The Role of Manufacturing Flexibility on Product Platform Development

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Soumen Ghosh  
DuPree College of Management  
Georgia Institute of Technology  
800 West Peachtree Street, NW  
Atlanta, GA 30332-0520  
U.S.A.  
Tel: (404) 894 4927  
Fax: (404) 894 6030  
Email: soumen.ghosh@mgt.gatech.edu

B. Joon Park  
Singapore Management University  
School of Business  
469 Bukit Timah Road  
Singapore 259756  
Singapore  
Tel: 65 6822 0733  
Fax: 65 6822 0777  
Email: jpark@smu.edu.sg
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Abstract

In recent years firms from a range of industries have responded to growing market uncertainty by investing heavily in manufacturing flexibility. Manufacturing Flexibility is understood as “process flexibility”, that is a process that results from being able to build different types of products on the same production line at the same time. One benefit of manufacturing flexibility is the reduction of “change over cost” from building one product to another. Flexible manufacturing also relieves the problem of overcapacity, since excessive overcapacity could be avoided through the introduction of flexible manufacturing plants.

Recently, firms have examined a new concept of enabling manufacturing flexibility: exploiting common design among products. “The key enabler for flexible manufacturing (for Ford Motor Company) is having common vehicle architectures. Vehicles are assembled in the same way, with shared programme engineering and shared components.”

The idea of exploiting common designs has been extensively studied in academic literature. The main interest of those studies is the development of product platform strategies or component sharing strategies. No literature on Product Platform Development has so far recognised the potential of common design among products as a mean of enabling manufacturing flexibility.

The fundamental assumption of this research is that common designs among products could reduce the investment cost of manufacturing flexibility. Among the many aspects of common designs, this research focuses on product platform development. We have assumed that manufacturing setup cost for two products are lower if the two products share the common platform.

We have proposed a decision support model that comprehensively decides Product Offering, Product Platform Development, and Manufacturing Setups. We also have discussed computation procedures that could solve industry size problems within a very reasonable computation time.

Finally, we have demonstrated through numerical analysis that manufacturing related parameters could be more detrimental for Product Offering/Product Platform Decision than the cost of Product Platform Development itself.

1. Introduction

In recent years firms from a range of industries have responded to growing market uncertainty by investing heavily in manufacturing flexibility. Examples of such investments are readily found in the auto industry in particular.

- *Ford invested Euro 660 million in Cologne to replace 11-year old production equipment with new tooling that can produce three separate derivatives on the same assembly line.*
As new vehicles are introduced, all four large plants – Cologne, Valencia; Saarlouis, Germany; and Genk, Belgium – will progressively become more flexible. With all four plants using flexible manufacturing, Ford hopes to meet changes in demand for its models more smoothly (Automotive News Europe, 26 September, 2002)

- The world’s automakers have a new reason to chase Honda Motor Co.: flexible factories. Companies from Detroit to Munich are installing turn-on-a-dime assembly lines in their plants. Automakers saddled with traditional assembly plants cannot respond quickly to unexpected shifts in consumer demand. (Automotive News, 14 October, 2002)

The exact definition of manufacturing flexibility differs from industry to industry. Auto manufacturers, Jordan and Graves (1995) have understood it as “process flexibility”, a process that results from being able to build different types of products on the same production line at the same time, and where products are defined as vehicles at the nameplate level, such as Chevrolet Camaro, Pontiac Grand Prix, Buick Riviera.

One of the benefits of manufacturing flexibility is the reduction of change-over costs from building one product to another. Jordan and Graves (1995), Graves and Tomlin (2003), however, have evaluated the manufacturing flexibility by minimising the amount of demand that cannot be met by the supply chain. Recently, it has been recognised that the improving of the utilisation rate becomes a major benefit of having manufacturing flexibility. “Improving utilisation” would mitigate the issue of overcapacity, since excessive overcapacity could be avoided through flexible manufacturing plants.

- “We have an enormous overcapacity problem in the (auto) industry. We know that some predictions for market share or sales are over-optimistic at best and unrealistic at worst. We acknowledge that some of our capacity is in the wrong places at the wrong cost
structure. While we are unable to eliminate or reduce our current overcapacity, we keep expanding and adding more,” said J.T. Battenberg III, CEO and President of Delphi Corporation (Automotive News World Congress, Keynote Dinner Remarks, 13 January, 2003)

- “We know what we want to build today. We just want to keep our options open about tomorrow. When you improve your utilisation rate, you are going to be more profitable,” said Peter Gordon, vice president and plant manager at Honda of Canada Manufacturing Inc. (Automotive News, 14 October, 2002)

- Ford Cologne can build any combination and sequences of Fiesta and Fusions to match demand, said Hans-Peter Sulser, plant operations manager. “When the volumes increased we were limited in our ability to respond to the demand and had to invest more and more.” Cologne’s flexible assembly lines are also designed to eliminate lost production capacity during model changeovers. (Automotive News Europe, 23 September, 2002)

- The auto industry likely will take the better part of the decade to convert all plants and shake out bugs. But the potential benefits are clear – automakers will be able to operate plants closer to full capacity.

Firms in various industries have developed their own ways of implementing manufacturing flexibility. For example, as reported by Jordan and Graves (1995), GM has implemented the concept of “chaining” in their product assignment decisions, i.e., decisions on which products are to be built at which plants, or on which line.

More recently, firms have looked into a new approach of enabling manufacturing flexibility: exploiting common designs among products.
• **Enabling Flexible Manufacturing with Fewer Vehicle Architectures**: The keys to flexible manufacturing (at Ford) include common vehicle architectures and standardised manufacturing processes that can be changed easily for new products. The key enabler for flexible manufacturing is having common vehicle architectures. Vehicles are assembled the same way, with shared programme engineering and shared components. Multiple vehicle segments—cars, sports utility vehicles, vans, trucks or crossover vehicles—can be built using the same architecture. Variability in body styles and sizes, chassis sizes and other differences are easily accommodated. (Ward’s Auto World, 01 January, 2003)

• **Interview with Gary Cowger, president of General Motors North America**: The secret to success is to have flexible architectures that are integrated into flexible manufacturing systems, and then drive lots of variants where you have absolutely no clue that underlying platform is shared by anything else. Because you’ve got converged engineering, manufacturing is back in one group again, so you’re really able to drive the synergies of the technology today. Not only in design, with math-based design all the way through the manufacturing floor, but the hardware flexibility that you have in the plants allow you to drive that. (Automotive News, 05 May, 2003)

The idea of exploiting common designs has been extensively studied in academic literature, particularly in the area of product development. The main interest of such literature is in identifying and exploiting the commonality across products to reduce operational complexity (Ramdas, Fisher, and Ulrich, 2003; Fisher, Ramdas, and Ulrich, 1999; Gupta and Krishnan, 1999; Krishnan and Gupta, 1998; Krishnan, Singh, and Tirupati, 1998). The primary consideration in pursuing commonality is not to sacrifice product diversity too severely.
Described by a general term of *product family management*, a typical interest of those studies is the development of product platform design strategies or component sharing strategies.

