An Investigation on Centralized and Decentralized Supply Chain Scenarios at the Product Design Stage to Increase Performance

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An Investigation on Centralized and Decentralized Supply Chain Scenarios at the Product Design Stage to Increase Performance

Ming-Chuan Chiu and Gül E. Okudan Kremer

***Abstract*—Design for supply chain has become an essential consideration while designing a new product. Previous studies pointed out that early supplier involvement can contribute to the success of the product development and enhance the competitive advantage of the enterprise. However, most of the studies coordinating supplier selection and supply chain configuration make these decisions during the detail design stage, which is the last phase of product design. This research aims to investigate the supply chain scenarios for their relevant performance at the conceptual design stage. The performance of different supply chain scenarios (i.e., centralized and decentralized), are compared and discussed. The results show that the decentralized supply chain scenario is advantageous for the time performance of the supply chain network, whereas the centralized supply chain scenario demonstrates superiority on the cost performance.**

***Index Terms*—Bilevel programming, product design, supply chain design, supplier selection.**

NOMENCLATURE

X_{pi}	Variable indicating component supplier i is selected for process p (binary variable).
X_{pj}	Variable indicating that subassembly supplier j is selected for process p (binary variable).
X_{pk}	Variable indicating that final assembly location k is selected for process p (binary variable).
Y_p	Variable indicating that process p is performed (binary variable).
L_MAX	Longest acceptable lead time for the supply chain.
L_MIN	Shortest acceptable lead time for the supply chain.
C_MAX	Highest acceptable product cost.
T_{sp}	Entity value of the transition matrix. As shown in Table II, $T_{sp} = 1$ when $s = 1$ and $p = 1$. In the same manner, $T_{sp} = -1$ when $s = 2$ and $p = 1$.
C_{pi}	Unit cost of component supplier i in process p.
C_{pj}	Unit cost of subassembly supplier j in process p.
C_{pk}	Unit cost of final assembly k in process p.
L_{pi}	Process time for component supplier i in process p.
L_{pj}	Process time for subassembly supplier j in process p.
L_{pk}	Process time for final assembly k in process p.
LEAD	Total lead time for supply chain network.
$\mathrm{TRANCX}_i\mathrm{X}_j$	Transportation cost between component supplier i and subassembly supplier j.
$\mathrm{TRANCX}_j\mathrm{X}_k$	Transportation cost between subassembly supplier j and final assembly supplier k.
$\mathrm{TRANTX}_i\mathrm{X}_j$	Transportation time between component supplier i and subassembly supplier j.
$\mathrm{TRANTX}_j\mathrm{X}_k$	Transportation time between subassembly supplier j and final assembly supplier k.
$\mathrm{INVX}_i\mathrm{X}_j$	Inventory cost of module supplier j.
$\mathrm{INVX}_j\mathrm{X}_k$	Inventory cost of final assembly supplier k.

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I. INTRODUCTION

SUPPLY chain design and management is one of the most critical issues facing enterprises today. The purpose of supply chain management is to connect and harmonize the flows between upstream and downstream players during the supply flow execution for efficiency. It can provide a competitive advantage for a company through increasing flow performance and reducing operational cost.

A product can be viewed as a physical entity that performs a specific function or provides a service. Its components are functional units that cooperate to accomplish distinct objectives. Product architecture is the schema of these functional units, illustrating the physical building blocks and the ways in which they interact. Fixson [1] pointed out the importance of product architecture in product, process, and supply chain decisions. A multidimensional framework was developed to model product architecture characteristics such as component commonality, product platforms, and product modularity and to investigate their impacts on the supply chain network. Essentially, Fixson's work [1] confirmed that the product architecture could link decisions across different domains. Relevant to this, Yassine and Wissmann [2] indicated that product architecture has broad implications on engineering design, process design, systems engineering, marketing, and organizational science perspectives. It serves as the link between customer and enterprise, managing the process and portfolio design that directs the change, variety, performance, and manufacturability of the product [2]–[4].

