x}_{\pi,Optimum,j}$ is the optimum platform design vector for $j^{th}$ market segment and $\mathbf{x}_{\pi,Leader,j}$ is the platform design vector for the sales leader in the market segment.

The elements of product platform design variable $\mathbf{x}_\pi$ in set $\mathcal{X}_\Pi$ may vary, but there are critical elements that need to be included and imposed upon all product variants that are based on the particular platform. They are the target price of the platform based product variant, the Theoretical First Unit cost of the platform ($TFU_\pi$), the Theoretical First Unit costs of the product variant components ($TFU_c$). The target price for a product that is based on a particular platform is the sales price of the market sales volume leader where the platform originated from. $TFU_\pi$ and $TFU_c$ are also functions of the market leader sales volume as follows:

$$\begin{aligned} TFU_\pi &= C_\pi \frac{SV_{Leader,j}}{SV_{Leader,j}^B} \\ TFU_c &= C_c \frac{SV_{Leader,j}}{SV_{Leader,j}^B} \end{aligned} \tag{10}$$

where

$$B = 1 - \frac{\ln((100\%)/S)}{\ln 2} \tag{11}$$

$$\begin{aligned} C_\pi &= P_{Leader,j}\,(\text{1 - Profit Margin})\,(\text{Cost Margin}) \\ C_c &= P_{Leader,j}\,(\text{1 - Profit Margin})\,(\text{Component Cost Margin}) \end{aligned} \tag{12}$$

$S$ is the learning curve coefficient. The cost of platform $C_\pi$ and the cost of component $C_c$ are determined from the percentage of total cost, which in turn, is the price of the sales leader for $j^{th}$ market segment minus the profit margin for that market segment. An example of a generic product profit and cost decomposition is shown in Figure 9.

In all, $N$ product platforms are created, where $N = 1, 2, ..., M$. The purpose of creating platforms for each individual market segment is that when determining the optimum number of platforms for the entire product family, the platform will be utilized in the order of their sales volume. For example, when a single platform is used for the entire product family, the platform with highest sales volume is used. For two platform utilization, two platforms with largest sales volume are used, and so on. This process continues until each market segment uses their own platform, indicating customization for each market segments.

*Step 3: Identify market specific performance objective functions*

Define the market specific performance objective function set $\mathcal{J}_{\mathcal{M}}$, where $\mathcal{J}_{\mathcal{M}} = \{\mathbf{J}_1, \mathbf{J}_2, ..., \mathbf{J}_M\}$. Objective functions are defined by translating the customer preferred attributes to target specifications. Examples of objective functions are the CPU speed for personal computers, 0-60 mph acceleration time for automotive vehicles, and copies per minute rate for copiers. Each objective vector $\mathbf{J}$ in set $\mathcal{J}_{\mathcal{M}}$ has objective values of the corresponding market sales leader. Also, all objective vectors have the same attributes. The purpose of establishing $\mathcal{J}_{\mathcal{M}}$ is to establish the benchmark values for $\mathcal{J}_{\mathcal{P}}$, which is the objective function vector set for product variants set $\mathcal{P}$, subject to optimization.

Usually performance objectives are identified through customer survey and conjoint analysis. It is assumed that the set of objective functions are already established.

*Step 4: Establish objective weight factors for each market segment*

Each market segment has its own order of objective function preference. For example, a truck buyer might consider the cargo volume to be the most important feature, compared to a compact car buyer, who prefers fuel economy above all other attributes. To mathematically express different customer preferences for different market segments, the objective weight factors matrix, $\Omega$, is defined:

$$\Omega = \begin{bmatrix} \omega_{11} & ... & \omega_{1M} \\ ... & ... & ... \\ \omega_{Q1} & ... & \omega_{QM} \end{bmatrix} \tag{13}$$

where

$$\sum_{i=1}^{Q} \omega_{ij} = 1 \tag{14}$$

The rows represent different objective functions; columns represent individual market segments; $Q$ is the number of objective functions; and $M$ is the number of market segments. For example, if $i^{th}$ objective in $j^{th}$ market segment has a 40% impact on consumer preference, 0.4 is placed on that particular cell. The sum of all objective preference for a single market segment must equal one. This matrix helps to calculate the product variant's aggregate performance value, which in turn, is used to calculate the product variant's weighted performance distance from the leader. Equations for the weighted performance distance are explained in the later section.

*Step 5: Establish the sales volume equation for each market segment*

Determining the sales volume of each product variant is a key step of this methodology. It can be stated that the sales volume of a product variant is a function of its performance weighted distance, which in turn, is a function of the normalized price and the aggregate sum of a variant's performance objective values. The sales volume of $i^{th}$ variant in $j^{th}$ market segment is:

$$SV_{ij} = \frac{SV_{Leader,j}}{\beta_j D_{ij} + 1} \tag{15}$$

where $SV_{Leader,j}$ is the sales volume of the market leader in $j^{th}$ market segment, $D_{ij}$ is the performance weighted distance of $i^{th}$ variant in $j^{th}$ market segment, and $\beta_j$ is the curve fitting coefficient for $j^{th}$ market segment.

