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# PRODUCT FAMILY AND PLATFORM PORTFOLIO OPTIMIZATION

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## ABSTRACT

In this paper, a methodology is presented to determine the optimum number of product platforms to maximize overall product family profit with simplifying assumptions. This methodology is attempting to aid various manufacturing industries who are seeking ways to reduce product family manufacturing costs and development times through implementation of platform strategies. The methodology is based on a target market segment analysis, market leader's performance vs. price position, and a two level optimization approach for platform and variant designs. The proposed methodology is demonstrated for a hypothetical automotive vehicle family that attempts to serve seven different vehicle market segments. It is found that the use of three distinct platforms maximizes overall profit by pursuing primarily a horizontal leveraging strategy.

**Keywords:** Product Platforms, Product Families, Two-Level Optimization

## NOMENCLATURE

$\mathcal{C}_c$ Set of product components
$\mathcal{J}_\mathcal{M}, \mathcal{J}_p$ 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
$C_{Comp}$ Cost of a product component
$C_{Cap}$ 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 elements
$SV$ 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 produc-

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tion 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 strategy is 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 [1]. 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 printer product family [2]. 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 platform set $\Pi$.

### Previous Research

Many product platform strategies are developed by various scholars throughout academia. Simpson et al. [3] 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 [4] 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. [5] Martin and Ishii [6] 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, Papalambros et al. [7] 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, Papalambros et al. [8] for family products with mild variation. Gonzalez-Zugasti, Otto et al. [9] 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 have been 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 are very little research on defining clear and rigorous methodology to determine the optimum number of platforms to cover wide market segments. Seepersad, Mistree, Hernandez and Allen [10,11] developed a methodology to determine the number of scalable and generational product platforms using the compromise Decision Support Problem. In this paper, we propose a new quantitative methodology to determine the optimum number of platforms, using sales volume sensitivities of market segments with respect to the product variant performance.

In the following section, various platform strategies are presented. In subsequent 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 applied to an 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 [2] define platform as a collection of assets, including component designs, shared by multiple products. Simpson and Souza [4] define platform as a group of related products that share common components and/or subsystems.

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 that share common components such as engine, transmission, brakes, seat, axles, etc. Boeing is currently in the process of developing the Blended Wing Body 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.

Once the decision to implement platforms is made, there are different strategies for the product implementation. 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 [12], reduces product design lead times [2], makes coverage of market niches easier [13], 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 its specific market segment due to inferior performance caused by sharing constraints.

## PLATFORM STRATEGY FORMULATION

### Two-Level Design Optimization

The product platform strategy can be divided into product family level design plan and product variant design plan (see Figure 1). 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 determine the best combination of the product platforms and product variants that yields maximum

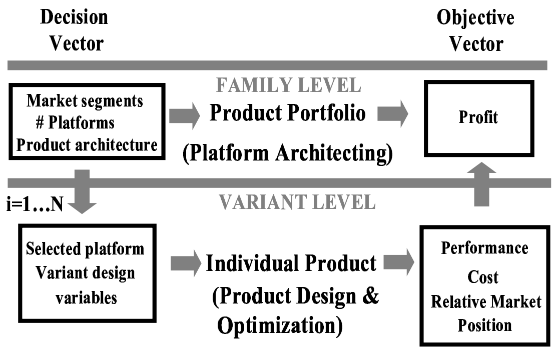


Figure 1. TWO LEVEL OPTIMIZATION APPROACH

overall profit. The optimization process continuously iterates until the product family with the best aggregate product variant performance and profits is found.

Proposed two-level optimization is implemented with certain limitations. It is assumed that, on the product family level optimization, the contending market segments and the product platform architecture are known *a priori*, leaving the number of product platforms as the only family level variable. By optimizing the number of product platforms from $N = 1, 2, \ldots, M$, where $M$ is the number of market segments, the overall performance and profitability of the product family can be plotted for given number of platforms. 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 is commonly shared across the product family. 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 design vector, $\mathbf{x}_\pi$, that is common across the platform-sharing variants in the product family set, $\mathcal{P}$. The platform set $\mathcal{X}_\Pi$ is defined as

$$\mathcal{X}_\Pi = \left\{\mathbf{x}_{\pi_1}, \mathbf{x}_{\pi_2}, \ldots, \mathbf{x}_{\pi_N}\right\} \quad (1)$$

where $\mathbf{x}_\pi$ is the individual platform design vector. Product variants sharing a same platform will have same design vector $\mathbf{x}_\pi$ and must be optimized within the boundary of the platform vector.