Whereas no literature has recognised product platform (i.e. common design among products) as a means to enabling manufacturing flexibility strategy, the quotations from interviews alert us to the idea that common design among products could reduce the investment cost of manufacturing flexibility. In fact, manufacturing flexibility literature itself is very rare indeed. Graves and Tomlin (2003) have reported that “a number of authors have examined investments in dedicated plants versus total flexible plants, where a total flexible plant can process all products. Partial flexibility, whereby a plant can produce a subset of products, has received less attention (Jordan and Graves, 1995)”.

It is reasonable to expect that an optimal level of manufacturing flexibility would lie somewhere between no flexibility (i.e. dedicated plant) and total flexibility. However, there are difficulties in developing a model to find an optimal level of flexibility. Facing market uncertainty, one might expect to build a stochastic model to minimise total changeover cost over a certain period of time, assuming probability distribution functions of product demands over time could be estimated. In reality, however, such probability distributions for individual product models are very difficult to obtain. Even if they are obtainable, they are quite often very inaccurate. For instance, BMW forecasted 100,000 units of the New Mini would leave their newly furbished Oxford plant during the first four to five years of production when they introduced the New Mini onto the market in 2001. In 2002 alone, however, the plant was operating at its full capacity of 160,000 units. It is unrealistic to expect that any probability distribution function could have forecasted such a huge jump in production volume. Also,
stochastic models tend to have a problem in tractability, i.e. one might be able to model the problem but not be able to obtain analytical results.

Utilising a deterministic model also has its own difficulties. As Jordan and Graves (1995) have pointed out, investing in manufacturing flexibility is very expensive. Therefore, decision makers tend not to invest in manufacturing flexibility. Since manufacturing flexibility involves a great investment, a deterministic model wouldn’t choose manufacturing flexibility, unless a certain level of manufacturing flexibility could be forced onto the model as a hard constraint.

An alternative approach of studying manufacturing flexibility is first to develop a “strategy” for implementing manufacturing flexibility, and then to assess the benefits of manufacturing flexibility resulting from the strategy. In fact, total flexibility itself and “Chaining Strategy” at GM are both examples of strategies for implementing manufacturing flexibility. We adopt a similar approach in this paper. We assume that a company has a few manufacturing flexibility strategies to choose from. We then investigate how different manufacturing flexibility strategies would affect the magnitude of common design among products. The fundamental basis of the investigation is that common designs among products could reduce the investment cost of manufacturing flexibility.

The rest of the paper is organised as follows: Section 2 provides an overview of the proposed model of this paper. Most of the literature on manufacturing flexibility typically assumes that product offering decisions—decisions on which products to offer to the market—have already been made. Our proposed model chooses which product model to offer among a set of potential product models. The proposed model then determines the development of product platforms for product models to be offered. There are many different aspects to sharing a common design. In this paper we only look into sharing a product platform, i.e. “Product A
and Product B shares a common design”, means Product A and Product B share the common platform. The proposed model finally decides which products each manufacturing plant will have a capability of manufacturing. Section 3 discusses computational issues. We have identified a couple of necessary optimality conditions, which substantially reduce the number of searches. Section 4 illustrates the interactions between manufacturing flexibility and product platform development through a simple example. Section 5 provides a numerical analysis in order to further probe the role of manufacturing flexibility strategy on product platform development. The purpose of the analysis is not to argue the benefits of manufacturing flexibilities, nor to present which manufacturing strategy performs best in different circumstances. The purpose is to demonstrate how manufacturing parameters and product platform development interact with each other. Quotations and examples cited in this section are primarily from the auto industry. However, the contents of analysis are broadly applicable to any industries that produce physical, modular, discrete, engineered, and manufactured products. Finally, Section 6 concludes the paper.

2. Overview of the Model

Our model has four elements of decision-making. The first element is to decide which products to offer among a set of potential products. We adopt a generally accepted approach in marketing literature, such that it is assumed that each potential product model represents a specific level of perceived quality; a market price that customers are willing to pay for the level of perceived quality and the associated demand volumes are known; that if a product model is not to be offered, customers who prefer the product model would buy the closest product model
offered. More generally, let $\pi_i^j$ and $\pi_k^j$ (where $i < j < k$ and a higher index figure represents a higher level of perceived quality) be the portion of customers of “product $j$” who will buy “product $i$” or “product $k$” when “product $i$” and “product $k$” are the closest offered ones to “product $j$”. High figures of $\pi_i^j$ or $\pi_k^j$ indicate significant cannibalisation exists. Especially, if $\pi_k^j = 1$, there is no incentive to offer “product $j$”, since all customers of “product $j$” will buy higher end “product $k$”, assuming higher end products are more profitable.

The second element of the model is to develop product platforms for products to be offered. We assume that a company has already decided which set of components and modules should construct product platforms. In the auto industry, for instance, a platform typically consists of a chassis, drive-train, and other supporting components and modules.

Design sharing strategy typically assumes complete Downward Substitutability, such that a component can be shared across a set of products if the component meets the most stringent performance requirements in the set (Ramdas, Fisher, Ulrich, 2003; Fisher, Ramdas, Ulrich, 1995). Downward Substitutability may easily be applied to a component sharing strategy when components can be arranged in an order of a certain performance characteristic. On the other hand, Downward Substitutability is not always readily applicable to product platform development when product platforms consist of numerous components and modules. For example, frequently quoted, “Honda’s flexible global platform”, is not adequately explained by Downward Substitutability. Cars with a narrower wheel-base could not be built on the platform developed for cars with a wider wheel-base. Honda’s engineers had to make extra efforts to develop a platform that could be used by cars with different widths of wheel-base. In this research, we assume that more effort is required to develop a product platform shared by a wider range of products (of different levels of perceived quality.)
The proposed model itself does not require any assumptions on the structure of the platform development cost. However, the analysis of this paper will be limited to the cases satisfying the following conditions.