The weighted distance, $D_{ij}$, of $i^{th}$ product in $j^{th}$ market segment is a function of the normalized price ($\hat{P}$) and the normalized aggregate performance value ($\hat{J}$) of a product variant:

$$D_{ij} = \frac{\hat{P}_{ij}}{\hat{J}_{ij}} \sqrt{(\hat{J}_{ij} - 1)^2 + (\hat{P}_{ij} - 1)^2} \tag{16}$$

where

$$\hat{P}_{ij} = \frac{P_{ij}}{P_{Leader,j}} \tag{17}$$

and

$$\hat{J}_{ij} = \sum_{k=1}^{Q} \omega_{kj} \frac{J_{ij,k}}{J_{Leader,j,k}} \tag{18}$$

$\hat{P}_{ij}$ is a normalized price of $i^{th}$ variant in $j^{th}$ market segment respect to the price of the market leader in $P_{Leader,j}$. $\hat{J}_{ij}$ is the normalized aggregate performance objective value of $i^{th}$ product in $j^{th}$ market segment. Note that $\hat{J}_{ij}$ is the aggregate sum of $k$ normalized objective functions multiplied by the corresponding objective function preference weights $\omega_{kj}$, where $\omega_{kj} \in \Omega$. The curve fitting coefficient $\beta_j$ for $j^{th}$ market segment is obtained by plotting sales volume vs. $D_{ij}$ (see Figure 8) for all competitors in the market segment and calculating the best curve fitting coefficient from the regression analysis. The equations of sales volume vs. weighted distance curve for each market segment can be obtained by Equations (15) - (18).

*Step 6: Product variant optimization*

In order to create the best product variant, a good product platform must be assigned to the target market segment. If there are $N$ product platforms available, the best platform for $j^{th}$ market segment is determined using following criteria:

$$\max_{N} \sqrt{\sum_{k=1}^{n} \left(x_{\pi,k} - x_{\pi,Leader,jk}\right)^2} \tag{19}$$

where $x_\pi$ is is the platform variable vector element for one of the $N$ platforms available, and $n$ is the number of platform design variables. At the end, all platforms are assigned to the appropriate market segment, thus populating the assignment matrix $\mathbf{A}_{\Pi\mathcal{M}}$.

Once the product platform is assigned to the market segment, a market specific product variant must be optimized to generate the best performance output that will maximize the sales volume. The optimization problem can be stated as:

$$\begin{aligned} &\min_{\mathbf{x}_p} \left|\hat{J}_{ij} - 1\right| \\ &\text{subject to } \{\mathbf{x}_\pi\} \end{aligned} \tag{20}$$

where $\mathbf{x}_p$ is the product variant design vector, and $\mathbf{x}_\pi$ is the product platform design vector that acts as a constraint in variant optimization. The objective of the product variant optimization is to bring the product variant's total aggregate performance as close to the market leader's value. It is clear from the established equations that the sales volume and profit of a product variant is closely related to the proximity of the product performance to that of the market leader.

*Step 7: Estimate the total profit of the product family*

The total cost of the product family can be expressed as:

$$C_{\text{Total}} = C_{\mathcal{P}} + C_{\text{Cap}} \tag{21}$$

where $C_{\mathcal{P}}$ is the total sum of the product family variant cost and $C_{\text{Cap}}$ is the total capital investment cost. $C_{\text{Cap}}$ is aggregate sum of investment costs, such as factory cost, die cost and research and development cost. The capital investment cost is relatively insensitive to the product family sales volume, and is treated as constant in this paper.

The total variable cost of the product family variant is a function of the $TFU$'s and the sales volume of each variant. The variable cost of an individual product variant $i$ in market segment $j$ can be expressed as:

$$C_{ij} = C_{\pi,ij} + C_{\text{Comp},ij} \tag{22}$$

where

$$C_{\pi,ij} = TFU_{\pi,j} SV_{ij}^{\text{B}} \tag{23}$$

and

$$C_{\text{Comp},ij} = \sum_{k=1}^{c} \text{TFU}_{c,k} SV_{ij,k}^{\text{B}} U_{c,k} \tag{24}$$

$\text{TFU}_{\pi,j}$ is the Theoretical First Unit cost of a product platform assigned to $j^{th}$ market segment and $SV_{ij}$ is the sales volume of platform based variant $i$ in the market segment. The total cost of $c$ number of components can be written in a similar way, with exception of the usage coefficient $U_{c,k}$, which represents the quantity of $k^{th}$ components used in a single product variant.

Calculate the total profit of the product family using Equation (7), given the constraints $V = M$ and $N = \{1...M\}$. Repeat the process by varying the number of platforms from $N = 1...M$.

**Limitations:**

The proposed method has certain limitations which must be considered:

- the methodology is applicable to existing, well established market segments and products, with known customer preferences and sales volumes;

- since the product platform specifications for each market segment complies with the market leader specifications, the product platform model is quite sensitive to annual changes in the market leader.

- Proposed methodology benchmarks against the current market leader.

In the next section, a case study of an automotive vehicle family optimization is presented as a hypothetical example. The optimum number of platforms is determined through the execution of the proposed methodology.

## Case study: An automotive vehicle family

### Problem Background

A new automotive manufacturer is preparing to enter the competitive automotive market. The manufacturer has identified seven market segments for its entry products. The manufacturer has to determine the optimum number of vehicle platforms, $N$, that will maximize the profit of the vehicle product family.

### Methodology Implementation

*Step 1: Identify market segments and corresponding market leaders*

The manufacturer decided to develop vehicles for following market segments: Low Compact Sedan (LOW), Mid-size Sedan (MED), Luxury Sedan (LXD), Sports Car (SPT), Sports Utility Vehicle (SUV), Pickup Truck (PUP), and the Van (VAN) segment, respectively. The vehicle market segments selected for product entry are shown in Figure 10.

For the vehicle product family, following family level decisions were made:

- only one product entry per market segment ($V = M$);
- the basic vehicle architecture is body-on-frame (BOF);
- the fixed operating cost per year ($C_{\text{Cap}}$) is four billion dollars;
- each vehicle will be offered at the same price as the segment leader ($P_{ij} = P_{Leader,j}$).