New products, which are introduced to the market within five years, might account for up to 33% of company sales [5]. However, According to a survey in 2004 [6], more than 40% of new products failed to launch. Researchers have pointed out that a lack of coordination between a product and its supply chain is one of the key reasons for this failure [5]–[7]. Building on these observed failures, Butler *et al.* [8] indicated that new products have different supply chain configurations due to demand patterns, customer locations, and market sizes. Furthermore, product design is argued to support a leaner and more agile supply chain by postponing the point of differentiation [9].

Despite the significant bidirectional implications of product and supply chain design, most of the research on design and management of supply chains emphasizes production and distribution. Only few efforts integrated the product design and supply chain design decisions at the product design stage, but starting at the detail design stage. The objective of our overall research is to develop a method that can combine and streamline the product design and supply chain configuration problems at an earlier phase during product design. With the disclosure of supply chain related information early on, we intend to introduce higher flexibility and a longer time to prepare and respond to potential downstream challenges. Supporting this objective, Choi *et al.* [49] argued that a supply chain network is a complex adaptive system, and too much control or autonomous actions can obstruct the efficiency of the supply chain. Managers should properly balance the control exerted versus the emergent behavior. In this paper, we specifically study the implications of adopting a centralized or decentralized coordination in a supply chain; this can be seen as studying the level of appropriate control. Although, this topic in itself is not new, our way of evaluating the consequences (i.e., taking into account all potential product design architectures and using a realistic case study) makes it comprehensive and conclusive.

In order to investigate the supply chain performance of various product architectures, we use a mix integer programming (MIP) model for the centralized supply chain. Then, we extend the MIP model to a bilevel programming model. The extended model has two levels of decision makers: an upper level player (leader) and a lower level player (follower). A key difference between the MIP model and the bilevel programming model is that the former selects all tiers of suppliers in the supply chain network (module suppliers and component suppliers in this study), while the latter selects only the first-tier suppliers. Hence, in applying the bilevel model, the focal (OEM) company determines its module suppliers, who in turn select their component suppliers.

In the following sections, we first introduce the relevant literature, and then describe the method with which we analyze the two supply chain management scenarios. The comparisons are then made using a case study, which was developed in collaboration from Cannondale Bicycle Corporation.

II. Literature Review

A. Importance of Product Design and Supply Chain Design Coordination

The importance of the coordination between the product and its supply chain has been discussed in the literature. Fisher [7] posited that matching a product type to the appropriate supply chain type could create a high likelihood of success. In Fisher's model, products are categorized into two types: functional and innovative. A functional product has stable demand, a low profit margin, and many competitors (e.g., staple items). Conversely, an innovative product refers to a newly introduced and differentiable product with versatile demand. Likewise, supply chains can be classified as either efficient or responsive. Efficient supply chain, which is also called as "lean supply chain", emphasizes making and delivering a low-cost product (with cost as the major concern), while responsive supply chains, which are known as "agile supply chains," focus on delivering a variety of products quickly in order to achieve a high level of customer satisfaction. For example, matching a functional product and an efficient supply chain is thought to create a high likelihood of success. In support of this, Selldin and Olhager [10] verified Fisher's model for the appropriateness of functional products with physically efficient supply chains based on their field study of 128 companies. Vonderembse *et al.* [12] extended Fisher's framework to hybrid products and supply chains. Hybrid supply chains combine the capabilities of both lean and agile supply chains to create a network that meets the needs of hybrid products. Here, the term hybrid product refers to one with some standard and some innovative product characteristics. Vonderembse *et al.* [12] indicated that supply chains with different features should be carefully coordinated for various types of products and suppliers. In addition, product design strategies should vary based on the supply chain type. For a lean supply chain, a new product design strategy should focus on maximizing product performance while minimizing cost. Since the agile supply chain aims for a high degree of customization, new product design strategies should focus on satisfying individual customer needs. Because a hybrid supply chain has some lean supply chain characteristics and some agile supply chain characteristics, a modular design that can postpone product differentiation would be recommended, as shown in Table I.

Appelqvist *et al.* [11] presented a framework for supply chain management and product design coordination. In this framework, potential strategies for supply chain management are categorized based on if the product or the relevant supply chain is in existence, or to be developed (i.e., existing and new categorization). "Breakthrough" is the most challenging situation to manage, when both the product and the supply chain are newly developed. If a supply chain is new for an existing product, "Reengineering" is suggested to fit the product attributes. On the other hand, a new product design should consider "Design for Logistics" to better suit an existing supply chain.

