An Integrative Methodology for Product and Supply Chain Design Decisions at the Product Design Stage

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Abstract

Many studies have pointed out that the integration of product and supply chain is a key factor for profitability and efficiency. However, most studies address supply chain performance after the creation of a new product; and only a few studies discuss when and how to incorporate supply chain decisions during product design. This paper presents a graph theory based optimization methodology to tackle this problem and the supplier selection issue is considered by evaluating its impact on both internal (e.g., ease of assembly) and external enterprise performance (e.g., transportation and lead time). These sub-performance measures are aggregated into the supply chain performance at the conceptual design stage with a case study in the bicycle industry.

Keywords

Product Design, Supply Chain Design, Transition Matrix, Design Repository

1. Introduction

Product development is an innovative process that transforms and realizes the potential market opportunities into a product according to product and process technologies [1]. Around 70\% of product cost [2] and 80\% of product quality [3] are decided during the design stage. Meanwhile, product flexibility (e.g., color, shape, materials, etc.) drops sharply during the design stage. From the enterprise perspective, new products, which are introduced to the market within five years, account for a staggering 33\% of company sales [4]. Therefore, new products have a high association with the profitability and growth of a company. Besides high profitability, new product development is also known to have high risk. The New Product Failure Rate, which is a statistical datum that computes the success percentage of new products, shows that only 40\% of new products survived in 2004 [5]. Bulter et al. [6] pointed out that the new products have different supply chain configurations due to the demand patterns, customer locations, and market sizes.

Many researchers found that supply chain performance cannot be optimized without considering the compatibility of product and supply chain attributes [4, 6-8]. The appropriate coordination between supply chain type and product type, for example, a functional product and an efficient supply chain can assure a high likelihood of success. Despite the significance, only a few methods concurrently consider product design and its supply chain. The objective of this research is to develop a method that can connect and harmonize the product design and supply chain configuration problems. Therefore, some limitations of supply chain can be recognized at the very beginning, and both product design and supply chain configuration can be optimized.

2. Literature Review

2.1 Product Architecture

Product architecture is the schema of physical building blocks in a product and the ways in which they interact [1]. The product architecture has broad implications on engineering design, process design, systems engineering, marketing, and organizational science perspectives [9]. Product architecture serves as the kernel that connects the customer and the enterprise; it impacts process and portfolio design and directs the change, variety, performance, and manufacturability of the product [1, 9-11]. During the last two decades, traditionally standard, uniform customer requirements became divergent and variant. This trend necessitated the demand for mass customization. The goal of mass customization is to produce customized goods at mass production efficiency by means of providing outstanding service to meet customers’ needs at low costs. Many studies have developed design for variety [10] and
product platform methodologies [10-11] based on modular architecture due to its superiority in reducing design efforts. In addition, production process can be simplified by assembling common components in the front-end process, and delaying the assembly of variant components, which represent variety for customization, to the back-end (a.k.a., postponement). Postponement and differentiation can be achieved with affordable cost. As per the reasons above, this study adopts modular architecture.

2.2 Coordination between Product and Supply Chain Management

To analyze the capability between product and supply chain, Fisher [8] constructed a model that qualitatively divided the dimensions of products into “functional” and “innovative.” A functional product has stable demand, a low profit margin, and many competitors. Conversely, an innovative product refers to a newly introduced and differentiable product with versatile demand. Accordingly, supply chains can be classified as “efficient” and “responsive” supply chains. Efficient supply chains emphasize making and delivering a product with low cost, and cost is the major concern. On the other hand, responsive supply chains aim for delivering a variety of products quickly to achieve a high level of customer service. The appropriate coordination between supply chain type and product type, for example, a functional product and an efficient supply chain—can assure a high likelihood of success. Fisher’s framework is then extended with a hybrid product type along with hybrid supply chain [7]. “Hybrid” refers to the combination of characteristics of two types of supply chains and products. Fisher’s model is verified on the fit of functional products and a physically efficient supply chain according to a field study of 128 companies [12]. Vonderembse et al. [7] suggested that the supply chain network should reconfigure in different phases of product life cycle. When a new product is launched into the market, it should embrace an agile supply chain at introduction and growth phase of product life cycle. After that, enterprises can adjust to a lean or hybrid supply chain type according to the degree of demand variation. The above research demonstrates that the product design is highly related to supply chain structure. We assert that improvement of supply chain performance can be achieved through its simultaneous consideration of product structure and supply chain attributes. However, only a limited number of studies have addressed this issue. In this paper, we present a methodology which utilizes a design repository, Design for Assembly (DfA) index, and graph based transition matrix along with Mixed Integer Programming model to simultaneously optimize design and supply chain management decisions.