Next, the market leader for each market segment is identified according to the vehicle sales volume for year 2001. For example, the Ford Explorer is designated as the market leader for SUV market segment. Manufacturer suggested retail price of the market leader is obtained through publicly available data on the internet.[?]

*Step 2: Identify the product platform variables set and product variant variables set for each market segment*

It is important to define the vehicle platform design variable set $\mathcal{X}_\Pi$ and the vehicle variant design variable set $\mathcal{X}_\mathcal{P}$:

$$\mathcal{X}_\Pi = \{\mathbf{x}_{\pi_1}, \mathbf{x}_{\pi_2}, ..., \mathbf{x}_{\pi_7}\};\ \mathbf{x}_\pi = \{WB, WT\}$$
$$\mathcal{X}_\mathcal{P} = \{\mathbf{x}_{p_1}, \mathbf{x}_{p_2}, ..., \mathbf{x}_{p_7}\};\ \mathbf{x}_p = \{ED, HT\}$$

$WB$ is the vehicle wheelbase, $WT$ is the vehicle wheel track, $ED$ is the engine displacement, and $HT$ is the vehicle height. All market segments have same platform design vector and product variant design vector variables, but the values of these variables are different depending on the market segment specifications.

Next task is to establish the appropriate product platform design vector values. Since there is one platform for each market segment, total of seven platform design vectors are created. Using the Equation (9), market leader's design vector values are assigned as the optimum platform design vector values for that particular market. For example, in the mid-size sedan segment (MID), the optimum platform design vector elements $WB$ and $WT$ values are values of Honda Accord, current sales volume leader in the market.

Final task in creating the platform model for each market segment is to calculate the $TFU$s for the platform and other components. For this particular case study, the cost decomposition of the automotive vehicle is shown below:
Each market has different profit margin. This is due to the fact that in general corporate strategy, a company sets higher profit margin for more luxurious products, since customers in this market segments are more willing to pay for them.

In the vehicle family example, a vehicle cost is decomposed into a platform cost, an engine cost, and a body cost. Their respective cost margin is shown in the Figure 11. With Equation (10) and 23), $TFU_{\pi}$ and $TFU_c$ for each platform was determined.

*Step 3: Identify market specific performance objective functions*

When customers purchase automotive vehicles, many performance criteria are considered. Example of such criteria are acceleration (AC), horsepower (HP), fuel efficiency (FE), passenger volume (PV), and cargo volume (CV), to just name a few. For this case study, five performance criteria that mentioned previously are used as elements of **J** for each market segment. Translating it in mathematical terms:

$$\mathcal{J}_{\mathcal{M}} = \{\mathbf{J}_1, \mathbf{J}_2, ..., \mathbf{J}_7\}$$
$$\mathbf{J}_{\mathrm{M}} = \{AC, HP, FE, PV, CV\}$$

*Step 4:Establish objective weight factors for each market segment*

The object preference weight matrix ($\Omega$) is created. The values of $\Omega_{ij}$ for seven different market segments is shown below:

| | LOW | MED | LXD | SPT | SUV | PUP | VAN |
|---|---|---|---|---|---|---|---|
| AC | 0.1 | 0.15 | 0.15 | 0.4 | 0.1 | 0.15 | 0.05 |
| HP | 0.1 | 0.1 | 0.15 | 0.3 | 0.25 | 0.35 | 0.1 |
| FE | 0.4 | 0.2 | 0.05 | 0.05 | 0.05 | 0.1 | 0.05 |
| PV | 0.3 | 0.4 | 0.45 | 0.2 | 0.3 | 0.05 | 0.4 |
| CV | 0.1 | 0.15 | 0.2 | 0.05 | 0.3 | 0.35 | 0.4 |

These values reflect the customer preference of each objective element in their respective market segment. For example, the acceleration is the most important objective element in the sports car market segment, but is not as important in other market segments. For a vehicle developer, it is crucial to identify the most important objective elements for different market segment, since they have the highest sensitivity on the aggregate performance of the individual vehicle.

*Step 5: Establish the sales volume equation for each market segment*

The sales volume equation for each individual market segment is established using Equation(15). The sales volume curve and the curve fitting coefficient $\beta$ is obtained by:

1. Gather all objective element values of all competitors in the market segment.
2. Calculate $\hat{P}_{ij}$ for all competitors in the market segment.
3. Calculate $\hat{J}_{ij}$ for all competitors in the market segment.
4. Plot sales volume vs. $\hat{J}_{ij}$ for all competitors.
5. Using the regression analysis, obtain the sales volume curve and the curve fitting coefficient $\beta_j$ for the market segment.
6. Repeat the procedure for all market segments.

*Step 6: Product variant optimization*

With given criteria in Equation (19), determine the best fit vehicle platform $\mathbf{x}_\pi$ for each market segment, with the number of vehicle platform ($N$) as a constraint. The vehicle platforms are utilized in the order of their sales volume. For the automotive example, the truck platform is used first, because it has the largest sales volume. The automotive platforms were used in following order: PUP, SUV, MED, LOW, VAN, SPT, and LXD. After $N$ number of platforms are assigned to seven vehicle market segments, proposed product entry $\mathbf{x}_p$ in each market segment is optimized to satisfy the condition imposed by Equation (20). In order to map $\mathbf{x}_\pi$ and $\mathbf{x}_p$ to $\mathbf{J}_p$, a trained neural network is used (see Figure 12).