TABLE I
PRODUCT TYPE AND SUPPLY CHAIN ENGAGEMENT [12]

Supply Chain Type / Factors	Lean	Agile	Hybrid
Definition	Employ continuous improvement to focus on the elimination of waste or non-value-adding steps in the supply chain.	Build the capability to respond rapidly to changing and continually- fragmenting global markets.	Achieve some degree of customization in the back-end of the supply chain and "leanness" in the front-end.
Product Type	Standard Product	Innovative Product	Hybrid Product
Supplier Selection	Supplier attributes consist of low cost and high quality.	Supplier attributes consist of speed, flexibility and quality.	Supplier attributes consist of low cost and high quality, along with the capability for speed and flexibility when required.
Product Design Strategies	Maximize performance and minimize cost.	Design product to meet individual customer needs.	Apply modular design in order to postpone product differentiation for as long as possible.

The scope of design for logistics was broadened to the design for supply chain management (DfSCM) by Lee and Sasser [9] with the aim of designing products and processes in order to more effectively manage supply chain cost and performance. The DfSCM utilizes product line structure, the bill of materials, and product customization processes in order to optimize logistics costs and customer service performance. Lee and Sasser's quantitative model [9] covers manufacturing and logistics costs, and provides insightful information when negotiating process and design requirements with strategic partners.

B. Modular Product Design

The two main categories of product architecture are modular and integral [3]. Modular products decompose the overall functionality of a product into subfunctions, which are embodied in separate product modules. These modules are designed to be independent, standardized, and interchangeable. Within modular designs, there are two types of components: common and variant. Common components are the static portion of product architecture; they are reusable and thereby they can save design effort. Correspondingly, variant components can help fulfill dynamic customer requirements at a given service level [13]–[15]. Product variety can be realized by substituting variant modules, and thus improving economies of scale in production. In addition, quality problems can be isolated at the modular level, which eases the burden of future maintenance and repair. Another advantage of modularity is that it enables concurrent design activities, since it decouples the product into small development tasks. This capability shortens the overall product development time. To realize modularity, however, interface standardization is necessary [3], [16].

Conversely, integral product architecture views the product as a whole. It aims to achieve full optimization of a new product without risking over- or under-design of product modules in order to conform to a range of different products. Integral product design may provide better differentiation, as components are designed specifically for a particular product. One integral design methodology is the design for manufacturing and assembly, a technique which emphasizes a reduction in the number of components and the inclusion of multifunctional parts [17]. However, the modification of one component usually affects another, and hence may result in a significant increase in redesign effort.

C. Product Design and Supply Chain Design Coordination Methodologies

Lau *et al.* [50] conducted an empirical study of supply chain and product co-development and suggested that managers should involve suppliers, internal functional units, and customers early at the product design stage to accomplish better performance. Sharifi *et al.* [51] presented that agile supply can be achieved by simultaneously having "design of" the supply chain holistically and "design for" supply chain at the product design stage. Similarly, Fine *et al.* [18] discussed the concept of the integral supply chain and the modular supply chain. An integral supply chain network has high formalization, centralization, and complexity, and its members are in close proximity to each other (where proximity is measured along the four dimensions of geography, organization, culture, or electronic connectivity). Conversely, a modular supply chain is relatively dispersed geographically and culturally, with few close organizational ties and modest electronic connectivity. They argue that integral products should be matched with integral supply chains, while modular products should be matched with modular supply chains to ensure optimal efficiency.