### Product Variant Model

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

$$\mathcal{X}_{\mathcal{P}} = \{\mathbf{x}_{p_1}, \mathbf{x}_{p_2} \ldots, \mathbf{x}_{p_V}\}$$
$$\mathcal{J}_{\mathcal{P}} = \{\mathbf{J}_{p_1}, \mathbf{J}_{p_2} \ldots, \mathbf{J}_{p_V}\} \quad (2)$$

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 by constraints that is imposed by the product platform design vector $\mathbf{x}_\pi$. One of the key processes in the product variant level optimization is to choose the variant design vector, $\mathbf{x}_p$, that has high sensitivity effect on $\mathbf{J}_p$ with minimal perturbation for achieving wide variant differentiation with small investment.

### Market Segment Model

A market segment model can be generated using the sales volume ($SV$), the price ($P$) and the objective vector ($\mathbf{J}_p$) of each competing product. An example plot of sales volume vs. price for the Sports Utility Vehicles (SUV) sold in U.S. in year 2001 [14] is shown in Figure 2.

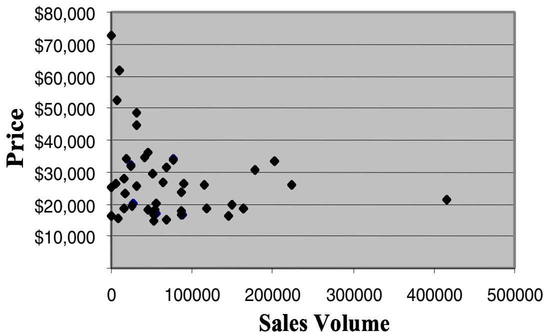


Figure 2. PRICE VS. SALES VOLUME (SUV)

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 3, relative positions to the market leader 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 the center (1,1) in Figure 3, the competitor's positions

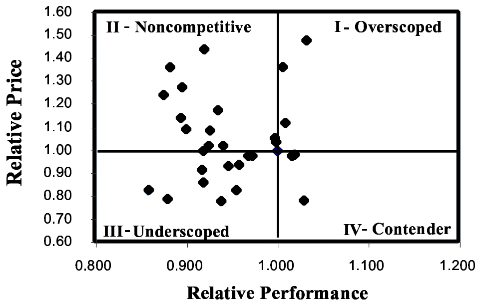


Figure 3. RELATIVE POSITION OF MARKET COMPETITORS

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. An example of the fourth quadrant contender can be found in the mid-size sedan market segment, where Honda Accord commands the market with the highest sales volume. Possible contenders in the market segment are Nissan Altima, Hyundai Sonata, Saturn L-Series and Chevy Malibu with lower prices and better performances in acceleration, cargo volume and passenger volume. However, their sales volumes are less than Honda Accord's sales volume. To identify possible causes for this phenomenon, one might need to consider the issue of vehicle styling, brand image, past maintenance records and other customer preferences.

## 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 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 and limitations.

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

- The design vector $\mathbf{x}_\pi$,$\mathbf{x}_p$, and the objective vector $\mathbf{J}_p$ are predetermined.
- Competitors will offer 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 the sales price of the target marker leader. Competition occurs over relative performance.
- The sales volume of the product is equal to the number of products produced and cannot exceed corresponding market leader's sales volume.
- The product platform model is sensitive to annual changes in the market leader.

### 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

$$\max_{N, \mathcal{X}_\Pi, \mathcal{X}_\mathcal{P}} \sum_{i=1}^{V} \sum_{j=1}^{M} SV_{ij} P_{ij} - C_\mathcal{P} \tag{3}$$

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 the $j^{th}$ market segment, $P_{ij}$ is the sales price of the $i^{th}$ variant in the $j^{th}$ market segment, and $C_\mathcal{P}$ is the total variable and fixed cost for the product family.

### Proposed Methodology

**Step 1: Identify market segments and corresponding market leaders.** Define a set of market segments $\mathcal{M}$, where $\mathcal{M} = \{m_1, m_2, ..., m_M\}$ and $M$ is the number of market segments. 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 variable and is usually determined through marketing and financial analysis. In this study, the market segment set $\mathcal{M}$ is predetermined.