Seven neural networks are trained to simulate the design variable to objective function mapping in seven vehicle market segments. Each neural network was trained using all competitor's data for a specific market segment. For example, the neural network for the mid-size sedan market was trained using data of over twenty five vehicles that are competing in the market segment. If there are clear mathematical relationship between the design vectors and the objective functions, it can take place in lieu of neural network.

With constraint imposed on the vehicle family by the number of platforms it can use, vehicle objective function $\mathbf{J}_p$ in their respective market segments were optimized by perturbing $\mathbf{x}_p$, while keeping $\mathbf{x}_\pi$ constant.

*Step 7: Estimate the total profit of the product family*

Total cost of the product family is calculated by summing up the cost of vehicles manufactured for each market segment plus the capital investment. For this particular vehicle family, the vehicle cost is divided into a platform cost, an engine cost, and a body cost. With TFUs obtained from Step 2 and implementing Equation (21) - (24), the total cost of individual vehicle variant is obtained.

Summing up the cost from seven vehicle variants and the initial $4 Billion investment, the total cost of the vehicle family ($C_{\mathcal{P}}$) for $N$ platform is calculated. Finally, the total profit is obtained by Equation (7). Repeat the procedure with $N = 1..7$ platforms.

## Results and observation

Figure 13 shows the profit for total product family, $\mathcal{P}$, given $N = 1, 2, \ldots, V$ platforms.

Profit is maximized when three vehicle platforms are implemented. A vehicle family produced lowest profit when $N = 1$, due to the fact that performance had to be compromised by an excessively high level of commonality. It is interesting to note that the product family with customized platforms for each market segment ($N = 7$) was able to generate the second highest profit. This was due to the fact that the vehicle entry in each market segment was optimized to match the market leader performance without the constraint of the number of platform, $N$. It was also observed that with increasing number of platforms, the performance penalty decreases, but with increasing $C_{\mathcal{P}}$ as the consequence.

The platform strategy corresponding to the highest profit is shown in Figure 14. The truck market segment has its own customized platform, since it commands the highest sales volume. The other two platforms are shared among similar sized vehicles, which indicates a horizontal levering strategy.

## Conclusion

In this paper, a quantitative method to determine the optimum number of platforms for a product family is proposed. Using the sales volume function based on relative product performance, the total sales volume of a platform-based product can be estimated. The total profit of a product family based on fixed number of platform was obtained from product family sales volume and total product family costs. The optimum number of platforms compromises the best balance between variable cost savings and performance losses due to parts commonality. The proposed methodology was applied to a hypothetical automotive vehicle family, where the optimum number of vehicle platforms was determined for a given number of variants. Both the aggressive platform strategy (use $N = 3$ platforms for seven market segments) as well as the *no leveraging* strategy appear to be promising based on this case study.

## Further research

In this study, a limited two level optimization scheme was implemented to find the optimum number of product platforms. The next step is to develop a methodology to determine best product architecture and to determine the best market segments. Proposed task will be possible by measuring the sensitivity of different objective functions with respect to different family design variables. The decision maker's task is to choose architecture design variables with high sensitivity and low change cost. As part of research effort, a fully integrated two level optimization scheme will be developed.

