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A Small to Medium-Size Enterprise Oriented Methodology for Optimizing Product and Supply Chain Design Decisions

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ABSTRACT
Today supply chain management has become one of the crucial factors for gaining and sustaining a competitive advantage. Enterprises that can more effectively manage their supply chain network have a higher likelihood of success in the marketplace. To this end, companies need not only make the “make” or “buy” decisions but also differentiate across potential suppliers in order to improve operational performance, and hence, supplier selection is one of the key decisions aiding effective supply chain management. Many studies have also pointed out that the integration of product and supply chain is a key factor for profitability and efficiency. However, prior studies mostly 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. In the studies that cover product design, product family and product platform concepts are presented as enabling vehicles for mass customization, which require a considerable investment, and hence might be out of reach for small to medium size enterprises (SME). Accordingly, there is a need to develop a methodology that can consider manufacturability and supply chain issues at the product design stage. This paper presents a graph theory based optimization methodology to tackle this problem. The supplier selection issue is considered by evaluating its impact on both engineering (e.g., process planning) and operational performance (e.g., cost and time), which are then aggregated as the supply chain performance at the conceptual design stage. A case study in the bicycle industry demonstrates the advantages of this methodology. The synchronized structure of the supply chain and the product design results in simultaneous optimization of both design and supply chain decisions during the early design stages.

Keywords: Product Design, Supply Chain Design, Branch and Bound Search, 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 as depicted in Figure 1. From the enterprise perspective, new products that are introduced to the market within five years might account for as high as 33% of company sales [4], presenting a high association with the profitability and growth of a company. Despite the potential for 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].

Many researchers found that supply chain performance cannot be optimized without considering the compatibility of product and supply chain attributes [4, 6-8]. Further, 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. Accordingly, 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 above mentioned significance of product design and the need to coordinate between product and supply chain designs, only a few methods concurrently consider product design and its supply chain. For small to medium size enterprises (SMEs) supply chain network management might be more critical than large companies since they tend to rely heavily on suppliers [9]. While the specific numbers change across countries, SMEs are classified based on the number of employees, revenues, or balance sheets. For example, European Commission classifies a company as an SME if it has fewer than 250 employees and a balance sheet with no more than 43 million euros [10].

The objective of this research is to develop a method that can combine and streamline the product design and supply chain configuration problems for SMEs. With this streamlined view, the product design team can extend its scope to supply chain execution and planning. Meanwhile, the management of the enterprise can clearly identify the operational influence of a new product. Therefore, potential limitations of supply chain options can be recognized at the very beginning, and both product design and supply chain configuration can be improved.

The next section in the paper reviews the relevant literature on product architecture, previous work on coordination between product and supply chain, and supplier selection at the product design phase. Section 3 proposes a methodology that can consider product functions, manufacturability, and supply chain perspectives simultaneously during the product design stage. A case study is presented in section 4 to demonstrate the proposed methodology. Section 5 presents conclusions.

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. The product architecture has broad implications on engineering design, process design, systems engineering, marketing, and organizational science perspectives [11]. Product architecture serves as the kernel that connects the customer and the enterprise; it impacts process and portfolio design that directs the change, variety, performance, and manufacturability of the product [1, 11-12]. Two main typologies of product architecture are the modular product and the integral product [1].

Integral product architecture views the product as a whole, and aims to achieve full optimization of product functions. Integral product design may provide better product differentiation as product components are designed to be specific to a particular product. One of the integral design methodologies is Design for Manufacturing and Assembly (DFMA) [13], which emphasizes reducing the quantity of components and creating multifunctional parts. However, the modification of one component usually impacts other related components, which results in a significant redesign effort. This may lead to a longer design time and renders integral product architecture uncompetitive in comparison to modular product architecture.

Modular products decompose the overall functionality of a product into sub-functions that are embodied in separate modules. These modules are designed to be independent, standardized, and interchangeable. There are two main types of components in modular design: common and variant components. Common components serve as static and shared portions of the product architecture in product design, which enable reusability and save design efforts. Meanwhile, the goal of a variant component is to fulfill diverse and dynamic customer requirements within a given specific service level [14-15]. Product variety can be realized by substitution of variant modules, which improves economies of scale in production. In addition, quality problems can be contained at the modular level facilitating ease of maintenance and repair. Another advantage of modularity is that it enables concurrent design activities since it decouples a product into module development tasks to shorten product development time.