2.3 Previous Supplier Selection Methods Proposed for Product Design Stage

Supplier involvement at the product design stage has recently drawn much attention from researchers. Involving supplier in new product development phase provides both short term and long term benefits. In the short term, it can reduce product development time and cost with improved quality. In the long term, the collaboration will enhance the partnership and be able to result in a more effective coordination, which enables focal company to differentiate products [13]. A robust supplier set selection method that can support various needs of product architecture over a planning horizon is presented to response to the challenge of mass customization. This method incorporates Taguchi’s quality loss function and Ant Colony Optimization (ACO) method to evaluate various product architectures for minimum total acquisition costs while selecting suppliers [14]. Gökhan et al. [15] developed a mixed-integer program that considered supply chain decisions on cost, lead-time, and demand satisfaction to achieve an overall profit at the design stage. However, in this study, the product refers to a set of components; and the interactions among components and potential multi-echelon supply chain structures that result in different possible product architectures and supply chain configurations are not considered. From the literature review, only a few studies point out how the supply chain is shaped at the product design stage. This finding motivates the integration of supply chain decisions at the product design phase so that we can identify and evaluate optimal component acquisition and possible supply chain alternatives.

3. Proposed Methodology

The goal of the proposed methodology is to simultaneously optimize product functions, manufacturing, and supply chain considerations during the early design stages. Therefore, there are two phases in this method. The first phase generates the design concepts, evaluates these concepts with Design for Assembly (DfA) index, and modularizes these concepts to possible product architectures. Then, the second phase develops a transition matrix and mixed integer programming model to optimize the supply chain performance regarding cost and time. A design repository, which integrates Java Swing within the NetBeans IDE 6.1 programming environment, MySQL database, and Java Database Connectivity (JDBC) is developed in phase I [16]. Accordingly, Lingo software serves as an optimization tool to solve the Mixed Integer Programming model. The concept that has the best score in assemblability will be modularized by the Decomposition Approach [17] as the output of the phase I. It will later be compared with the graph based methods in the phase II. The graph theory based method consists of a transition matrix [18] and Mixed Integer Programming model. It is a mathematical model that optimizes the best product architecture as well as the supply chain.
3.1 Product Design Concept Generation and Modularization
Product design starts with interpreting customer needs and transforming them into functional requirements. These functional requirements are then defined and decomposed into the most basic sub-functions to form an Energy-Material-Signal (EMS) functional model. After that, a repository synthesizes potential components of all sub-functions and provides multiple options for the conceptual design. These concepts are evaluated using a 13 Design for Assembly criteria [19] from the perspectives of the assembly, component, and process properties. Finally, these concepts will be modularized with the Decomposition Approach as the output of the phase I.

3.2 Transition Matrix Method Based on Product Architecture
The transition matrix was developed to solve the disassembly sequence with the purpose of optimizing the profit of the product at the end-of-life stage. While disassembling the product, all possible status of sub-graph or sub-assemblies are denoted as a stage set (set S). The disassembly process or action that results in the transferring between two sub-assemblies is represented as the vertex (Set A). Here, we apply the transition matrix in a reverse manner. For the components in a complete design concept, they have multiple candidate suppliers who have capability to manufacture them. It is noteworthy that every supplier has various attributes in process cost, time, etc. Based on the output of Phase I, design concepts are modularized and possible assembly sequences can form a transition matrix. According to this matrix, suppliers’ information as well as customized constraints can be formulated into a mixed integer programming model.