Let $DC_i$, $DC_j$ be the development cost of a uniquely tailored product architecture for product $i$ and product $j$, respectively. And let $DC_{ij}$ be the development cost of a platform module that could be shared by product $i$ and product $j$. Then, we assume $DC_{ij} > \max\{DC_i, DC_j\}$. It could be either $DC_{ij} < DC_i + DC_j$ or $DC_{ij} > DC_i + DC_j$ depending on the technical complexity. If $DC_{ij} > DC_i + DC_j$, the benefits of sharing the same platform, such as unit cost reduction from economies of scale, should outweigh the increased development cost to justify the development of the platform. Similarly, let $DC_{ijk}$ be the development cost of the platform that could be shared by product $i$, product $j$, and product $k$. Then, we assume $DC_{ijk} > \max\{DC_{ij}, DC_{jk}, DC_{ik}\}$. The argument will be extended in a similar manner beyond the scope of three products.

A similar assumption is made to unit (manufacturing) cost of platform. Let $UC_i$, $UC_j$ be unit cost of the tailored module for product $i$ and product $j$, respectively. And, let $UC_{ij}$ be the unit cost of platform module that could be shared by product $i$ and product $j$. Then, we assume $UC_{ij} \geq \max\{UC_i, UC_j\}$ at any given production volume. In other words, it is more expensive to produce, say, 100 units of a platform module than 100 units of either of the tailored modules. Similarly, we assume $UC_{ijk} \geq \max\{UC_{ij}, UC_{jk}, UC_{ik}\}$ at given production volume. The unit cost of the platform module could be lower than that of the tailored modules if substantial economies of scale were materialised.
The third element of the model is to develop products. Here, product development refers to the design of the non-platform portion of the product in order to achieve its target perceived quality level. One could argue that the products’ target perceived quality level could be achieved solely by non-platform components no matter which product platform is being used. However, the choice of product platform that the product is going to be built on could affect the level of perceived quality. For example, VW Audi TT did not fascinate car critics on performance due to it having being built on the Golf platform. The choice of product platform also affects product development cost. The strength of our proposed model is that it does not rely on demand volume and product development cost of products being independent from the choice of product platform.

Component sharing could take place among non-platform components. To remain focused, however, the analysis of this paper will be limited to product platform sharing.

The final element of the model involves investing in manufacturing flexibility. Manufacturing flexibility involves deciding on a set of products for each manufacturing plant that the plant will have the capability of producing. It is somewhat similar to the product allocation decision, deciding which products will be built at which manufacturing plants or production lines. The primary purpose of the product allocation decision is to satisfy expected demand volume without violating plant capacity constraints. On the other hand, the primary purpose of the manufacturing flexibility decision is to have extra manufacturing capability of products for situations where the demand of certain products surges unexpectedly.

The key assumption of this research is that manufacturing flexibility investment for producing product $i$ and product $j$ at a given plant would be lower, if product $i$ and product $j$ are built on the same product platform than otherwise.
We now formally present the proposed model.

(Sets and Indexes)

$I$: Set of potential products, indexed by $i$.

$J$: Set of potential product platforms, indexed by $j$.

$J(i)$: Set of potential product platforms that product $i \in I$ could be developed from, and $J(i) \subseteq J$.

$I(j)$: Set of potential product models $i \in I$ that could be developed from product platform $j \in J$.

$K$: Set of manufacturing plants, indexed by $k$.

(Decision Variables)

$X_i$: Binary variable to indicate whether product $i \in I$ is to be offered.

$Y_j$: Binary variable to indicate whether product platform $j \in J$ has been chosen.

$W_{jk}$: Binary variable to indicate whether manufacturing plant $k \in K$ is to have a setup for product platform $j \in J$.

$Z_{ik}$: Binary variable to indicate whether manufacturing plant $k \in K$ is to have the manufacturing capability of product $i \in I$.

$x_{ik}$: Continuous variables of production volume of product $i \in I$ at plant $k \in K$.

$y_j$: Continuous variables of total volume of product platform $j \in J$.

Let $\{X_i\}$ and $\{Y_j\}$ be the real value vectors of $X_i$ and $Y_j$, respectively. Loosely speaking, total revenue is a function of $\{X_i\}$. As mentioned earlier, the demand volume of products could be affected by the choice of the product platform. In such cases, total revenue should be stated
as a conditional function of $\{X_i | Y_j\}$. However, the interaction between $X_i$ and $Y_j$ does not present any ambiguity to the model as long as the demand volume table could be estimated on the combinations of $X_i$ and $Y_j$. The total revenue could be computed in a straightforward manner on any given $X_i$ and $Y_j$. Cannibalisation does not impose any problem either. The total revenue can be easily computed for any given $\{X_i\}$ assuming the cannibalisation factor $\pi$ is readily available. For clarity of exposition, therefore, total revenue is stated in the model as a function of $\{X_i\}$ without using product platform index $j \in J$.

The Product Platform Development Cost and the Product Development Cost are presented in a similar manner in the model. Here, Product Platform Development cost is defined as the cost of developing a common architecture among products, and Product Development Cost is defined as the cost of developing the non-platform portion of each product in order to achieve its perceived target quality. Similar to demand volume, the Product Development Cost could be varied by the choice of Product Platforms. Again, the interaction between Product and Product Platform on development cost does not present any problem as long as the development cost table could be built on the combinations of $X_i$ and $Y_j$. Such representation further simplifies the formulation of the model. The objective function of the proposed model does not contain product development cost terms. The Product Development Cost is adjusted into its Total Revenue.

In this research, product architecture is broken down into two components, Product Platform components and Non-Platform Components. It is natural to assume, therefore, that the assembly lines at the manufacturing plants are also broken down into two parts: Platform Assembly and Non-Platform Portion Assembly. Our proposed model has two elements of
manufacturing setup cost, P-cost and I-cost. P-cost is defined as the manufacturing setup cost for
the assembly of the Product Platform. I-cost is defined as the manufacturing setup cost for the
assembly of the Non-Platform Portion of products. As before, the interaction between the
Product and the Product Platform on manufacturing setup cost does not present any problem as
long as the P-cost and I-cost table can be built on the combinations of $X_i$ and $Y_j$. Another type of
interaction exists in the manufacturing setup cost. The manufacturing setup cost for the
assembly of a specific product platform $j$ (or product $i$) could be varied by the selection of other
product platforms (or products) also assigned to the same plant. In principle, the interaction
could be handled in a similar manner by constructing manufacturing setup cost tables for
$\{W_{jk}\}$ and $\{Z_{ik}\}$. To keep the analysis tractable, however, we do not investigate such interaction
in this paper. Manufacturing Setup Costs will appear as linear cost terms to $W_{jk}$ and $Z_{ik}$ in the
objective function of the model. The focus of the analysis will adhere to the key assumption
such that the manufacturing flexibility investment for producing product $i$ and product $i'$ at a
given plant would be lower, if product $i$ and product $i'$ are built on the same product platform
than otherwise.

Similar to the Manufacturing Setup Cost, the unit manufacturing cost of each product is
also broken down into two elements, Unit Platform Cost (indexed by $j \in J$) and Unit Non-
Platform Cost (indexed by $i \in I$). We now define the parameters.