Despite the advantages, there are some potential drawbacks of modular product architecture, such as performance optimization, under or over design, and a considerable design investment. Also, in addition to component modularity, the standardization of the interface is necessary [16-17]. Despite these drawbacks, in recent years, modular product architecture has become the mainstream due to its advantages in development time, cost, and economy of scale [16-17]. 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 providing outstanding service to meet customers’ needs at low costs. Many studies have developed design for variety [18] and product platform methodologies [17-18] based on modular architecture due to
its superiority in reducing design efforts. In addition, products can be simplified while common components are assembled in the front-end process, and variant components, which represent variety for customization, are assembled in the back-end (a.k.a., postponement). Postponement and differentiation can be achieved with an affordable cost. As per the reasons stated above, this study adopts modular architecture.

2.2 Coordination between Product and Supply Chain Management

Many researchers found that supply chain performance cannot be optimized without considering the compatibility of product and supply chain attributes [7-8]. One way of classifying products could be based on demand levels and profitability. A “functional product” has stable demand, a low profit margin, and many competitors, such as with staple items. 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 [8]. Efficient supply chains emphasize making and delivering a product with low cost, while 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. Selldin and Olhager [19] verified Fisher’s model on the fit of functional products and a physically efficient supply chain according to a field study of 128 companies.

Vonderembse et al. [7] extended Fisher’s framework [8] to include a hybrid product type as well as a hybrid supply chain. Efficient supply chain is renamed as lean supply chain, which focuses on reducing lead-time, increasing efficiency, expanding manufacturing flexibility, and cost cutting is recommended for the standard (functional) product. In contrast, a responsive supply chain is renamed as agile supply chain, which aims to respond to rapidly changing, continually fragmenting markets by being dynamic, context specific, growth-oriented, and customer focus is advised for innovative products. Hybrid supply chains combine the capabilities of lean and agile chains to create a network that meets the needs of hybrid products. Hybrid product here refers to a product that has some of the standard product’s characteristics as well as some of an innovative product’s characteristics. Different types of supply chains with different features should be carefully coordinated for varied types of products and suppliers with different attributes. In addition, design strategies of products should vary from type to type. For lean supply chain, new product design strategy should focus on maximizing product performance meanwhile minimizing the cost. Agile supply chain aims for high degree of customization, hence new product design strategies should focus on satisfying individual customers. A hybrid supply chain has some of lean supply chain characteristics as well as some of agile supply chain characteristics. Therefore, a modular design that can postpone product differentiation might be the suggested new product design strategy. Vonderembse et al. [7] further argued that the supply chain network should be reconfigured in different phases of product life cycle. Enterprise should embrace an agile supply chain during introduction and growth phases 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 summarized research indicates that the supply chain design is highly related to the relevant product structure. Thus, we assert that improvement of supply chain performance can be achieved through 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 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. Van Echtelt et al. [20] described the benefits of supplier involvement in new product development phase. They indicated that in the short term, it can reduce product development time and cost with improved quality, and in the long term the collaboration will enhance the partnership and can result in more effective coordination, and thereby the ability of focal company to differentiate products. Secondly, supplier involvement during the design phase can provide access to suppliers’ new technologies, which may be of strategic importance for future product development activities. For example, the focal company can align the technologies with key suppliers. Finally, the transfer of specific solutions and knowledge during the collaboration to the other projects will benefit the focal company.

Ogot and Kremer [21] classified the design stages into four phases: problem definition, conceptual design, preliminary design, and detailed design. Table 1 illustrates the possible supplier involvement activities [22] at these periods. Suppliers can support the formation of the product architecture at the conceptual design stage. Tenneti and Allada [24] presented a robust supplier set selection method in supporting various needs of product architecture over a planning horizon in response to the challenge of mass customization. Taguchi’s quality loss function and Ant Colony Optimization (ACO) method are applied to evaluate various product architectures for minimum total acquisition costs while selecting suppliers. Gökhan et al. [26] developed a mixed-integer program that considered the impact of supply chain decisions on cost, lead time, and demand satisfaction to achieve an overall profit at the product detail design stage. However, the product, in this study, 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 accounted for.

Fixson and Park [27] and Itoh [12] claimed that integral architecture is a better choice in product design since it optimizes the performance of a product at the time it is first introduced into the market. To better support this integral product architecture, the vertical integration strategies of a supply chain might be superior because component technology, design, and management of specifications are performed within a company under a vertical integration strategy. As the product matures and customers are satisfied, the product’s modular architecture will be more competitive in response time and cost. Accordingly, a horizontal integration strategy will be more compatible because components are standardized and different companies have the capability to specify, manufacture, and assemble them. To maximize profit, the focal company needs to control the core capability.