Fine *et al.* (2005) developed a goal programming model, which was the first to quantitatively connect products, processes, and supply chains. This model highlighted the importance of matching modular (integral) products to appropriate modular (integral) supply chains. However, a weakness of the goal programming method is the subjective compromise solution it provides, because the weights of goals and changes of goal values are assigned by a decision maker, creating combinations that lead to different results. In addition, Fine et al. assumed that there are conflicts among criteria such as fidelity and cost, which might not be true in a global supply chain network. Furthermore, their research started at the product *selection* phase, after the design concepts had been generated. There is a need to develop a method that begins at the time of product *design* in order to provide the optimal solution based on both

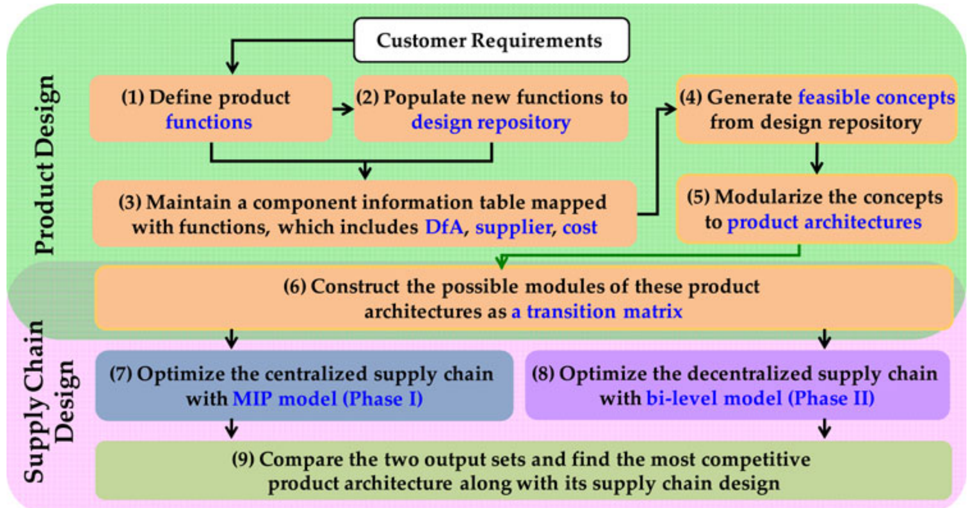

Fig. 1. Overview of methodology.

assemblability and supply chain performance instead of generating a compromising solution among multiple criteria. More recently, Nepal *et al.* [46] proposed a fuzzy logic-based goal programming model to both minimize total supply chain cost and maximize supply chain compatibility, which is an aggregation of structural, managerial, and financial indices; however, this study also fails to consider all possible design options.

According to the literature review provided previously, we assert that only a few studies point out how the supply chain should be shaped at the product design stage. Among these studies, most propose to shape the respective supply chain network at the detail design stage. This finding motivates the idea of integrating supply chain decisions during the conceptual design stage using the product architecture formation, so that optimal component acquisition and possible supply chain alternatives can be evaluated and determined earlier, and suppliers can be involved in the product design process as well as in the supply chain network formation.

III. Proposed Methodology

With an aim to integrate design and supply chain decision making, our proposed method includes both the product design function and supply chain design function. Fig. 1 presents an overview of the method execution. The product design function includes functional requirements, assemblability evaluation, concept generation, and modularization. First, the functional requirements of a product are defined and decomposed into their most basic subfunctions to form an energy-material-signal (EMS) model (shown with step (box) (1) in Fig. 1). Then, a repository is utilized to synthesize the potential components of all subfunctions, providing multiple options for the conceptual design [see Fig. 1(2)].These components are evaluated using a design for assembly (DfA) index [see Fig. 1(3)]. According to the functions required of a product, feasible design concepts are generated [see Fig. 1(4)], and then modularized with the decomposition approach [see Fig.1 (5)].

The key of integrating supply chain and product design decisions is product architecture, which can be interpreted in several different ways. It can represent the functions of the product, the components that execute the functions, and/or the suppliers who produce the components, as shown in Fig. 2. A graph-based transition matrix is applied to represent various product architectures and to connect product design and supply chain design functions. Supply chain design function comprises of the graph theory-based transition matrix [see Fig. 1(6)], a MIP model, a bilevel programming model, and the bootstrap technique. The comparison of supply chain performance consists of two phases. Phase I [see Fig. 1(7)] presents the centralized supply chain scenario, and phase II involves decentralized supply chain scenario [see Fig. 1(8)].