(Parameters)

$TR_i$: Total Revenue of product $i \in I$ after subtracting the Product Development Cost.

$PDC_j$: Platform Development Cost of platform $j \in J$. 

\( P - \text{cst}_j \): Manufacturing setup cost for the assembly of product platform \( j \in J \).

\( I - \text{cst}_i \): Manufacturing setup cost for the assembly of the non-platform portion of product \( i \in I \).

\( \text{UPC}_j \): Unit Manufacturing Cost of product platform \( j \in J \).

\( \text{UNC}_i \): Unit Manufacturing Cost of the non-platform portion of product \( i \in I \).

The proposed model is presented below.

Maximise
\[
\sum_{i \in I} TR_i X_i - \sum_{j \in J} PDC_j Y_j - \sum_{k \in K} \sum_{j \in J} P_{cst} W_{jk} - \sum_{k \in K} \sum_{i \in I} I_{cst} Z_{ik} - \sum_{j \in J} \text{UPC}_j y_j - \sum_{k \in K} \sum_{i \in I} \text{UNC}_i x_{ik}
\]

Subject to:
1. \( X_j \leq \sum_{j \in J(i)} Y_j \) for all \( i \)  
2. \( W_{jk} \leq Y_j \) for all \( j, k \)  
3. \( Z_{ik} \leq \sum_{j \in J(i)} W_{jk} \) for all \( i, k \)  
4. \( x_{ik} \leq (\text{capacity})_k Z_{ik} \) for all \( i, k \)  
5. \( \sum_i x_{ik} \leq (\text{capacity})_k \) for all \( k \)  
6. \( \sum_k x_{ik} \geq (\text{demand})_k X_i \) for all \( i \)  
7. \( y_j = (\sum_{i \in J(j)} (\text{demand})_i) Y_j \) for all \( j \)
Most equations are self-explanatory since the formulation is similar to an ordinary product-assignment formulation. Constraints (3) insure that the manufacturing setup for at least one product platform $j$ that product $i$ can be built on, must be done at plant $k$ before the plant $k$ to have the manufacturing capability of product $i$. Constraints (7) compute the total volume of platform $j$. The value of $y_j$ is used in the objective function term $\sum_{j \in J} UPC_j y_j$ to compute the total platform production cost. It may look as if constraints (7) overestimate the total volume of platform $j$. Theorem 3.1 in the next section will argue otherwise. Also, it is implicitly assumed that if platform $j$ could be shared by more products, then it has a higher unit manufacturing cost. It implies that the objective function term $\sum_{j \in J} UPC_j y_j$ could be interpreted as over-design cost.

If we assume very restrictive conditions, such as no cannibalisation; no interaction between $\{X_i\}$ and $\{Y_j\}$ on demand volume and unit manufacturing cost; and linear manufacturing setup costs; then, the above proposed model could be solved as MIP. Otherwise, the model has to be solved iteratively by branching on $\{X_i\}$ and $\{Y_j\}$. On each branch of $\{X_i\}$ and $\{Y_j\}$, constraints (1) check the feasibility, and the rest of the constraints are solved on $W_{jk}$, $Z_{ik}$, $x_{ik}$, and $y_j$ as MIP. $\{X_i\}$ and $\{Y_j\}$ that result in the best objective function value will be chosen for optimal solutions.

3. Computational Complexity

A complete search on $\{X_i\}$ and $\{Y_j\}$ generates far too many MIP to solve. We are particularly interested in reducing the number of searches on $\{Y_j\}$, since we have found from
computational experience that controlling the number of searches on \{Y_j\} turned out to be vital to finding an optimal solution within a reasonable computation time. For example, suppose there are potential products. Then, vector \{X_j\} consists of ten binary variables such that each variable represents each potential product. Vector \{Y_j\}, on the other hand, will have $2^{10}$ binary variables since the set of potential platforms consists of a “platform shared by product 1 and product 2”, a “platform shared by product 1 and product 3”, and a “platform shared by product 1, product 2, and product 3”, and so on. More formally, let $n$ be the number of potential products. Then, the total number of potential platforms is $\sum_{i=1}^{n} \binom{n}{i} = 2^n - 1 = Z$, and a complete search on \{Y_j\} alone will generate $\sum_{z=0}^{Z} \binom{Z}{z} = 2^Z$ different branches.

We have made a simple, but justifiable assumption. If potential products were sequenced in order of the level of perceived quality, it would make little practical sense to develop a product platform shared only by the lowest end product and the highest end product. Extending the idea further, we assume that product platforms are to be shared only by products that are adjacent in perceived quality level.

The idea of adjacent platforming is illustrated next. Suppose there are five products to offer, where product 0 represents the lowest end product and product 4 represents the highest end product. The set of potential platforms is given as follows, where $Y_{l,h}$ is defined as the product platform shared by the product of the $l$-th lowest perceived quality through the product of the $h$-th lowest perceived quality.

<table>
<thead>
<tr>
<th>Products to offer</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Platform:</td>
<td>$Y_{0,0}$</td>
<td>$Y_{1,1}$</td>
<td>$Y_{2,2}$</td>
<td>$Y_{3,3}$</td>
<td>$Y_{4,4}$</td>
</tr>
</tbody>
</table>
More formally, let \( I_1 \) (indexed by \( i_1 \)) be the set of potential product models such that \( X_1 = 1 \), and \( i_1 \) be arranged in an order such that \( i_1' < i_1'' \) implies \( i_1'' \) is a higher end product than \( i_1' \). Then, the adjacent platforming is defined as follows.

**Definition 3.1:** Adjacent platforming is a platform strategy with the following characteristic:

If platform \( j \in J \) is \( j \in J(i_1') \) and \( j \in J(i_1'') \) where \( i_1', i_1'' \in I_1 \) and \( i_1' \leq i_1'' \), then

\[ j \in J(i_1''') \] for any \( i_1''' \in I_1 \) such that \( i_1' \leq i_1''' \leq i_1'' \).

If we assume the adjacent platforming, the total number of potential product platforms is \( n(n + 1)/2 \), where \( n \) is the total number of potential product models, i.e. \( |I| \). A realistic figure for \( |I| \) differs from industry to industry, and company to company. Hyundai Motor Company, the world’s 7th largest auto manufacturer, produces 32 different models in commercial and passenger car lines, and Honda has about half of the different models. (Chosun Ilbo, 9 November 2001) With real industry figures, even adjacent platforming generates far too many branches of \( \{Y_j\} \).