Table 1. Supplier Involvements During Design Stages [21-22]

<table>
<thead>
<tr>
<th>Design Stages</th>
<th>Supplier Involvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem definition</td>
<td>Establish specifications, Avoid ambiguity and information distortion, Identify early changes</td>
</tr>
<tr>
<td>Concept Design</td>
<td>Key product and process technologies, Product architecture, Contribute key ideas/concepts/critical components, Establish interfaces between product subsystem(s)</td>
</tr>
<tr>
<td>Preliminary &amp; Detailed design</td>
<td>Selection of proprietary parts and components, Tolerance design, Prototype testing and demonstration, Design for manufacturability, Material selection &amp; Bill of Materials (BOM)</td>
</tr>
<tr>
<td>Production Design</td>
<td>Tooling design, Design for manufacturability, Quality control and assurance, Raw materials</td>
</tr>
</tbody>
</table>

As illustrated by the literature review in this section, 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 the optimal component acquisition and possible supply chain alternatives can be identified and evaluated.

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. Product architecture is the key to achieve this. As Figure 2 shows, product architecture can represent as a set of functions that are generated by components. These components are manufactured by suppliers. Here, we view the focal company as one of the suppliers. Accordingly, the production process of these components should consider the manufacturability issues.

The proposed method has four steps. First, the functional requirements of a product are defined and decomposed into the most basic sub-functions to form an Energy-Material-Signal (EMS) model. Second, a repository is utilized to synthesize potential components of all sub-functions, providing multiple options for the conceptual design. These concepts are evaluated using a Design for Assembly (DfA) index and then modularized with the Decomposition Approach. The final step filters the design concepts to a selected few, and the design concept with the best DfA score will be selected. This design concept will then be compared to the other selected few using a graph theory based search. The search consists of a Branch and Bound method, which aims to optimize the best product architecture as well as the supply chain.

Indeed, graph theory has been used widely in engineering design. For example, the component modularity has been represented using a graph [23], tree and forest representations were used to represent a functional design artifact and its idle condition [28]. Product family designs were shown where modules are vertices [25]. Variant derivation is achieved by applying a series of operations to the starting graphs via attaching, removing, swapping, and/or scaling various modules to modify the base product. Relationships among product development processes form a process net [29]. Processes of product development are denoted as vertexes, where directed edges represent the time sequence among processes. Core processes are identified and optimized to improve the performance with minimum efforts. Effort flow analysis based on graph theory is proposed to achieve design for assembly to reduce the number of parts in a product, and hence assembly operations, procurement costs, and cycle time to increase profit potential [30]. Kuo [31] proposed a design...
for disassembly method, which can disassemble a product systematically and economically at the product design stage.

There are also some supply chain related research efforts that incorporated graph theory. The agility of a supply chain is measured with a digraph [32]. The agility index measures how good an enterprise can respond to changes in a supply chain network. The supply chain is also modeled as a Petri net in Drzymalski and Odrey [33], where processes are vertices and edges are transitions among these processes. Attributes such as time and cost are embedded in the edges. The Petri net serves as a supervisory control tool and performance measure of total supply chain system. Lim and Wang [34] apply a graph coloring method for uncertainty management in a supply chain.

The advantages of graph theory methods are visual and intuitive. Some studies applied it on product design and others on supply chain management. Despite these, however, no graph theory method, which simultaneously considers both product design and supply chain design, has been reported. This finding also motivates the development of a graph based method that can integrate supply chain decisions at the product design phase so that the optimal component acquisition and possible supply chain alternatives can be evaluated and determined. Below we explain the flow of the methodology.

### 3.1 Software Framework

In this study, a software framework [35], developed by Java Swing within the NetBeans IDE 6.1 programming environment, has been employed. MySQL database is used for storing all the various database tables within the design repository and Java Database Connectivity (JDBC) is used to open MySQL tables within the Java environment.

In the software, first the Energy-Material-Signal (EMS) model is applied to present the functions of the whole product. This model is obtained by decomposing the overall function of the product into simpler sub-functions and flows, which are generally described in a verb-object form. These sub-functions and flows are obtained from a standard set of vocabulary referred to as a functional basis. Then, the generated options for each sub-function are input to a design repository. A design repository can be defined as a heterogeneous product design database in which various design solutions can be searched and reused. Design repository is selected as a product design tool for Small and Medium size Enterprises (SME) because of its flexibility and knowledge management capabilities.