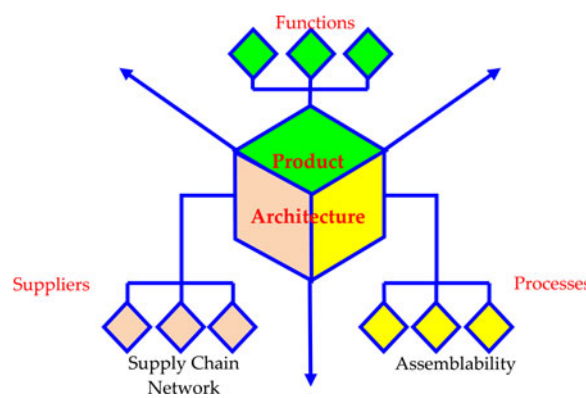

Fig. 2. Foundation of the proposed method.

In phases I and II, all possible architectures of the product concept are analyzed and arranged in a transition matrix. A transition matrix provides a representation that treats the assembly sequences of a whole product as bipartite graphs. An MIP model that can compute the overall supply chain cost is connected with the transition matrix. The combination of the transition matrix and the MIP model will optimize product architecture as well as the supply chain network by selecting a set of suppliers that can produce the entire product. The optimized supply chain performance regarding lead time and total cost of the design concept is generated in phase I, which represents a centralized supply chain network. The method adopted for

TABLE II
TRANSITION MATRIX WITH POSSIBLE ASSEMBLY PROCESSES

Process(P) / State (S)	Final Assembly		Module Assembly									Component Process					
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*
1.Final Product	1	1															
2.Module ABC	-1		1		1	1											
3. Module DEF	-1			1			1										
4. Module AB		-1			-1			1									
5. Module BC						-1			1								
6. Module CD		-1								1							
7. Module EF		-1					-1				1						
8. Component A			-1			-1		-1				1					
9. Component B			-1					-1	-1				1				
10. Component C			-1		-1				-1	-1				1			
11. Component D				-1			-1			-1					1		
12. Component E				-1							-1					1	
13. Component F				-1							-1						1

phase II is a bilevel programming model extended from phase I to demonstrate a decentralized supply chain network. The difference between the centralized and decentralized networks is that a centralized network can determine all tiers of suppliers, while a decentralized network only assigns first-tier suppliers (who arrange their own suppliers). To identify the differences of supply chain configurations under cost and lead-time minimization situations, the performance of all design concepts in terms of cost and lead time are computed and compared using the bootstrap technique [see Fig. 1(9)].

A. *Product Design Function*

An in depth discussion on the product design function was provided elsewhere [19] and hence is not repeated here. However, as part of the case study implementation sufficient details are provided.

B. *Construction of Centralized Supply Chain Model*

The construction of a centralized supply chain model includes two components: a transition matrix that connects the product design and the supply chain design using product architecture, and an MIP model that optimizes the supply chain performance.

The transition matrix, as it is used here, is intended to analyze the disassembly sequence with the purpose of optimizing product profit at the end of its life cycle [20]–[23]. In this matrix, product architecture is viewed as a graph where the nodes are components and the edges are connections between components. While assembling the product, all possible states of the subgraphs or subassemblies are denoted as a stage set ($\boldsymbol{P}$). The assembly process or action that results in a transfer between two subassemblies is represented as an edge (Set $\boldsymbol{S}$). The whole assembly sequence will generate a new bipartite graph. A ($\boldsymbol{P} \times \boldsymbol{S}$) transition matrix is summarized to describe the relationship of subassemblies and related processes. Destruction of two or more original subassembly states will create one new subassembly state. The destructed subassembly is assigned a value of -1, while created subassemblies are denoted with $+1$. These values will be inserted into columns of the specific action, while all other unrelated states will remain empty or at zero.