3.3 Mathematical Formulation of Supply Chain

**Index Sets:**
- \( p \) represents possible processes of a product, \( p = 1, \ldots, N_p \);
- \( s \) represents possible states of a product manufacture and assembly, \( s = 1, \ldots, N_s \);
- \( i \) represents potential component suppliers, \( i = 1, \ldots, N_i \);
- \( j \) denotes potential sub-assembly suppliers, \( j = 1, \ldots, N_j \);
- \( k \) is potential final assembly locations, \( 1, \ldots, N_k \).

**Decision Variables:**
- \( X_{pi} \) is variable indicating that component supplier \( i \) is selected for process \( p \).
- \( X_{pj} \) is variable indicating that sub-assembly supplier \( j \) is picked for process \( p \).
- \( X_{pk} \) is variable indicating that final assembly location \( k \) is selected for process \( p \).
- \( Y_{pj} \) is variable indicating that process \( p \) is performed.
- \( L_{MAX} \) and \( L_{MIN} \) are the longest and shortest acceptable lead time of supply chain. Finally, \( C_{MAX} \): Highest acceptable cost of product

**Parameters:**
- \( T_{si} \) is entity value of transition matrix.
- \( C_{pi} \) is the unit cost of component supplier \( i \) in process \( p \).
- \( C_{pj} \) is the unit cost of sub-assembly supplier \( j \) in process \( p \).
- \( C_{pk} \) denotes the unit cost of final assembly \( k \) in process \( p \).
- \( L_{pi} \) is the process time of component supplier \( i \) in process \( p \).
- \( L_{pj} \) is the process time of sub-assembly supplier \( j \) in process \( p \).
- \( L_{pk} \) is the process time of final assembly \( k \) in process \( p \).
- \( LEAD \) is total lead time of supply chain.
- \( T_s \) is the unit transportation cost of state \( s \).
- \( V_s \) is unit transportation speed of state \( s \).
- \( H_s \) is the unit holding cost of state \( s \).
- \( D_{ij} \) is geographic distance between component supplier \( i \) and sub-assembly supplier \( j \).
- \( D_{jk} \) is the geographic distance between sub-assembly supplier \( j \) and final assembly location \( k \).

**Objective Function:** the objective function in equation (1) is to minimize the total cost under acceptable lead time. Total cost is the sum of process costs \( C_i \), transportation cost \( C_T \), and inventory cost \( C_I \) in equation (2), (3), and (4) respectively. Process cost summarizes the process cost of all selected suppliers in the process \( p \), which contains component, module assembly, and final assembly processes. Transportation cost is the distance between the upstream suppliers and downstream suppliers for all processes. Inventory cost counts the front end inventory of selected suppliers. In this study, inventory cost is the summary value of all processing time and transportation time of selected suppliers in a product architecture, which is then multiplied by the unit holding cost.

**Constraints:** To avoid the incoherent sequences, equation (5) is crucial, because it presents the condition that explains coexistence of inflow and outflow in the component, module, and final product stages in the transition matrix. In addition, the number of parts will decrease during assembly processes. Therefore, the summary of the entity value will be smaller than 0 in every process. Every process is assigned to only one supplier who is capable in process \( p \). The supplier who provides the process will be marked as 1, otherwise as 0. The total lead time of the supply chain is summarized layer by layer, which begins from the component level, sub-assembly level, to final assembly level. All parts in the component level treats as a starting point of possible routes. The maximum lead time is the maximum value that exists among all possible routes, which include component process time, component transportation time, module assembly time, module transportation time and final assembly time. The acceptable supply chain lead time can be constrained with equations (11) and (12) below. The total cost constraint of the supply chain \( C_{MAX} \) expresses in equation (13). All variables are defined in equation (14). The best concept after the transition matrix and Mixed Integer Programming model will be selected as the output of phase II.
Where