The software filters through all potential design combinations using Design for Assembly (DfA) as the criterion. The purpose of DfA is to consider the assembly problems in the early phases of product design, which can increase the productivity significantly without any investment. In this study, 13 criteria [36-37] are collected and evaluated from the perspectives of the assembly, component, and process properties. The formula for calculating the DfA index is as follows:

$$\text{DfA index} = 10 \left( \frac{\sum P_i - \sum V_{\text{min},i}}{\sum V_{\text{max},i} - \sum V_{\text{min},i}} \right)$$

Here,
- \(P_i\) : point value for each criterion, \(i = 1, \ldots, 13\)
- \(V_{\text{min},i}\) : minimum value for each criterion
- \(V_{\text{max},i}\) : maximum value for each criterion

The calculated DfA index can have a value from 0 to 10, with 0 being the most favorable value for ease of assembly and 10 being the worst.

Afterwards, the Decomposition Approach (DA) [38], which is a matrix based methodology, is applied to modularize the design concepts. There are two matrices utilized in this method: an interaction matrix and a suitability matrix. An interaction matrix represents the interactions between the components, while the suitability matrix represents the suitability for inclusion in a module. The interaction matrix can be generated by analyzing the functional rules. These two matrices combine as a modularity matrix. The suggested modules will be presented after seven steps, namely, triangularization, rearrangement, combination, deletion, duplication, classification, and termination. The concepts that have the best DfA scores will be selected.

### 3.2 Graph Theory Based Optimization

We consider the product architecture as a spanning tree \(G (v, w)\), where \(v\) is a node and \(w\) is an edge. A spanning tree is a graph where all vertices (nodes) are connected [39-40]. In the \(G (v, w)\) representation, \(v\) not only represents the module or component of a product, but also supplier(s) in the supply chain. \(w\) is the hierarchy relation of the component and its suppliers.

The Branch and Bound (BB) method [41] is applied to summarize and aggregate the supply chain assembly, transportation and inventory costs. BB compares the minimum value every time it reaches the bottom node. If the current value of the current concept is larger than the minimum value, then this product architecture will be labeled as searched. Otherwise, it will become the new minimum value until all concepts are searched. When the search is completed, the node with minimum supply chain index value is the optimal concept. The flow of search procedure is shown in Figure 3.

### 4 CASE STUDY

We use a bike case study to demonstrate the methodology. The general architecture of a bike can be broken down as shown in Figure 4. The components of the first level are structure, braking system, transmission system, and the 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 effort and environmental consideration. The EMS model considers a total of seven components and functions, excluding the motor.

The supply chain structure of a bike can be described in four layers. The upstream layer is sub-suppliers, which provide components. The second layer contains suppliers who assemble components/modules. The next one is the focal company, which focuses on the final assembly process and might manufacture key components. Finally, the last layer is distributors who set up the market channels and provide services to customers. For example, in the U.S. mass market distributors include Walmart and Target, which emphasize the market segment with unit prices lower than $250 [42]. Independent bike distributors and sports stores, on the other hand, sell specialized bikes in niche market areas. The U.S. bicycle industry was a $6 billion industry in 2008 [42]. In addition, road bike sales occupied 30.6% of the market share in 2005 [43], which is the biggest segment of the market.

In this case study, X-bike is a new bike company located in central Pennsylvania. The purpose of this design is to attack the low-end road bike market segment where the price is in the range of $60 to $100 USD. The transportation speed from upstream players to downstream players in the supply chain network is 100 mile/hr. The unit transportation cost is $0.001 USD, and the unit inventory holding cost is $0.05 USD. In addition, the planned total quantity of the final product is 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.
4.2 Design Repository and Modularization

The functional rules in the EMS model are input separately into the design repository. Every component is associated with a functional rule and evaluated using the DfA index. After all functional rules and components have been input, design concepts can be generated. The user needs to input the EMS model of a complete product as shown in Figure 6. All possible design concepts will be generated automatically. In this case, 64 concepts with DfA scores are selected as shown on the left part in Figure 7. The DfA index serves as a filter screening for the better design concepts.

A set of filtered concepts is further modularized using the DA to generate various viable product architectures. In our case, the possible components of the bike are as follows: (A) comfortable saddle, (B) steel frame with suspension, (C) steel fork with suspension, (D) brake with brake shoes, (E) wheels with plastic spokes, and (F) transmission with freewheels. After DA, a three-module bike architecture in Figure 8 is generated according to the suitability matrix provided on the right in Figure 7.