Take Table II as an example; column 2 denotes the assembly process #1 with which module ABC and DEF are assembled as the final product. During the process, module ABC and DEF vanish indicated by values of -1, and the final product is produced with a value $+1$. Accordingly, the module ABC is formed in the assembly process #3 by components A, B, and C. Transition matrix utilizes values of $+1$ and -1 to control if an assembly state exists or not in (3). For example, processes #1 and #2 are mutually exclusive assembly processes of the final product. At the time process #1 is selected ($y_1 = 1$), state 2 (module ABC) and state 3 (module DEF) become active. In the same manner, the state 2 (module ABC) can be formed by either processes #3, #5, or #6, which are different assembly processes. Therefore, processes #1 and #3 can coexist. In the same manner, assembly process #2 represents the process where modules AB, CD, and EF are destructed when final product is constructed. When process #2 is active ($y_2 = 1$), processes #8, #9, and #10 coexist as well. Here, the transition matrix provides a means to make sure that all components are assembled, and one best assembly process is selected among all possible processes. Final assembly process #1 is mutually exclusive of process #2 since it represents a different product architecture with different modules, although it assembles the same final product. Equation (2) describes the coexistence of inflows and outflows during the component, module, and final product phases. In addition, the number of parts will decrease during assembly. Therefore, the sum of the entity values will be smaller than 0 in every process; this is represented by (3).

The advantages of a transition matrix are: 1) its ability to present all possible assembly sequences of the whole product at the product level, module level, and component level in a simple matrix; and 2) that the entity values of $+1$ and -1 will ensure the product is correctly assembled into components and disassembled only once. Therefore, the matrix is used as the foundation for the MIP model that constructs a unique and complete product architecture, and a supply chain network after optimization.

C. *Mathematical Formulation of the MIP Model*

The goal of the MIP model [19] is to examine the supply chain performance of design concepts with three tiers, which are component, module, and final product levels. Supply chain input comprises costs and time information of processes, suppliers, transportation, and inventory. Detailed mathematical formulation is summarized as follows:

1) Mathematical Formulation of Centralized Supply Chain: The objective function in (1) is to minimize total supply chain costs that include process cost, transportation cost, and inventory cost. The process cost summarizes costs from component level, subassembly level to final assembly level. Transportation cost includes those between upstream (input state) suppliers and downstream (output state) suppliers for all processes. Inventory cost accounts for the front-end inventory of selected suppliers based on the lead time and other issues. This study includes two inventory types: component inventory (before module suppliers are involved in the process) and module inventory (before final assembly suppliers are involved in the process). Equations (2) and (3) denote constraints of transition matrix that make sure that a complete product architecture is built and no redundant components are selected. Every process is assigned to only one supplier that is capable of completing process *p*. The supplier completing the process will be marked as 1 and others as 0. Equations (4)–(6) represent this mathematically. Lead time refers to the total time required to manufacture a final product which includes: component manufacturing, module assembly, final assembly, transportation, wait time, inspection, and other tasks. The maximum lead time is the maximum value that exists among all possible routes. Lead time serves as an agility measure for the supply chain network. The mathematical formulation is provided in (7). Equations (8) and (9) serve as constraints for decision making. When there is a tradeoff between cost and time, a decision maker can regulate the acceptable total lead-time range to find the corresponding total cost. Cost constraints for a supply chain can be expressed using (10), which identifies the budget control for a product. All variables in (11) are binary variables. Other variables in (12) are positive values.

$$\begin{aligned}\text{Min}\quad F(x) = &\sum_p\sum_i \mathrm{C}_{pi} * \mathrm{X}_{pi} + \sum_p\sum_j \mathrm{C}_{pj} * \mathrm{X}_{pj}\\ &+\sum_p\sum_k \mathrm{C}_{pk} * \mathrm{X}_{pk}\\ &+\sum_p\sum_i\sum_j \mathrm{TRANCX}_i\mathrm{X}_j * \mathrm{X}_{pi} * \mathrm{X}_{pj}\\ &+\sum_p\sum_j\sum_k \mathrm{TRANCX}_j\mathrm{X}_k * \mathrm{X}_{pj} * \mathrm{X}_{pk}\\ &+\sum_p\sum_j\sum_k \mathrm{INVX}_i\mathrm{X}_j * \mathrm{X}_{pj}\\ &+\sum_p\sum_j\sum_k \mathrm{INVX}_j\mathrm{X}_k * \mathrm{X}_{pk} \qquad (1)\end{aligned}$$

such that

$$\sum_p \mathrm{T}_{sp} * \mathrm{Y}_p \geq 0 \quad \forall p \in P \qquad (2)$$