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

$$\begin{aligned} \mathcal{X}_\Pi &= \{\mathbf{x}_{\pi_1}, \mathbf{x}_{\pi_2}, ..., \mathbf{x}_{\pi_M}\} \\ \mathcal{X}_\mathcal{P} &= \{\mathbf{x}_{p_1}, \mathbf{x}_{p_2}, ..., \mathbf{x}_{p_M}\} \end{aligned} \tag{4}$$

Set $\mathcal{X}_\Pi$ is a collection of product family level design vectors 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 vectors 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 also predetermined.

One of the tasks of optimizing the product family is the assignment of the best product platforms for each individual market segment from the 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

$$\mathbf{x}_{\pi,Optimum,j} = \mathbf{x}_{\pi,Leader,j} \tag{5}$$

where $\mathbf{x}_{\pi,Optimum,j}$ is the optimum platform design vector for the $j^{th}$ 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 platform Theoretical First Unit cost ($TFU_\pi$) and the product variant components Theoretical First Unit costs ($TFU_c$). $TFU_\pi$ and $TFU_c$ are also functions of the market leader sales volume as follows:

$$\begin{aligned} TFU_\pi &= C_\pi \frac{SV_{Leader,j}}{SV^B_{Leader,j}} \\ TFU_c &= C_c \frac{SV_{Leader,j}}{SV^B_{Leader,j}} \end{aligned} \tag{6}$$

where

$$B = 1 - \frac{\ln((100\%)/S)}{\ln 2} \tag{7}$$

$$C_\pi = P_{Leader,j}\,(1 \text{ - Profit Margin})\,(\text{Platform Cost Margin})$$
$$C_c = P_{Leader,j}\,(1 \text{ - Profit Margin})\,(\text{Component Cost Margin}) \quad (8)$$

where $S$ is the learning curve slope that represents the percentage reduction in cumulative average cost when the number of production units is doubled [15]. 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. The platform and variant components cost margins vary according to the percentage of platform components and variant components cost in the total cost of a single product. An example of a generic product profit and cost decomposition is shown in Figure 4.

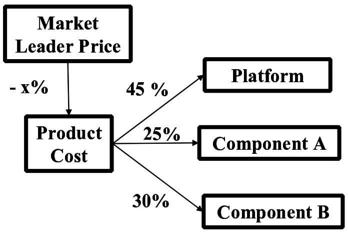


Figure 4. DECOMPOSITION OF A PRODUCT COST

In all, $N$ product platforms are created, where $N = M$. 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 two platforms are used for the entire product family, platforms with the highest and second highest sales volume are used.

**Step 3: Identify market specific performance objective vectors.** Define the market specific performance objective vector set $\mathcal{J}_{\mathcal{M}}$, where $\mathcal{J}_{\mathcal{M}} = \{\mathbf{J}_1, \mathbf{J}_2, ..., \mathbf{J}_M\}$. Objective vector elements are defined by translating the customer preferred attributes to target specifications. Examples of objective vector elements 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 element 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 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 is already established.

**Step 4: Establish objective preference matrix $\Omega$.** Each market segment has its own order of attribute preference. For example, a truck buyer might consider the cargo volume to be the most important objective element, compared to a compact car buyer, who prefers fuel economy above all other attributes. To express different customer preferences for different market segments, the objective weight factors matrix, $\Omega$, is defined:

$$\Omega = \begin{bmatrix} \omega_{11} & \dots & \omega_{1M} \\ \dots & \dots & \dots \\ \omega_{Q1} & \dots & \omega_{QM} \end{bmatrix} \quad (9)$$

where, for every $j^{th}$ market segment,

$$\sum_{i=1}^{Q} \omega_{ij} = 1 \quad (10)$$

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. By setting $\omega_{ij}$ to zero, an irrelevant objective function for particular market segment can be eliminated. For example, off-road endurance rate is not relevant in the sedan market segment but is an important objective function in the SUV market. This can be reflected by assigning a zero weight factor to the endurance rate in the sedan market segment and assigning a different weight factor to the SUV market segment. It was assumed that the weight factor matrix is provided by the marketing research on customer preferences for each market segment. The preference weight matrix is used for its simplicity. However, very careful consideration must be given when assigning a weight factor to each objective function, since it will have significant effect on product variant's estimated sales volume and the overall product family profit.