One obvious necessary optimality condition is:

\[ \sum_j Y_j \leq \sum_i X_i \quad (8) \]
Condition (8) states that no optimal solution will have more product platforms developed than products to be offered. Combined with condition (8), the next theorem substantially reduces the number of MIP to solve.

**Theorem 3.1:** The following is a necessary optimality condition.

\[ \sum_{j \in J(i)} Y_j \leq 1, \text{ for all } i \quad (9) \]

The proof is omitted since it can be easily demonstrated by contradiction. In the previous section, we have assumed that more effort is required to develop product platforms shared by a greater number of products. With this assumption, condition (9) states that an optimal solution will have only one developed product platform for potential product \( i \in I \) that \( X_i = 1 \). As mentioned earlier, unless we assume no cannibalisation and no interaction between \( \{X_i\} \) and \( \{Y_j\} \) on demand volume and unit manufacturing cost, the model has to be solved iteratively by branching on \( \{X_i\} \) and \( \{Y_j\} \). On each branch of \( \{X_i\} \) and \( \{Y_j\} \), constraints (1) check the feasibility and the remaining constraints are solved on \( W_{jk}, Z_{ik}, x_{ik}, \text{ and } y_j \) as MIP. Conditions (8) and (9) reduce the number of MIP since conditions (8) and (9) test the need of solving MIP generated by a specific branch of \( \{X_i\} \) and \( \{Y_j\} \). The next example illustrates the idea. Suppose there are five products to offer, and \( X_o \) is the binary variable for the lowest end product and \( X_4 \) is the binary variable for the highest end product. For \( \{X_i\} \) that \( \{X_0 = X_1 = X_2 = X_3 = X_4 = 1\} \), there are only 16 MIP to solve generated by the following \( \{Y_j\} \); \( \{Y_{0..4} = 1\}, \{Y_{0..1} = Y_{1..4} = 1\}, \{Y_{0..1} = Y_{2..4} = 1\}, \{Y_{0..2} = Y_{3..4} = 1\} \),
\{Y_{0,3} = Y_{4,4} = 1\}, \quad \{Y_{0,0} = Y_{1,1} = Y_{2,4} = 1\}, \quad \{Y_{0,0} = Y_{1,2} = Y_{3,4} = 1\}, \quad \{Y_{0,0} = Y_{1,3} = Y_{4,4} = 1\},
\{Y_{0,1} = Y_{2,2} = Y_{3,4} = 1\}, \quad \{Y_{0,1} = Y_{2,3} = Y_{4,4} = 1\}, \quad \{Y_{0,2} = Y_{3,3} = Y_{4,4} = 1\},
\{Y_{0,0} = Y_{1,1} = Y_{2,2} = Y_{3,4} = 1\}, \quad \{Y_{0,0} = Y_{1,2} = Y_{2,3} = Y_{4,4} = 1\}, \quad \{Y_{0,0} = Y_{1,2} = Y_{3,3} = Y_{4,4} = 1\},
\{Y_{0,1} = Y_{2,2} = Y_{3,3} = Y_{4,4} = 1\}, \quad \{Y_{0,0} = Y_{1,1} = Y_{2,2} = Y_{3,3} = Y_{4,4} = 1\}, \quad \{Y_{1,h} = 0\} \quad \forall \ Y_{1,h} \neq 1.

Conditions (8) and (9) have also simplified the presentation of the model. The proposed model has not been presented with variables $X_{i/j}$, where $X_{i/j}$ is defined as a binary variable to indicate whether product model $i \in I$ to be developed from product platform $j \in J$. The variable seems to be necessary if the demand volume of products is affected by the choice of product platforms. However, for any MIP generated by $\{X_{i}\}$ and $\{Y_{j}\}$ that satisfy conditions (8) and (9), there is no ambiguity on which products are developed from which product platform.

4. Illustration: Manufacturing Flexibility Strategy on Product Platform Development

This section illustrates the role of manufacturing flexibility on product platform development through a simple example. The illustration shows that the manufacturing flexibility strategy could alter the product platform development as well as the product offering decision that decides which products should be offered among the set of potential products. The example examines the Total Flexible Plant Strategy. Despite its immense investment cost, some companies have actually adopted the total flexible plant strategy. In the auto industry, for example, Honda has been recognised as the industry leader in manufacturing flexibility. Honda
has achieved almost full flexibility in their North American plants, such that each plant has a capability of manufacturing all models of Honda. (*Automotive News*, 14 October, 2002)

In modelling terms, utilising a total flexible plant strategy is to impose the following condition onto the decision model.

\[ Z_{ik} = 1 \text{ for all } k, \text{ if } X_i = 1 \]  

(10)

More specifically, it is equivalent to replacing (3) with the following equation, while making (2) redundant.

\[ Z_{ik} = X_i \text{ for all } i, k \]  

(11)

The example assumes three potential products and two manufacturing plants. The potential products are sequenced in an order of perceived quality level such that product 0 represents the product with the lowest level of perceived quality and product 2 represents the highest one. If all three products are offered, each product model will fetch 100 units of demand. Both \( \pi \uparrow \) and \( \pi \downarrow \) for all product \( i \in I \) are expected to be 0.4, where \( \pi \uparrow \) and \( \pi \downarrow \) are the portion of customers who will buy one level higher (or lower) product if product \( i \in I \) is not offered. Also, each manufacturing plant has 150 units of capacity. For the convenience of this discussion, binary variables for the product platform are defined differently here such that \( Y_{(*)} \) is a binary variable to indicate whether the product platform shared by (●) products is developed. (Figure 1.a)

The discussion here may look somewhat arbitrary. The point, however, is to illustrate that the manufacturing flexibility strategy could alter the product platform development as well as the product offering decision that decides which products to offer among the set of potential products.
Figure 1.b looks into the case that a total flexible plant strategy is not imposed and the cannibalisation effect does not merit the development of Product 1. Also, the development of a common architecture for Product 0 and Product 2 is not economically attractive either. The result is to have solutions of $X_0 = X_2 = 1$, $Y_{(0)} = Y_{(2)} = 1$, $Z_{00} = Z_{21} = 1$, and all the other binary variables are at zero. Product 0 and Product 2 are developed uniquely without sharing a common product platform, and Plant 0 and Plant 1 are dedicated to the production of Product 0 and Product 2, respectively. (Case 1)

Figure 1.c looks into the case that the total flexible plant strategy is now enforced. Plant 0 and Plant 1 must now have the manufacturing capability of both Product 0 and Product 2. We have assumed that the manufacturing flexibility investment would be lower if products share a common architecture. If the cost savings in manufacturing flexibility investment are large enough, developing a common architecture for Product 0 and Product 2 would be economically attractive. Consequently, solutions are now $X_0 = X_2 = 1$, $Y_{(0,2)} = 1$, $Z_{00} = Z_{01} = Z_{20} = Z_{21} = 1$, and all the other binary variables are at zero. (Case 2)

On the other hand, if the cost of implementing a total flexible plant strategy is too high (such as very high $I - cst_i$), no matter which products share a common architecture, enforcing a total flexible plant strategy would be a discouragement to having any product diversity. (Figure 1.d) The solutions of Case 3 are $X_1 = 1$, $Y_{(1)} = 1$, $Z_{10} = Z_{11} = 1$, where all the other binary variables are at zero. Manufacturing Flexibility is supposed to be a response to the growing market uncertainty. In Case 3, however, implementing a total flexible plant strategy results in offering a single product to the market, which is hardly the original intention of responding to growing market uncertainty.
The example has illustrated that a manufacturing flexibility strategy would have much broader consequences than the manufacturing setup costs at plants. The point will be further probed in the next section.