$$\sum_s \mathrm{T}_{sp} \leq 0 \quad \forall s \in S \qquad (3)$$

$$\sum_i \mathrm{X}_{pi} = 1 \quad \forall p \in P \qquad (4)$$

$$\sum_j \mathrm{X}_{pj} = 1 \quad \forall p \in P \qquad (5)$$

$$\sum_k \mathrm{X}_{pk} = 1 \quad \forall p \in P \qquad (6)$$

$$\begin{aligned}\mathrm{LEAD} = \mathrm{Max}\{&\mathrm{X}_{pi}*\mathrm{L}_{pi}+\mathrm{TRANTX}_i\mathrm{X}_j+\mathrm{X}_{pj}*\mathrm{L}_{pj}\\ &+\mathrm{TRANTX}_j\mathrm{X}_k+\mathrm{X}_{pk}*\mathrm{L}_{pk}\} \qquad (7)\end{aligned}$$

$$\mathrm{LEAD} \leq \mathrm{L\_MAX} \qquad (8)$$

$$\mathrm{LEAD} \geq \mathrm{L\_MIN} \qquad (9)$$

$$\mathrm{C}_1 + \mathrm{C}_2 + \mathrm{C}_3 \leq \mathrm{C\_MAX} \qquad (10)$$

$$\mathrm{Y}_p, \mathrm{X}_{pi}, \mathrm{X}_{pj}, \mathrm{X}_{pk} \in \{0, 1\} \qquad (11)$$

$$\mathrm{L\_MAX}, \mathrm{L\_MIN}, \mathrm{C\_MAX} \geq 0. \qquad (12)$$

Phase I represents the centralized supply chain scenario using the transition matrix and the MIP model. The output of phase I is the design concept that optimizes its supply chain performance under cost minimization condition.

D. Construction of the Decentralized Supply Chain Model

For a decentralized supply chain scenario where a focal company and suppliers make their own decisions separately, the original MIP model becomes inappropriate. Here we extend the MIP model to a bilevel programming model. Later, we present the reformulation of the MIP model to a bilevel model, and then describe the solution techniques applied.

In general, a bilevel programming problem, as its name suggests, has only two levels: the upper level (leader) and the lower level (follower) [24]. Bilevel programming originated from hierarchical optimization (or multilevel programming), where a variable subset is constrained in order solve a given optimization problem that is parameterized by the remaining variables. Wen and Hsu [25] reviewed and summarized the characteristics of bilevel programming problems. First, decision-making units interact and exist within a predominantly hierarchical structure. Decisions are executed sequentially, from upper to lower level, and although the lower level (follower) can exert influence, it cannot control upper level (leader) decisions. The follower executes its policies after (and based on) leader decisions. Each decision-making unit optimizes its objectives independently of other units, but each is affected by the actions and reactions of other units. Furthermore, external influences on a decision maker's problem can be reflected in both the objective function and the set of feasible decisions. Given these properties, we find the bilevel programming to suit our investigation of the decentralized supply chain scenario.

Gümüş and Floudas [26] developed a global optimization method for mixed-integer bilevel programming problems, and we adopt their approach here. The leader in the bilevel model is the focal company. The objective function of the focal company is to minimize the total cost in a decentralized supply chain. Cost items include the final assembly process, module transportation, and module inventory cost. These items are summarized as *UPCOST*. Accordingly, the rest of the costs in the objective function of the MIP model are denoted as *DOWNCOST*, including the cost of the component manufacturing process, the module assembly process, component transportation, and component inventory. The mathematical formulation of the bilevel programming model based on the MIP is:

$$\text{Min} \quad F(x) = UPCOST \tag{13}$$

where

$$\begin{aligned} UPCOST = &\sum_p \sum_k \mathrm{C}_{pk} * \mathrm{X}_{pk} \\ &+ \sum_p \sum_j \sum_k \mathrm{TRANCX}_j \mathrm{X}_k * \mathrm{X}_{pj} * \mathrm{X}_{pk} \\ &+ \sum_p \sum_j \sum_k \mathrm{INVX}_j \mathrm{X}_k * \mathrm{X}_{pj} * \mathrm{X}_{pk} \end{aligned} \tag{14}$$

s.t.