**Step 5: Establish the market specific sales volume equation.** 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 the $i^{th}$ variant in the $j^{th}$ market segment is

$$SV_{ij} = \frac{SV_{Leader,j}}{\beta_j D_{ij} + 1} \quad (11)$$

where $SV_{Leader,j}$ is the sales volume of the market leader in the $j^{th}$ market segment and $D_{ij}$ is the performance weighted distance of the $i^{th}$ variant in the $j^{th}$ market segment. The curve fitting coefficient $\beta_j$ for the $j^{th}$ market segment is obtained by plotting sales volume vs. $D_{ij}$ (see Figure 5) for all competitors in the market segment and performing the regression analysis.

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

$$D_{ij} = \frac{\hat{P}_{ij}}{\hat{J}_{ij}} \sqrt{(\hat{J}_{ij} - 1)^2 + (\hat{P}_{ij} - 1)^2} \tag{12}$$

where

$$\hat{P}_{ij} = \frac{P_{ij}}{P_{Leader,j}} \tag{13}$$

and

$$\hat{J}_{ij} = \sum_{k=1}^{Q} \omega_{kj} \frac{J_{ij,k}}{J_{Leader,j,k}} \tag{14}$$

$\hat{P}_{ij}$ is a normalized price of the $i^{th}$ variant in the $j^{th}$ market segment respect to the price of the market leader. $\hat{J}_{ij}$ is the normalized aggregate objective performance value of the $i^{th}$ product in the $j^{th}$ 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 equations of sales volume vs. weighted distance curve for each market segment can be obtained by Eqs. (11) - (14).

**Step 6: Product variant optimization.** In order to create the best product variant, a best fitted product platform must be assigned to the target market segment. If there are $N$ product platforms available, the best platform for the $j^{th}$ market segment is determined using following criteria:

$$\min_{N} \sqrt{\sum_{k=1}^{n} \left(x_{\pi,k} - x_{\pi,Leader,jk}\right)^2} \tag{15}$$

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.

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

$$\begin{aligned} &\min_{\mathbf{x}_p} \left|\hat{J}_{ij} - 1\right| \\ &\text{subject to } \{\mathbf{x}_\pi\} \end{aligned} \tag{16}$$

where $\mathbf{x}_p$ is the product variant design vector, and $\mathbf{x}_\pi$ is the product platform design vector. 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, given fixed $\mathbf{x}_\pi$. 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 profit of the product family.** The total cost of the product family is

$$C_{\text{Total}} = C_{\mathcal{P}} + C_{\text{Cap}} \tag{17}$$

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 $TFU$ cost for each variant components and the sales volume of each variant. The variable cost of the $i^{th}$ variant in the $j^{th}$ market segment can be expressed as:

$$C_{ij} = C_{\pi,ij} + C_{\text{Comp},ij} \tag{18}$$

where

$$C_{\pi,ij} = TFU_{\pi,j} SV_{ij}^{\text{B}} \tag{19}$$

and

$$C_{\text{Comp},ij} = \sum_{k=1}^{c} \text{TFU}_{c,k} SV_{ij,k}^{\text{B}} U_{c,k} \tag{20}$$

$TFU_{\pi,j}$ is the Theoretical First Unit cost of a product platform assigned to the $j^{th}$ market segment, $SV_{ij}$ is the sales volume of platform based variant $i$ in the $j^{th}$ market segment, $c$ is the number of components in the product variant, and $U_{c,k}$ is the usage quantity of $k^{th}$ components used in a single product variant.

Calculate the total profit of the product family using Equation (3), given the constraints $V = M$ and $N = \{1...M\}$. Repeat the process by varying $N$ from 1 to M.

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 implementation 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 company identified seven market segments for its entry products and has to determine the optimum number of vehicle platforms, $N$, that will maximize the profit of the vehicle product family. For the vehicle product family, following family level decisions were made:

- Only one product entry per market segment is placed.
- 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 ($P_{ij} = P_{Leader,j}$).

### Methodology Implementation

**Step 1: Identify market segments and corresponding market leaders.** The manufacturer decided to develop vehicles for the following market segments: Low Compact Sedan (LOW), Mid Size Sedan (MID), Luxury Sedan (LXD), Sports Car (SPT), Sports Utility Vehicle (SUV), Pickup Truck (PUP), and the Van (VAN) segment.

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 chosen as the market leader for the SUV market segment. The market leader's sale prices are obtained through publicly available data on the Internet [14].