5. Numerical Analysis

In this section, we further probe the role of a manufacturing flexibility strategy on product platform development through numerical analysis. As mentioned earlier, the purpose of the analysis is not to argue the benefits of manufacturing flexibilities, or to examine which manufacturing strategy performs best under different circumstances. The purpose is to demonstrate how a manufacturing flexibility strategy as well as manufacturing parameters interact with product platform development.
5.1. Test Factors

Parameters for the numerical analysis are generated to resemble the auto industry. All test problems have 12 potential products with an average demand of 100,000 units (total demand of 1.2 million units). Test problems have four manufacturing plants and each plant has 300,000 units of capacity. The unit revenue (market price) of each product ranges from $15,000 to $40,000 with an increment of $2,500. The parameters are chosen to closely resemble the operations of Honda in North America.

Test problems are systematically generated from the following six factors; Manufacturing Flexibility Strategies; Four elements of the proposed model’s objective function parameters, such as revenue element, product platform development cost element, manufacturing setup cost element ($P - cst_j$ and $I - cst_i$), and unit manufacturing cost element ($UPC_j$ and $UNC_i$); and Demand Pattern over Products. Detailed descriptions of the test problem factors are presented next.

Product Platform Development and Manufacturing Flexibility Strategies: This factor examines the integration of product platform development and manufacturing flexibility strategies. Here, we have looked into four different approaches.

- Conventional Product Platform Development Approach: Conventionally, Product Platform Development only considers the trade-off between the product platform development cost (fixed cost) and the over-design cost (variable cost). Manufacturing Setup costs are not typically considered when a company makes a Product Offering Decision that decides which products to offer and a Product Platform Development
Decision that decides to what extent a common architecture should be shared among products. The objective of the conventional approach is to select Product Offering and Product Platform Development strategies to maximise profit after deducting the total product platform development and over-design costs.

- Integrated with the Product Assignment Decision: Product Offering and Product Platform Development Decisions are now integrated with the Product Assignment Decision that decides which plant will produce which products. The objective is now to select Product Offering and Product Platform Development strategies to maximise profits after deducting the total product platform development, over-design, and manufacturing setup costs. However, no specific manufacturing flexibility requirements are imposed on any of plants.

- Total Flexible Plant Strategy: Each plant must have the capability of manufacturing all products that the company decides to offer.

- Pairing-Plant Flexibility Strategy: In this strategy, two out of four manufacturing plants are grouped in a pair to have exactly the same manufacturing capability. In fact, the Chrysler Group has adopted a similar approach. Their three plants in Michigan, Ontario, and Ohio can build any car models produced at the other two factories. (Automotive News 14 October 2002)

Composition of Manufacturing Setup Cost: In our model, the manufacturing setup cost has been broken down into P-cost and I-cost, where P-cost is the manufacturing setup cost for the assembly of product platform, and I-cost is the manufacturing setup cost for the assembly of the non-platform portion of products. The ratio of P-cost / I-cost, i.e. how much of the total
manufacturing setup cost is P-cost and I-cost, would be different from industry to industry. In the auto industry, GM spent about $1.2 billion on the development of the Saturn L model with almost half of that cost going towards the preparation of the plant to build the vehicles, implying the manufacturing setup cost at the plant was somewhere around $600 million. Assuming the total manufacturing setup cost is $600 million, we test five levels of (P-cost / I-cost) to explore the interaction between Product Offering/Product Platform Development and the composition of manufacturing setup cost. The five levels are; (P-cost / I-cost): ($100 million / $500 million), ($200 million / $400 million), ($300 million / $300 million), and ($400 million / $200 million), and ($500 million / $100 million). We have found from computation experiences that testing more levels would not contribute any further managerial insights.

Composition of Manufacturing Unit Cost: the unit cost, particularly the unit cost of the product platform portion, reflects the over-design cost. High over-design costs would negatively affect the magnitude of the common design to be exploited. Just the same as the composition of the manufacturing setup cost, the exact break-up of the unit material cost into product the platform portion and non-platform portion would differ from industry to industry. In the auto industry, local content clauses of NAFTA specify that COGS of a car is about 70% of retail price and 75% to 80% of COGS is credited to material cost. Therefore, we assume that the unit material cost of the product is about 60% of unit revenue.

Here, we have chosen three levels of (Unit Cost of Platform Portion / Unit Cost of Non-Platform Portion) to generate test problems. The three levels are, (Unit Cost of Platform Portion / Unit Cost of Non-Platform Portion): (50% of revenue / 10% of revenue), (30% of revenue / 30% of revenue), and (10% of revenue / 50% of revenue). As before, we have learned from
computation experiences that testing more levels would not contribute any further managerial insights.

Unit platform cost is set at the appropriate percentage of revenue for the product with the highest perceived quality level that shares the product platform.

Product Platform Development Cost: The previous GM’s example also implies that the product development cost of the Saturn L was about $600 million. However, exactly how much of that $600 million contributed to the development of the product platform is not known to us. In general, published data on the development cost of product platforms are rare. Here, we first assume that a product platform development cost is $300 million. Then, all test problems are re-computed with two other levels of product platform development cost to see whether different levels of product platform development cost have any impact on Product Offering/Product Platform Development.

It is reasonable to assume that the development cost of a platform would be higher if the platform is to be shared by a greater number of products. We have assumed $PDC_{ii} > \max\{PDC_{i}, PDC_{i'}\}$, where $PDC_{i}$, $PDC_{i'}$ are the development costs of a uniquely tailored product architecture for product $i$ and product $i'$ respectively, and $PDC_{ii}$ is the development cost of a product platform that could be shared by product $i$ and product $i'$. However, we have not made any assumption whether $PDC_{ii} < PDC_{i} + PDC_{i'}$ or $PDC_{ii} > PDC_{i} + PDC_{i'}$. The direction of inequality would depend on the technical complexity of the product.