\[
C_1 = \sum_{i} \sum_{p} C_{pi} \cdot X_{pi} + \sum_{j} \sum_{p} C_{pj} \cdot X_{pj} + \sum_{k} \sum_{p} C_{pk} \cdot X_{pk}
\]

\[
C_2 = \sum_{i} \sum_{j} \sum_{k} D_{ij} \cdot T_{ij} \cdot X_{pi} \cdot X_{pj} + \sum_{j} \sum_{k} \sum_{p} D_{jk} \cdot T_{jk} \cdot X_{pj} \cdot X_{pk}
\]

\[
C_3 = \sum_{i} \sum_{j} \sum_{k} \sum_{l} [(L_{pi} + \frac{D_{ji}}{V_{ji}}) \cdot X_{pi} + (L_{pj} + \frac{D_{kj}}{V_{kj}}) \cdot X_{pj}] \cdot H_{ij}
\]

\[
\sum_{p} T_{pj} \cdot Y_{j} \geq 0 \quad \forall p \in P
\]

\[
\sum_{p} T_{pj} \leq 0 \quad \forall p \in P
\]

\[
\sum_{i} X_{pi} = 1 \quad \forall s \in S
\]

\[
\sum_{j} X_{pj} = 1 \quad \forall p \in P
\]

\[
\sum_{j} X_{pj} = 1 \quad \forall p \in P
\]

\[
\text{LEAD} = \text{Max} \left\{ X_{pi} \cdot L_{pi} + X_{pj} \cdot \frac{D_{ji}}{V_{ji}} + X_{pj} \cdot L_{pj} + X_{pk} \cdot \frac{D_{kj}}{V_{kj}} + X_{pk} \cdot L_{pk} \right\}
\]

\[
\text{LEAD} \leq L_{\text{MAX}}
\]

\[
\text{LEAD} \geq L_{\text{MIN}}
\]

\[
C_1 + C_2 + C_3 \leq C_{\text{MAX}}
\]

\[
L_{\text{MAX}}, L_{\text{MIN}}, C_{\text{MAX}} \geq 0 \quad \text{and} \quad Y_{pj}, X_{pi}, X_{pj}, X_{pk} \in \{0, 1\}
\]

4. Case Study and Discussion

A new bike project aims to attack the low-end road bike market segment where the price ranges from $60 to $100 USD. The transportation speed is 100 miles/hr. The unit transportation cost is $0.001 USD, and the unit inventory holding cost is $0.05 USD. In addition, the estimated quantity of the final product is approximately 100,000 per month. The management of the company would like to have an acceptable lead time that can respond to market dynamics. Current lead time target is 100 hrs which starts at components manufacturing and ends at the completion of the final assembly process. The mission of the design team is to develop a design concept that satisfies both product design and supply chain considerations regarding cost and time.

4.1 EMS Model with Component Mapping and Design Repository

Bike architecture can be simply presented as left part of Figure 1 below. The first level of bike structure contains structure system, braking system, transmission system, and wheel system. Structure is composed of three sub-systems: fork, frame, and saddle. The braking system, as its name implies, is responsible for decelerating the bike speed. Another important sub-system is the transmission system, which defines the functions and usages of the bike. The wheel system enables the bike to move by creating friction with the ground. These four sub-systems are modular designs, which are mutually independent but cooperate as a whole product. Another two sub-systems are the electric motor with battery set and accessories, which are optional equipment for saving physical efforts and environmental considerations. As shown in right part of Figure 1, the EMS model considers a total of seven components and functions, excluding the motor. In our case, the possible components of the bike are as follows: (A) saddle, (B) frame, (C) fork, (D) brake, (E) wheels, and (F) transmission systems.