**Step 2: Establish the design and objective vector set.** Define the vehicle platform design vector set $\mathcal{X}_\Pi$ and the vehicle variant design vector set $\mathcal{X}_\mathcal{P}$:

$$\begin{aligned} \mathcal{X}_\Pi &= \{\mathbf{x}_{\pi_1}, \mathbf{x}_{\pi_2}, ..., \mathbf{x}_{\pi_7}\};\ \mathbf{x}_\pi = \{WB, WT\} \\ \mathcal{X}_\mathcal{P} &= \{\mathbf{x}_{p_1}, \mathbf{x}_{p_2}, ..., \mathbf{x}_{p_7}\};\ \mathbf{x}_p = \{ED, HT\} \end{aligned} \tag{21}$$

where $WB$ 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 the same platform design vector and product variant design vector, but the values of these vectors are different for each market segment.

The next task is to establish appropriate product platform design vector values. Since there is one platform for each market segment, a total of seven platform design vectors are created. Using Eq. (5), the optimum platform design vector values are set equal to the market leader's design vector values. For example, in the mid-size sedan segment (MID), the optimum platform design vector elements $WB$ and $WT$ values are equal to the Honda Accord's $WB$ and $WT$.

The final task in creating the platform model for each market segment is to calculate the TFU cost for the platform and other components. For this particular case study, the profit margin for each market segment is shown below:

Table 1. MARKET SPECIFIC PROFIT MARGIN

| | LOW | MID | LXD | SPT | SUV | PUP | VAN |
|---|---|---|---|---|---|---|---|
| % | 5 | 10 | 20 | 15 | 15 | 25 | 15 |

Note that each market has a different profit margin. This is because in general corporate strategy, a company sets a different profit margin for each market segment since customer's willingness to pay more price differs from segment to segment.

In the vehicle family example, the total cost is the sum of the platform (45%), engine (25%), and body (30%) costs. Implementing Eq. (6), $TFU_\pi$ and $TFU_c$ were determined.

**Step 3: Identify market specific performance objective vectors.** When customers purchase automotive vehicles, many performance attributes are considered. In this study, acceleration (AC), horsepower (HP), fuel efficiency (FE), passenger volume (PV), and cargo volume (CV) were elements of **J** for each market segment. Translating this into mathematical terms:

$$\begin{aligned} \mathcal{J}_\mathcal{M} &= \{\mathbf{J}_1, \mathbf{J}_2, ..., \mathbf{J}_7\} \\ \mathbf{J} &= \{AC, HP, FE, PV, CV\} \end{aligned} \tag{22}$$

**Step 4: Establish objective preference matrix Ω.** The object preference matrix (Ω) is created. The values of $\omega_{ij}$ for seven different market segments are shown in Table 2:

Table 2. THE OBJECTIVE PREFERENCE MATRIX $\Omega$

| J | LOW | MID | 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 customer preferences for each objective element in their respective market segments. For example, acceleration is the most important objective element in the sports car market segment, but it has low preferences in other market segments. For a motor company, it is crucial to identify the most important objective elements for different market segment, since they have the highest sensitivity to the aggregate performance of the individual vehicle.

**Step 5: Establish the market specific sales volume equation.** The sales volume equation for each market segment is established using Eq. (11). The sales volume curve and its fitting coefficient $\beta$ for the $j^{th}$ market segment is obtained by the following steps:

1. Calculate $\hat{P}_{ij}$ and $\hat{J}_{ij}$ for all competitors in the market segment.
2. Calculate $D_{ij}$ for all competitors in the market segment.
3. Plot sales volume vs. $D_{ij}$ for all competitors.
4. Use the regression analysis to calculate $\beta_j$ and create the sales volume curve.

A sales volume curve for the mid size sedan market segment is shown on Figure 5.

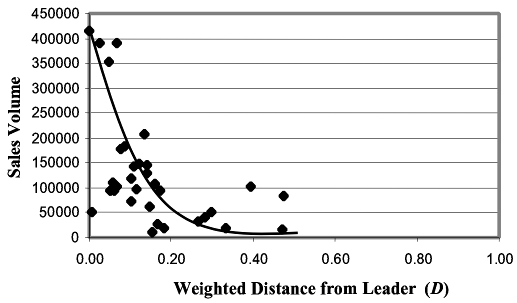


Figure 5. SALES VOLUME CURVE FOR THE MID-SIZE SEDAN MARKET SEGMENT

**Step 6: Product variant optimization.** Implementing Eq. (15), the best fitted vehicle platform $\mathbf{x}_\pi$ for each market segment is determined, with a number of vehicle platforms ($N$) as a constraint. The vehicle platforms are utilized in the order of their sales volume. According to this methodology, the truck platform is used first, because it has the largest sales volume. The automotive platforms are used in the following order: PUP, SUV, MID, LOW, VAN, SPT, and LXD. After $N$ platforms are assigned to seven vehicle market segments, the vehicle variant design vector $\mathbf{x}_p$ in each market segment is optimized to satisfy the condition imposed by Eq. (16). To map $\mathbf{x}_\pi$ and $\mathbf{x}_p$ to $\mathbf{J}_p$, a trained neural network [16] is used.