Here, we have used the following formula to compute the product platform development cost:
Product Platform Development Cost = (Base Cost of Platform Development) * \{(number of products sharing the platform) power to the (Technical Complexity Index)\}

For example, if two products share a platform and technical complexity index is 1.1, then the development cost of the product platform is computed at $643 million = $300 million * 2^{1.1}$, assuming that the Base Cost of Platform Development is $300 million.

For all test problems, the Technical Complexity Index is set at 1.1. Test problems are generated from three levels of Base Cost of Platform Development, such as $100 million, $300 million, and $500 million.

Market Cannibalisation: As mentioned earlier, total revenue is a function of \( \{X_i\} \). However, the demand volume as well as the unit revenue of the products could be affected by the choice of product platform and/or cannibalisation.

Here, we have tested two levels of cannibalisation, where \( \pi \uparrow \) and \( \pi \downarrow \) are defined as the portion of customers who will buy one level higher (or lower) product if product \( i \in I \) is not offered. The two levels are:

- No Cannibalisation. In other words, \( \pi \downarrow = \pi \uparrow = 0 \) for all product \( i \in I \).
- Cannibalisation with \( \pi \downarrow = 0.3 \) and \( \pi \uparrow = 0.2 \) for all product \( i \in I \).

Demand Pattern: For Honda America, Civic and Accord are credited to almost 60% of their entire sales volume. The existence of such high volume products could affect the Product Platform Development Strategies as well as the Manufacturing Setup. We have tested two
patterns of demand volume to examine whether high volume products do affect Product Platform Development Strategies. The two demand patterns are:

- **Even Demand:** All test problems have 12 potential products. Each product has 100,000 units of demand.
- **Twin Peak Demand:** Product 6 and Product 12 have 300,000 units of demand, and the rest of products have 60,000 units of demand.

The total number of test problems generated is 720. All computations are performed on Dell Precision M50 with 512 MB of RAM, equipped with a Pentium IV 2.00 GHz processor. The code is written in Microsoft Visual C++ 6.0 connected to CPLEX 6.6. The code and full solution files are kept in the authors’ personal file and are available from the authors upon request. The computation performance of the computational procedure described in Section 3 is quite satisfactory. Test problems could be claimed to be industry size problems since the test problems resemble the case of Honda America. Apart from a very few cases, most of the test problems were solved in a few minutes or less.

**5.2. Observations**

If the key enabler for flexible manufacturing is to have common vehicle architectures, our numerical tests are expected to observe more products that share a common product platform when manufacturing flexibility strategies are imposed on the product offering and product platform development decisions. We measure the magnitude of product platform usage by the average number of products per product platform, \((\text{number of products to offer}) / (\text{number of product platform developed})\).
Figure 2 plots the number of products on offer and the average number of products per product platform for four approaches of “Product Platform Development and Manufacturing Flexibility Strategies” at different \( (P\text{-}cost/I\text{-}cost) \) levels, assuming (Unit Cost of Platform Portion / Unit Cost of Non-Platform Portion) of \((30\% \text{ of revenue} / 30\% \text{ of revenue})\), $300 million Base Cost of Platform Development, No Cannibalisation, and Even Demand. We found from our numerical tests that other test problems show the similar pattern.

For all test problems, the Technical Complexity Index has been set at 1.1 to compute the Product Platform Development Cost. When the Technical Complexity Index is greater than 1, \( PDC_{ii} > PDC_{i} + PDC_{i'} \), where \( PDC_{i} \), \( PDC_{i'} \) are the development costs of a uniquely tailored product architecture for product \( i \) and product \( i' \) respectively, and \( PDC_{ii} \) is the development cost of product platform that could be shared by product \( i \) and product \( i' \). Therefore it is not surprising to observe that all twelve products are uniquely developed under a Conventional Product Platform Development Approach, since it only considers the trade-off between the product platform development cost (fixed cost) and the over-design cost (variable cost). When \( PDC_{ii} > PDC_{i} + PDC_{i'} \), no cost saving could be obtained by developing a common product platform.

A similar technical complexity index could exist for the manufacturing setup for the platform portion. For example, the manufacturing setup cost for a product platform shared by two products could be higher than the sum of two manufacturing setup costs for uniquely developed architecture for the two products. On the other hand, if the manufacturing setup cost for the platform portion does not increase too fast for the number of products sharing the platform, total fixed costs related to the product platform development (i.e. the sum of product platform development cost and manufacturing setup cost for the platform portion) could be
lowered when Product Offering/Product Development Decisions are integrated with product assignment decision to plants.

All test problems in this research implicitly assume that the manufacturing setup cost for the platform portion does not increase too fast compared to the number of products sharing the platform. As we expected, Figure 2 shows that the magnitude of the product platform usage is higher under the “Integrated with Product Assignment Decision” strategy than under the “Conventional Approach.”

The potential saving in total fixed costs related to the product platform development becomes greater, when either Pairing-Plant Flexibility Strategy or Total Flexible Plant Strategy is imposed. Unless plant capacity becomes a binding constraint, \( \sum_{k} Z_{ik} = 1 \) for \( \forall i \) such that \( X_i = 1 \) when the Strategy Integrated with Product Assignment Decision is imposed. In other words, there is only one manufacturing setup for any products on offer. Under Pairing-Plant Flexibility Strategy and Total Flexible Plant Strategy, on the other hand, \( \sum_{k} Z_{ik} = 2 \) and \( \sum_{k} Z_{ik} = 4 \), respectively, for \( \forall i \) such that \( X_i = 1 \). As the number of manufacturing plants to be setup for the production of product \( i \) such that \( X_i = 1 \), the potential saving in total fixed costs by sharing a common product platform would be doubled and quadrupled, respectively. Not surprisingly, the magnitude of platform usage is substantially higher when the manufacturing flexibility strategy is imposed than otherwise.

On the other hand, the increased number of manufacturing setups reduces the number of products on offer. Low revenue products cannot generate enough profit to justify so many manufacturing setups. Consequently, low revenue products are dropped from the products on
offer. In fact, a Total Flexible Strategy offers substantially fewer products compared to other strategies.

Offering fewer products has another implication. Total production volume is going to be substantially lower when manufacturing flexibility strategies are imposed. Unless the company can eliminate the unused capacity, the utilisation rate of their plants would be lowered.