# List of Figures

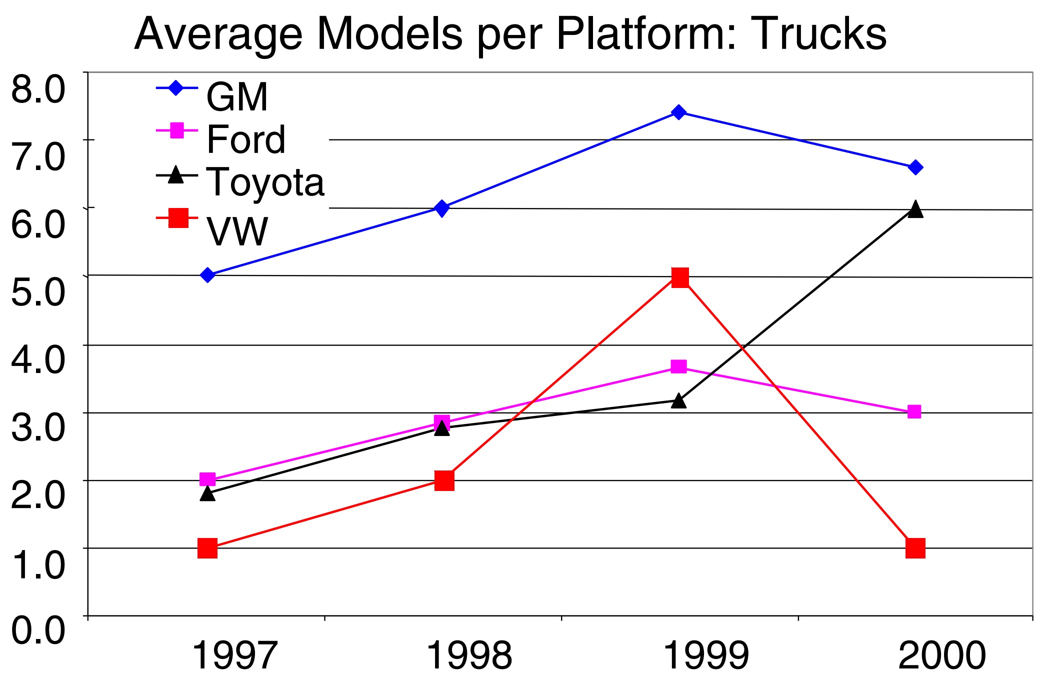


**Figure 1:** **The evolution of the ratio $V/N$ for a sample of leading automotive manufacturers**

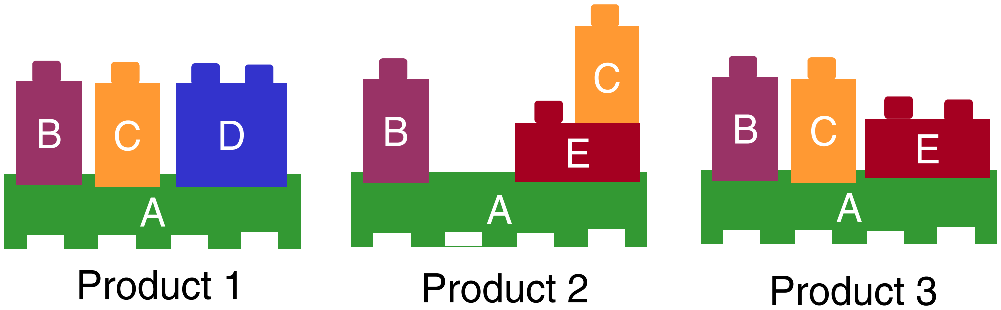


**Figure 2:** **Three products built on a common platform**

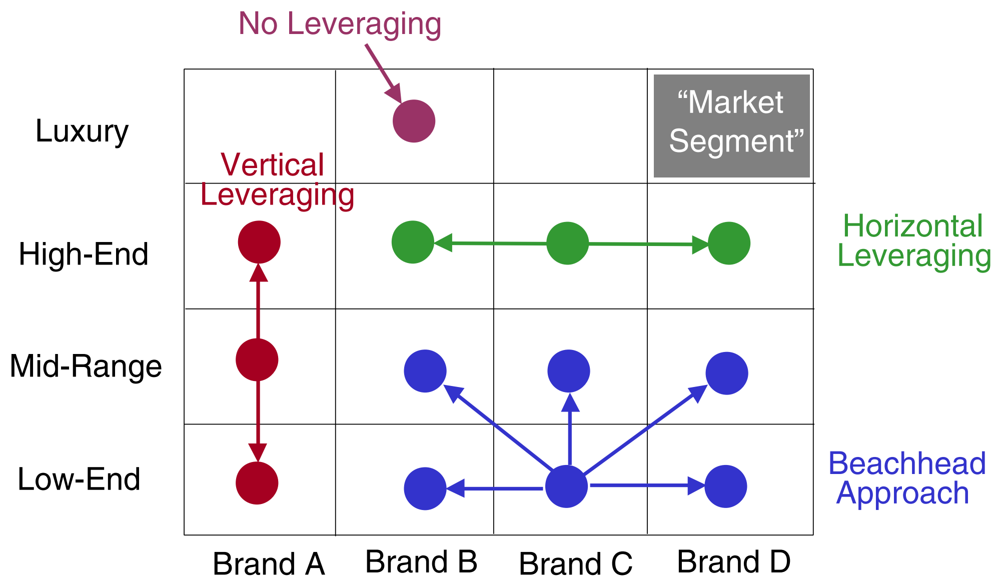


**Figure 3: Various platform strategies**

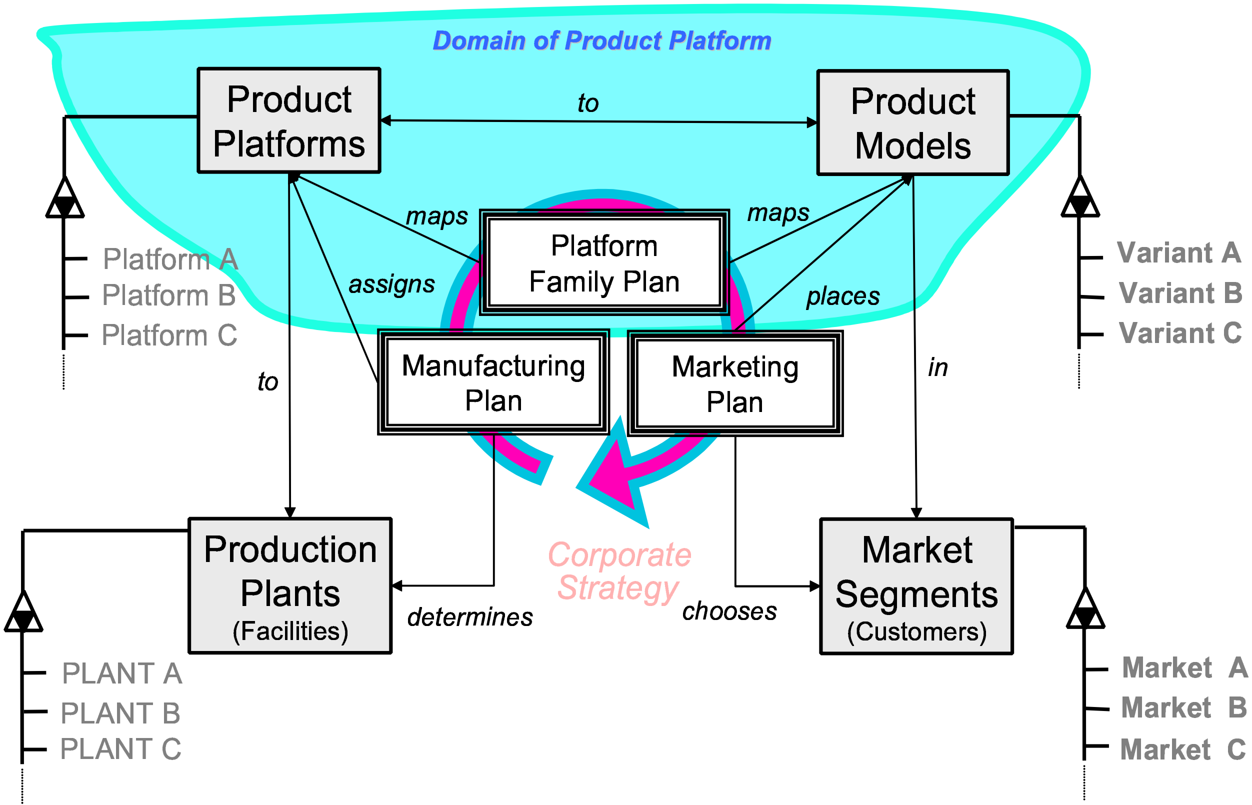