4.3 Optimization Algorithm: Brand and Bound Search

For the selected product architectures, there might be numerous types of supply chain networks. Figure 9 shows 6 possible supply chain configurations for a 3-module product architecture. Figure 9(a) denotes 6 components are provided by 6 different component suppliers, hence the focal company should also consider the 3 sub-assembly and final assembly processes. Figure 9(b) represents that one supplier can provide 2 components but they are at different modules, therefore focal company can have economies of scale in procurement when compared with (a). The difference between Figure 9(b) and 9(c) is that these 2 components are located in the same module. Supplier G can be viewed as a module supplier because of the capability that supplier G might be able to support sub-assembly of one module and ship module to the focal company. The focal company then only needs to consider 2 sub-assembly and final assembly processes. In the same manner, Figure 9(d) and (e) show two and three module suppliers, accordingly. Figure 9(f) represents a strong supplier that can support manufacturing and sub-assembly of two modules.

The planned total quantity of the final product is 100,000 per month, and the cost structure includes engineering cost, material cost, and manufacturing cost. Due to mass production, manufacturing costs dominate the cost structure. The cost drivers of the manufacturing costs contain batch setup cost, processing cost, and overhead cost. As for the process time, the key manufacturing process of every stage is analyzed [44-46]. In addition, possible bike suppliers are surveyed worldwide [47-49]. In this case, 12 suppliers were carefully selected as candidates for the supply chain partners according to their technology capability. The estimated process cost and time of every component and module are listed in Table 6 based on information from [1, 51].

Branch and Bound Search (BB) method is applied to compute the supply chain performance. The search process begins in the root of the tree, which is the product after final assembly process. It will continue searching adjacent descendant nodes until all nodes are visited. The search travels through the complete bike architecture and summarizes the process cost, transportation cost and inventory cost of this design concept. The $100 is the initial high bound of the BB method. When better (lower) total cost occurs, it will replace current high bound. During the search process, if the total cost of a design concept exceeds current high bound, it will be fathomed and BB will start another design concept until these 64 design concepts are searched through.

4.4 Results and Discussion

The product concept that has the best DfA score and Branch and Bound method are compared regarding the supply chain performance in Table 2. The product architecture along with the supply chain structure is illustrated in Figure 11. The output of Phase I, where only DFA is considered during filtering, has a higher cost (111%) and a longer lead time (222%). In addition, the lead time (120.40 hrs) is longer than the original target of 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 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 cost but also longer lead times. From the management’s vantage point, Phase I solution has to manage five suppliers. At the same time, Phase II solution, where supply chain configuration is also taken into account, only needs to handle four suppliers, potentially reducing operational complexity.

Indeed, prior published work analyzed similar issues. For example, Mikkola and Skjott-Larsen [52] analyzed the interrelated and complementary strategies among mass customization, postponement and modularization while managing supply chain integration; Lau and Yam [50] examined the relationship between product modularization and supply chain design and coordination with an industrial case study; Ro et al. [53] pointed out that modularity accompanied with reorganization of enterprises and supply chain structures are adopted in the US auto industry. With the presented approach in this paper, we overcome one of the major drawbacks of lean supply chains – reduced flexibility – through incorporation of a modular architecture. The new supply chain proposed is a vertical specialization network between focal company and suppliers. It forms a virtual organization that keeps the low cost level while maintaining quick response time. Selldin and Olhager [19] described this situation as a supply chain frontier, where a company can design its supply chain to be both physically efficient and market responsive while maintaining its profitability.

### Table 2. Comparison of Results

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process cost ($USD)</td>
<td>$85.00</td>
<td>$80.00</td>
<td>$5.00</td>
</tr>
<tr>
<td>Transportation cost ($USD)</td>
<td>$1.55</td>
<td>$0.74</td>
<td>$0.81</td>
</tr>
<tr>
<td>Inventory cost ($USD)</td>
<td>$10.52</td>
<td>$6.55</td>
<td>$3.97</td>
</tr>
<tr>
<td>Total cost ($USD)</td>
<td>$97.07</td>
<td>$87.29</td>
<td>$9.78</td>
</tr>
<tr>
<td>Difference in percentage</td>
<td>111.20%</td>
<td>100%</td>
<td>11.20%</td>
</tr>
<tr>
<td>Total lead time (HR)</td>
<td>120.40 hr</td>
<td>54.20 hr</td>
<td>66.20 hr</td>
</tr>
<tr>
<td>Difference in percentage</td>
<td>222.14%</td>
<td>100%</td>
<td>122.14%</td>
</tr>
<tr>
<td>Number of suppliers</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