Figure 2 also illustrates the relationship between the Composition of the Manufacturing Setup Cost and Product Offering/Product Platform Development. As the relative magnitude of the manufacturing setup cost for the assembly of product platform portion \((P\text{-}cost)\) to the manufacturing setup cost for the assembly of non-platform portion \((I\text{-}cost)\) increases from \((100\text{ million: }500\text{ million})\) to \((500\text{ million: }100\text{ million})\), more products are to be offered with a higher average number of products per product platform. High \(P\text{-}cost\) implies that having additional common product architecture would be very costly. On the other hand, Low \(I\text{-}cost\) implies that offering variant products that share the common product platform would be less expensive. Consequently, more products that share the common platform are to be offered as \(P\text{-}cost\) increases.

\[
\begin{array}{c|c|c|c}
\text{Composition} & \text{Number of Products to Offer} & \text{Avg. Number of Products per Product Platform} \\
\hline
\text{Conv} & 0 & 0 \\
\text{Assign} & 2 & 2 \\
\text{Paring} & 4 & 4 \\
\text{Total} & 10 & 10 \\
\end{array}
\]

\[
\begin{array}{c|c|c|c|c|c|c}
\text{Composition} & \text{Number of Products to Offer} & \text{Avg. Number of Products per Product Platform} \\
\hline
\text{Conv} & 0 & 0 \\
\text{Assign} & 2 & 2 \\
\text{Paring} & 4 & 4 \\
\text{Total} & 10 & 10 \\
\end{array}
\]

**FIGURE 2**
The composition of the Unit Manufacturing Cost also has a role on the Product Offering/Product Platform Development Decision. Figure.3 displays the number of products on offer and the average number of products per product platform for three levels of (Unit Cost of Platform Portion / Unit Cost of Non-Platform Portion) at different ($P\text{-cost}/I\text{-cost}$) levels, assuming a Pairing-Plant Flexibility Strategy, $300$ million Base Cost of Platform Development, No Cannibalisation, and Even Demand. As the relative portion of Unit Platform Cost decreases from 50% of Unit Revenue to 10% of Unit Revenue, the number of products on offer and the magnitude of platform usage have increased. A lower portion of the Unit Platform Cost means lower over-design cost. Consequently, more products share a common product platform as unit platform costs becomes less expensive.

![Figure.3](image_url)

FIGURE.3

As mentioned earlier, most of the literature on Product Platform Development only considers the trade-off between the product platform development cost (as fixed cost) and over-design cost (as variable cost). We have assumed in our test problems that the cost of developing a product platform is about $300$ million. We then re-solve all the test problems with two other platform development costs ($100$ million and $500$ million) to see whether the Product Platform...
Development Cost level has any effect on Product Offering/Product Platform Development Decisions.

Contrary to our expectation, we have not seen much difference in the Product Offering/Product Platform Development Decision for all three levels of product platform development costs. We have found from our test problems that Product Offering/Product Platform Development Decisions are more affected by manufacturing related parameters than product platform development costs. It is partly because, for any product to offer, the Product Platform Development Cost occurs only once, whereas manufacturing setup related costs (such as $P$-cost and $I$-cost) occur as many times as the number of manufacturing plants. This observation supports the fundamental argument of this research that the Product Offering/Product Platform Development Decision should look into manufacturing related parameters as well as the trade-off between product platform development cost and over-design cost.

Figure.4 shows Product Offering Decisions, $\{X_i\}$, of a few selected test problems with Cannibalisation. When cannibalisation exists among products, a firm has an incentive not to offer a specific product since a portion of its sales revenue could be recouped from the sales of products with lower or higher perceived quality levels. In Figure.4, the Product Offering Decisions of a Conventional Product Platform Development Approach does not show any skipping of products on offer, whereas the Product Offering Decisions of Integrated with Product Assignment Strategy show “leaping 1’s over 0’s” in $\{X_i\}$. For a Conventional Approach, the fixed cost related to offering a product is product platform development cost. In our test problems, the product platform development cost was not set at a high enough level to
materialise “leaping 1’s over 0’s” in \( \{X_i\} \). When manufacturing related costs are factored into the Product Offering Decision, the total fixed cost related to offering a product also includes the manufacturing setup cost. As the total fixed cost related to offering a product increases, the incentive of skipping products become stronger. The result is “leaping 1’s over 0’s” in \( \{X_i\} \) for test problems of Integrated with Product Assignment Decision Strategy.

<table>
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<tr>
<th>(P-cost / I-cost): ($100 million / $500 million)</th>
<th>Conventional Approach</th>
<th>Integrated with Product Assignment Decision</th>
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**FIGURE.4**

Finally, high volume products, such as Civic and Accord for Honda America, could affect the development of the product platform. We have tested two levels of demand patterns such that; each product has 100,000 units of demand (Even Demand) and Product 6 and Product 12 have 300,000 units of demand while the rest of products having 60,000 units of demand (Twin Peak Demand). As we expected, Product 6 and Product 12 were key products of the product platform development in the sense that Product 6 and Product 12 were either \( l \)-product or \( h \)-product of platform \( Y_{l,h} \), where \( Y_{l,h} \) was the product platform shared by \( l \)-th lowest perceived quality product through the \( h \)-th lowest perceived quality product.
6. Concluding Remarks

To reiterate our argument, as a response to growing market uncertainty, firms have invested heavily in manufacturing flexibility. Recently, firms have looked into exploiting common designs among products as a key enabler for flexible manufacturing. No literature in Product Platform Development has so far recognised common design among products as a mean of enabling manufacturing flexibility.

The fundamental assumption of this research is that common designs among products could reduce the investment cost of manufacturing flexibility. Among many aspects of common designs, this research focuses on product platform development. We have assumed that the manufacturing setup cost for two products are lower if the two products share the common platform.

Our decision support model produces a comprehensive decision on the Product Offering, Product Platform Development, and Manufacturing Setups. We have also discussed computation procedures that could solve industry size problems within a very reasonable computation time.

Finally, we have demonstrated through numerical analysis that manufacturing related parameters could be more detrimental for the Product Offering/Product Platform Decision than the Product Platform Development cost itself.

The biggest contribution of this paper is, to the best of our knowledge, the first research to demonstrate the interaction between a manufacturing flexibility strategy and product platform development. On the other hand, it leaves a great deal for future research.
Analytical analysis was not pursued to gain managerial insights. Therefore, insights of this research are limited to the test factors in Section 5. Pursuing analytical results would constitute valid future research to develop a more solid theory for the role of manufacturing flexibility on product platform development.

Also, this research demonstrates that choosing different manufacturing flexibility strategies could alter the results of the Product Offering/Product Platform Development Decisions. However, we have not addressed the issue of developing an optimal manufacturing flexibility strategy for a firm. To develop an optimal strategy, a firm must choose its objective. It could be to maximise (expected) profit overtime, to minimise (expected) total changeover cost overtime, or to maximise (expected) utilisation overtime. It would be interesting to investigate how different objectives produce different optimal strategies. We will leave that for future research.

References