**Figure 4: Overview of corporate product platform strategy**

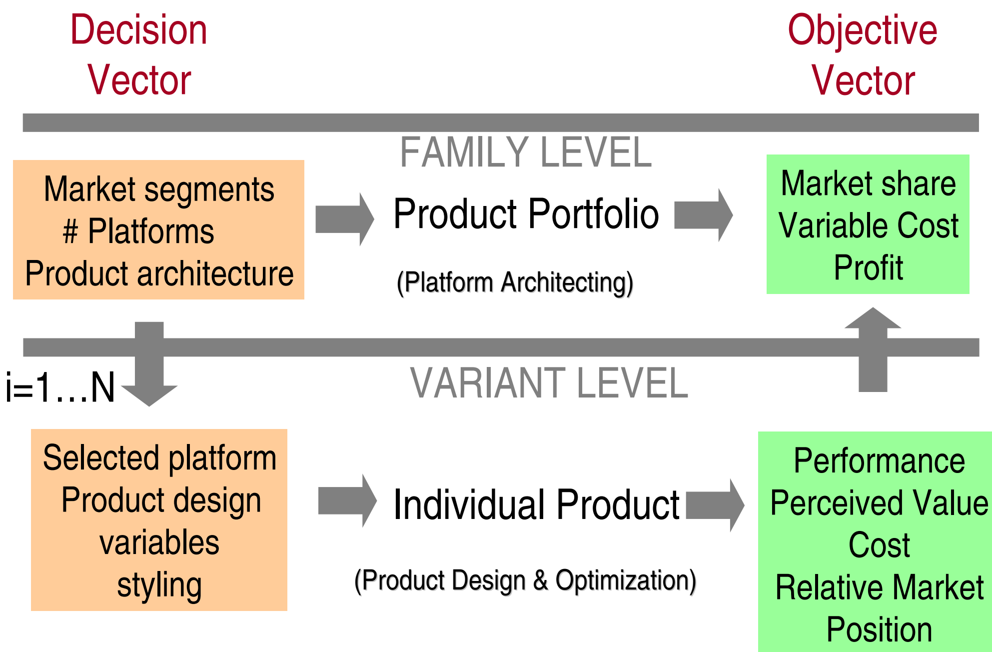


**Figure 5: Two level optimization approach**

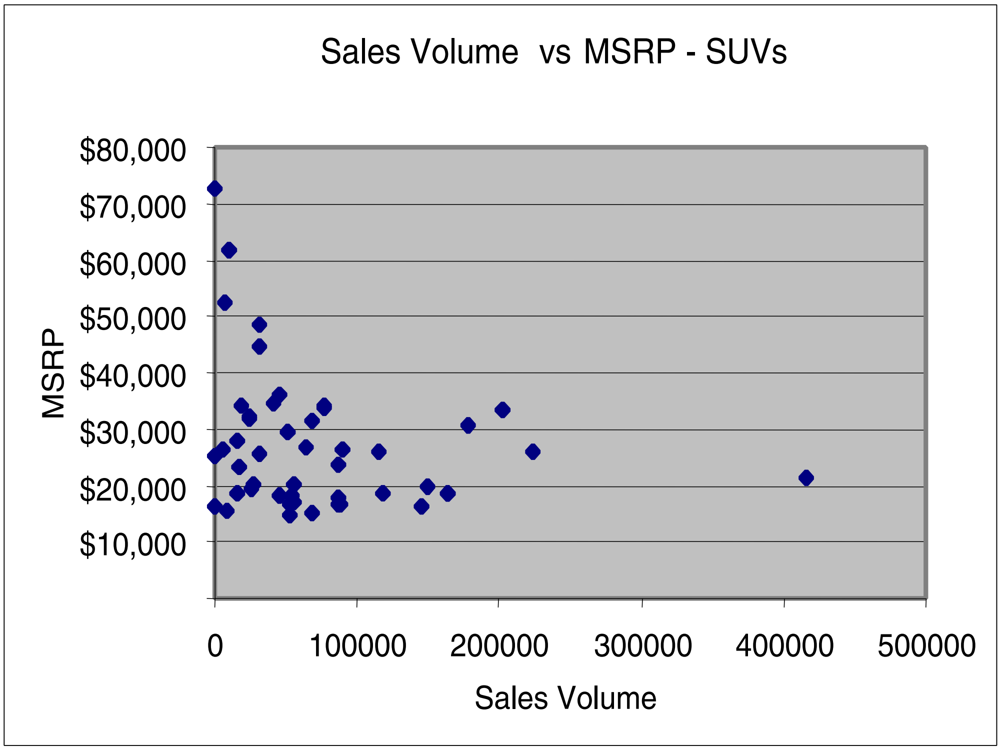


**Figure 6:** **Price vs. Sales Volume (SUV Market)**

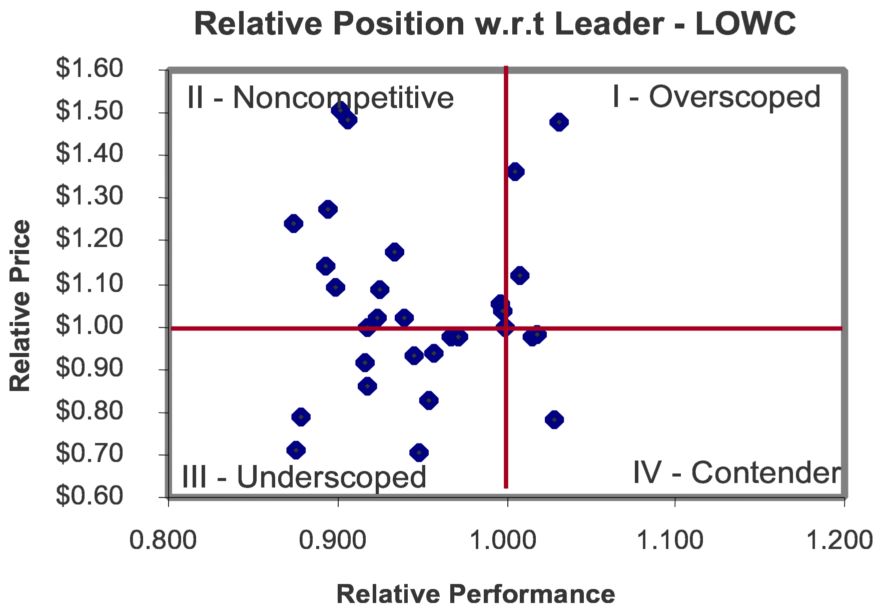