The EMS model starts with the human body climbing on the saddle. This action contains “import” and “assemble”. The saddle provides “position” and “support” functions. The frame “stabilize(s)” the human body and the fork will “orient” the direction based on the visual signal. The transmission system will “convert” human energy into rotational energy, and then the rotational energy converts to mechanical energy on the wheel to move forward. Accordingly, the braking system is “actuated” by a visual signal and “converts” human energy to mechanical energy to slow down the bike. As left and center parts of Figure 2 illustrated, design repository generates feasible design concepts after the input of EMS model and DFA index value. In this case study, design repository generates 2^6 = 64 combinations with DFA values. These concepts are further modularized in right part of Figure 2.
4.2 Graph Theory Based Optimization and Discussion

The estimated process cost and time of every component and module are calculated according to [12]. After solving the MIP model, the product concept that has the best DfA score, and transition matrix are compared regarding the supply chain performance, its product architecture, and the supply chain structure in Figure 3. The output of Phase I has a higher cost (111%) and longer lead time (222%) than phase II. In addition, the lead time (120.40 hrs) is longer than the original expectation (100 hrs). This might result in one or more iterations in design concept refinement. The key reason is that Phase I chooses Shimano as the supplier of transmission. Shimano is selected in phase because of its advantage in assembly. However, Shimano is the only supplier located in Asia and other suppliers are located in the USA. The long traveling distance causes not only higher transportation and inventory costs but also longer lead times. From the management’s vantage point, the solution of Phase I requires five suppliers while the solution of phase II only involves four suppliers, which reduces operational complexity.

<table>
<thead>
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<th>Criteria</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Difference</th>
</tr>
</thead>
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<tr>
<td>Proc. cost</td>
<td>$85.00</td>
<td>$80.00</td>
<td>$5.00</td>
</tr>
<tr>
<td>Trans. cost</td>
<td>$1.55</td>
<td>$0.74</td>
<td>$0.81</td>
</tr>
<tr>
<td>Inv. cost</td>
<td>$10.52</td>
<td>$6.55</td>
<td>$3.97</td>
</tr>
<tr>
<td>Total cost</td>
<td>$97.07</td>
<td>$87.29</td>
<td>$9.78</td>
</tr>
<tr>
<td>Diff. %</td>
<td>111.20%</td>
<td>100%</td>
<td>11.20%</td>
</tr>
<tr>
<td>Total lead time (HR)</td>
<td>120.40</td>
<td>54.20</td>
<td>66.20</td>
</tr>
<tr>
<td>Diff. %</td>
<td>222.14%</td>
<td>100%</td>
<td>122.14%</td>
</tr>
<tr>
<td>Supplier #</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

5. Conclusion

In this paper, a methodology that connects and harmonizes product design and supply chain design decisions is presented. Firstly, the design repository is a tool that provides flexibility and knowledge management while designing a new product. Focal company can decide to introduce single or multiple products to market at a time depends on demands, budget and other considerations. The knowledge management function can benefit the enterprises that might have weakness in design power. In addition, the DfA index evaluates the manufacturability of
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the design concept. Finally, with the support of graph based transition matrix and MIP model, supply chain consideration can aid in analyzing the transportation cost and lead-time of the supply chain execution, hence the agility can be improved without huge financial investment on facilities, equipments and management. This method covers product design, manufacturing, and supply chain configuration from a systematic perspective to achieve overall efficiency. It can serve as a decision-making support system, which enable decision makers to analyze, predict, control, and assure the success of both product and enterprise at the design stage. Disclosure of supply chain related information can convey higher flexibility and longer time to prepare and respond to potential impacts. Therefore, competitive advantage of an enterprise is established. Accordingly, this method can provide a precautionary function that prevents potential risk in supply chain execution. In addition, it is a communication tool between engineers and the managerial group (internal) as well as suppliers and focal company (external), which will construct a virtual organization and result in a win-win situation for both the focal company and the suppliers.

Acknowledgment

The authors would like to thank Cannondale Bicycle Corporation (Bedford, PA) and Freeze Thaw Cycles (State College, PA) for their assistance with this research.

References