With reference to the case study, we note that the upstream and downstream suppliers are geographically close to each other. The 13 enterprises can be clustered into three areas: East Asia, the Great Lakes, and California. This indicates that the trend of supply chain design and integration can bring competitive advantage to a company, and responds to the clustering effect coined by Michael Porter [54]. Attesting to this, Chen et al. [55] studied the bicycle industry in Taiwan and indicated the geographical proximity not only reduces transaction costs among the firms but also increases the cooperation and efficiency between manufacturers and their suppliers. The cooperative but competitive relationship among suppliers and manufacturers transfers to the constructive mechanism that enhances the competitive edge of all partners in this network.

The design repository in this research is a platform based database for SMEs to generate the new product designs with less time and cost. The frame of current design is steel. New materials such as carbon fiber, titanium alloy, aluminum alloy, magnesium alloy could be considered for different market segments. In addition, the form and aesthetics oriented concepts can also attract new customers.
In addition to the above cited advantages, we would like to acknowledge the limitations of our work. The actual component count of a bike is around 40, but the design repository only selects six key components to illustrate the design concepts. The design repository can further be augmented to house additional components and suppliers. In addition, the interface among components are assumed to be standard and all design concepts are compatible, this might cause problems when two standards appear at the same time, for instance, quick release and screw fasteners. Further, in the current model all variables are deterministic with sufficient information. However, uncertainty surely exists in both product design and supply chain configuration design.

The next step of the model should involve accommodation for uncertainty. The uncertainty might be the replacement of the deterministic cost values with a range of cost while the cost is influenced by numerous factors, e.g., economies of scale or gas price. Furthermore, the current model only considers cost and time. Other criteria such as quality, customers’ preference, and capacity have not yet been discussed. The methodology will be more practical and complete with the incorporation of these criteria. Finally, current method only considers design for assembly (DfA) and design for supply chain (DfSC), and other X factors [56], e.g., sustainability, environment, and recyclability can be further incorporated to benefit both the enterprise and the planet.

Figure 9. Six Potential Supply Chain Configurations

Figure 10. Phase I Result (a) and Phase II Result (b)
The next step of the model should involve accommodation for uncertainty. The uncertainty might be the replacement of the deterministic cost values with a range of cost while the cost is influenced by numerous factors, e.g., economics of scale or gas price. Furthermore, the current model only considers cost and time. Other criteria such as quality, customers’ preference, and capacity have not yet been discussed. The methodology will be more practical and complete with the incorporation of these criteria. Finally, current method only considers design for assembly (DfA) and design for supply chain (DfSC); and other X factors [56], e.g., sustainability, environment, and recyclability can be further incorporated to benefit both the enterprise and the planet.

5. CONCLUSION
In this paper, a methodology for SMEs is provided with the supply chain consideration at the conceptual design phase. The functional requirements of a product are collected and an EMS model is created. A graphical design repository is then applied to generate possible design concepts, and these concepts are evaluated using the DfA index and then are modularized. Singularly considered design for assembly (DfA) and a graph based Branch and Bound Search method with supply chain consideration are compared and discussed. The results demonstrate the benefit of simultaneously optimizing design and supply chain configuration issues. In the methodology presented, a design repository provides flexibility and knowledge management function. SMEs can decide to introduce single or multiple products to market at a time. This decision depends on the demand, budget and other considerations. The knowledge management function can cover for the potential weakness in design power in SMEs. Supply chain consideration can analyze the manufacturing process, transportation cost and lead time of the supply chain execution, and hence, the financial investment on facilities, equipment, and management can save while improving agility.

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 that decision makers can use to analyze, predict, control, and assure the success of both product and enterprise at the design stage. At this time, disclosure of supply chain related information can convey higher flexibility and longer time to prepare and respond to potential adverse impacts. Therefore, a competitive advantage is created. In addition, this method can provide a sensitivity analysis function, which will be a precautionary tool to prevent from potential risk in supply chain execution. Finally, it serves as a communication tool between engineers and the managerial group. Design teams can understand the concerns of the supply chain, and management can connect product design not only at the strategy level but also at the tactical horizon, which will result in a win-win situation for both the focal company and the suppliers.

REFERENCES