**Figure 7: Relative position of market competitors**

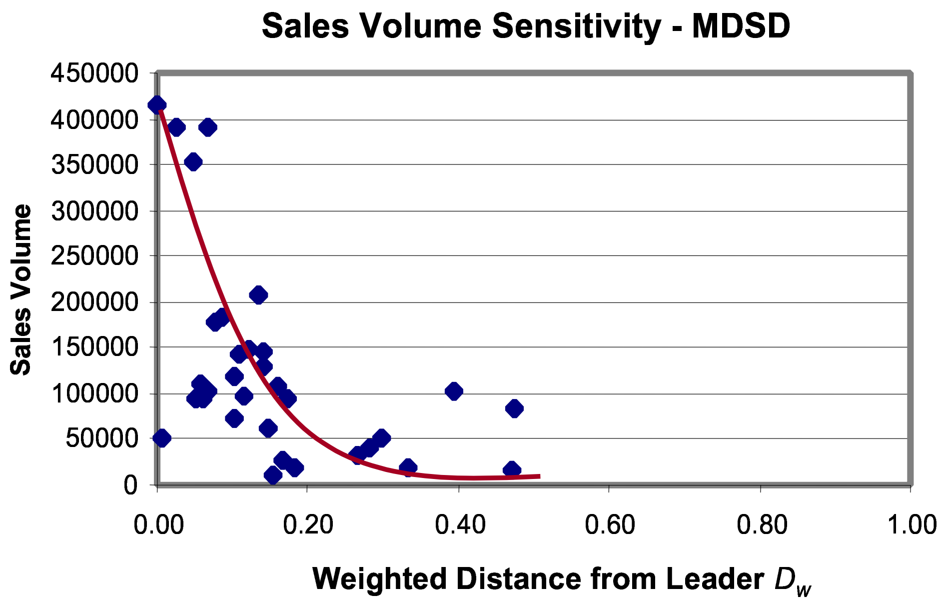


**Figure 8:** **Sales volume curve for mid-size sedan market segment**

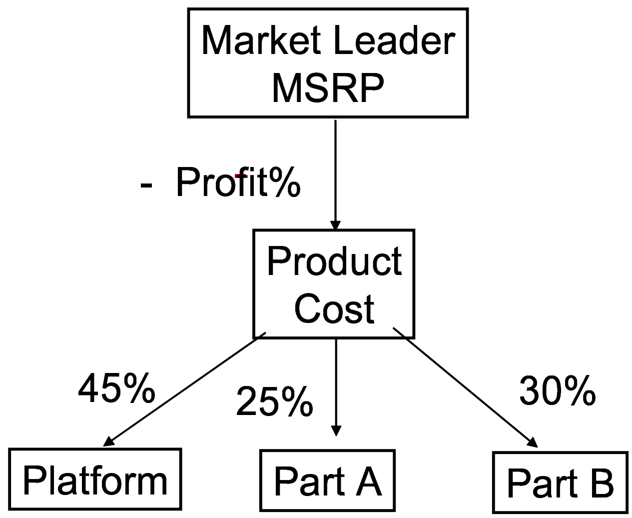


**Figure 9: Decomposition of a product cost**

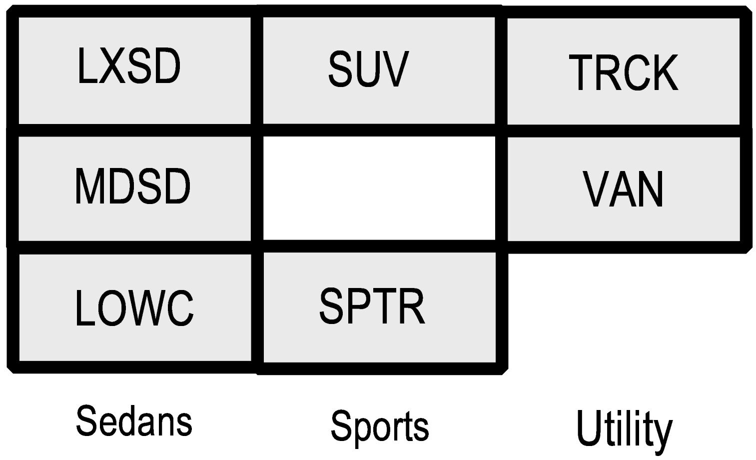


**Figure 10: Vehicle market segments**

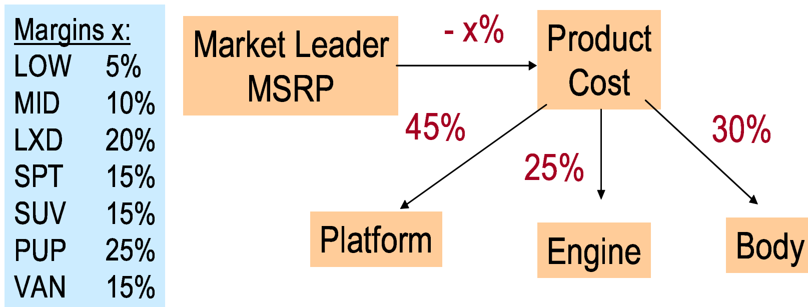