Seven different neural networks are trained to map $\mathbf{x}_\pi$ and $\mathbf{x}_p$ to $\mathbf{J}$ in seven 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.

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

**Step 7: Estimate the profit of the product family.** The total cost of the product family is calculated by totaling the cost of vehicles manufactured for each market segment with the capital investment. For this particular vehicle family, the vehicle cost is divided into the platform, engine, and body costs. With TFU cost obtained from Step 2 and using Eqs. (17) - (20), the total cost of each vehicle variant is obtained.

Totaling 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 Eq. (3). This procedure is repeated with $N = 1,\ldots,7$ platforms.

## RESULTS AND DISCUSSION

### Results

Figure 6 shows the profit for the total product family, $\mathcal{P}$, given $N = 1, 2, \ldots, 7$ platforms.

The profit is maximized when three vehicle platforms are implemented. A vehicle family produced the lowest profit when $N = 1$ because 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 because the vehicle entry in each market segment was optimized to match the market leader's performance without the constraint imposed by sharing a platform. It was also observed that, with an increasing number of platforms, the performance penalty decreases, while $C_{\mathcal{P}}$ increases. Finally, the product port-

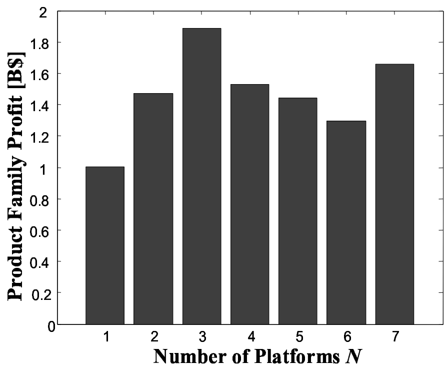


Figure 6. PRODUCT FAMILY PROFIT FOR $N$ PLATFORMS

folio did not do well with six vehicle platforms despite the level of customization. This is due to the fact that, for the luxury sedan market segment, a van platform is used. Resulting commonality caused a sharp drop in luxury vehicle sales volume, since the luxury vehicle market is particularly performance sensitive. With the profit margin of 20% for the luxury vehicle segment, heavy loss in profit occurred.

The strategy with three vehicle platforms is shown in Figure 7. The truck market segment has its own customized platform, because it commands the highest sales volume. The other two platforms are shared among similarly sized vehicles, which indicates a horizontal levering strategy.

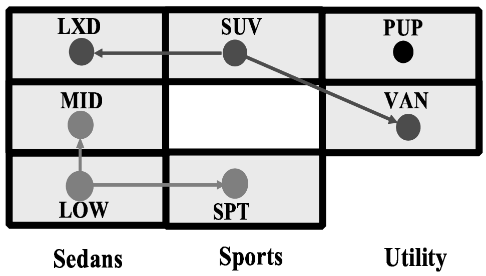


Figure 7. OPTIMUM PLATFORM STRATEGY

### Discussion

This methodology requires many crucial inputs from various teams throughout the company, such as customer preference for different market segments, market dynamics, engineering feasibility for available product platforms, etc. Some of these inputs are very straightforward and have high level of reliability. On the other hand, some inputs have very large variability, causing simulation to be inaccurate. One way of improving the fidelity of proposed methodology is to reduce the variability of inputs through more rigorous process. Another way of addressing this issue is to conduct simulations for variety of inputs, creating different strategies for different market situations. For example, the market condition is highly volatile, and is highly unpredictable. By conducting simulations for different market conditions (e.g. change in market leader's product specifications), one can examine the effect market condition on the product platform strategy.

## CONCLUSION

In this paper, a quantitative method to determine the optimum number of platforms for a product family was proposed. Using the sales volume function derived from the 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 platforms was obtained from total sales volume and costs of all product variants. The optimum number of platforms compromises the balance between the variable cost savings and performance losses resulting from the shared platform design vector. 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 horizontal platform strategy as well as the no leveraging platform strategy for a specific high-volume market segment appear to be promising.

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