**Figure 11: Cost decomposition of the automotive vehicle**

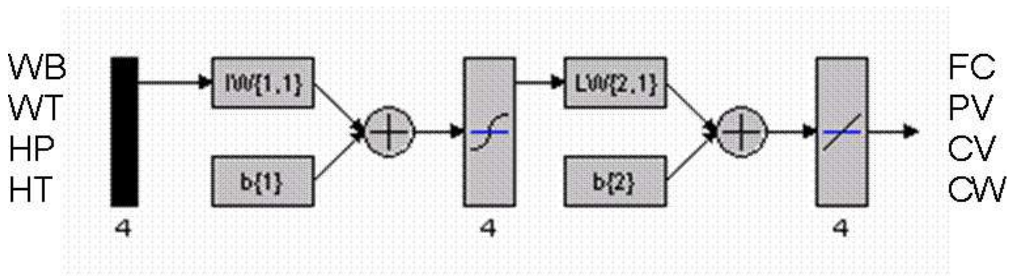


**Figure 12: Neural network model for an automotive vehicle**

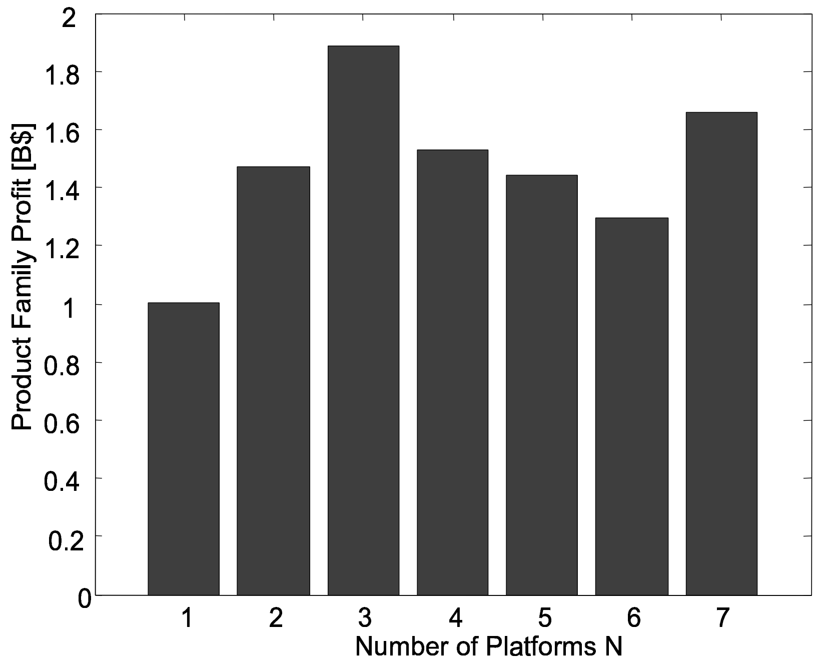


**Figure 13: Product Family Profit for Number of Platforms**

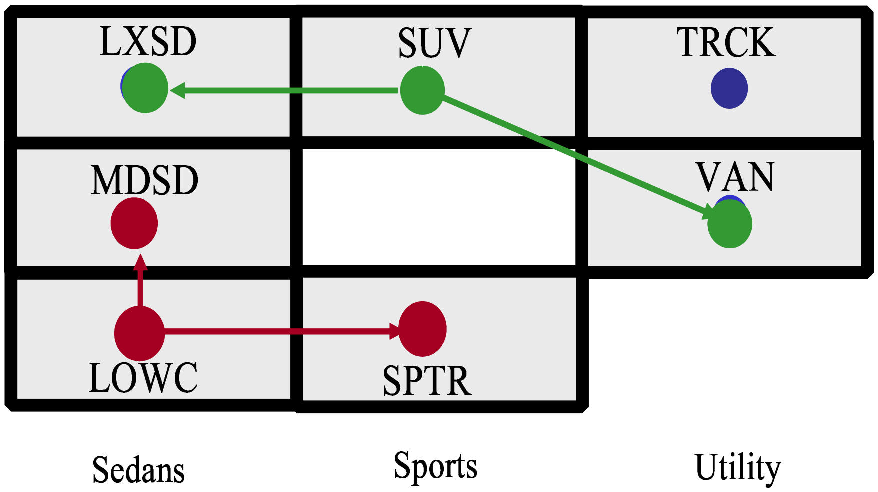


**Figure 14: Optimum Platform Strategy**