$$\sum_p \mathrm{T}_{sp} * \mathrm{Y}_p \geq 0 \quad \forall p \in P \tag{2}$$

$$\sum_s \mathrm{T}_{sp} \leq 0 \quad \forall s \in S \tag{3}$$

$$\sum_k \mathrm{X}_{pk} = 1 \quad \forall p \in P \tag{4}$$

$$\begin{aligned} \mathrm{LEAD} = \mathrm{Max}\{&X_{pi} * \mathrm{L}_{pi} + \mathrm{TRANTX}_i \mathrm{X}_j \\ &+ \mathrm{X}_{pj} * \mathrm{L}_{pj} + \mathrm{TRANTX}_j \mathrm{X}_k \\ &+ \mathrm{X}_{pk} * \mathrm{L}_{pk}\} \end{aligned} \tag{7}$$

$$\mathrm{LEAD} \leq \mathrm{L\_MAX} \tag{8}$$

$$\mathrm{LEAD} \geq \mathrm{L\_MIN} \tag{9}$$

$$\mathrm{C}_1 + \mathrm{C}_2 + \mathrm{C}_3 \leq \mathrm{C\_MAX} \tag{10}$$

$$\mathrm{L\_MAX}, \mathrm{L\_MIN}, \mathrm{C\_MAX} \geq 0 \tag{11}$$

$$\mathrm{Y}_p, \mathrm{X}_{pi}, \mathrm{X}_{pj}, \mathrm{X}_{pk} \in \{0, \quad 1\} \tag{12}$$

$$\text{Min} f(x) = DOWNCOST \tag{15}$$

where

$$\begin{aligned} DOWNCOST = &\sum_p \sum_i \mathrm{C}_{pi} * \mathrm{X}_{pi} + \sum_p \sum_j \mathrm{C}_{pj} * \mathrm{X}_{pj} \\ &+ \sum_p \sum_i \sum_j \mathrm{TRANC}_{ij} * \mathrm{X}_{pi} * \mathrm{X}_{pj} \\ &+ \sum_p \sum_i \sum_j \mathrm{INVX}_i X_j * X_{pi} * \mathrm{X}_{pj} \end{aligned} \tag{16}$$

s.t.

$$\sum_p \mathrm{T}_{sp} * \mathrm{Y}_p \geq 0 \quad \forall p \in P \tag{2}$$

$$\sum_s \mathrm{T}_{sp} \leq 0 \quad \forall s \in S \tag{3}$$

$$\sum_i \mathrm{X}_{pi} = 1 \quad \forall p \in P \tag{5}$$

$$\sum_j \mathrm{X}_{pj} = 1 \quad \forall p \in P. \tag{6}$$

The optimization technique of bilevel programming applied in this research is adopted from Sherali and Adams [27], [28] and from Gümüş and Floudas [29], [30]. The objective of the solution algorithm is to transfer these two objective functions to a single objective function and solve it with less computational burden. The process includes three steps: 1) reformulation, 2) linearization, and 3) the application of Karush–Kuhn–Tucker (KKT) conditions and complementarity.

The goal of the reformulation and linearization technique (RLT) is to generate a continuous convex hull projection [26]–[28] for the feasible space of the inner (lower level) problem. When that space can be projected as a convex hull, KKT optimality conditions can be applied to the inner problem. The inner objective function *f(x)* and inner constraints are transformed into a new set of additional constraints in the model. Hence, the bilevel programming model originally having two objective functions can be transformed to a single-level optimization problem, and then can be solved using optimization tools.

The feasible region of the lower level (inner) problem can be generated with the form (17) as shown at the bottom of the page, where the inner problem is parametric in the outer problem variable x. The original purpose of using the RLT technique is to save computational loading by projecting the original problem domain onto a hierarchy of polyhedral representation, in which the extreme points of the representation are the same as those in the original problem domain. The mathematical proof for this can be found in Sherali and Adams [27]. The way in which RLT converts the constraints set into a polyhedral representation is by multiplying them with a suitable n_y degree (given any level $n_{\mathrm{y}} \in \{0, \ldots, n\}$) of polynomial factors involving the n binary variables and their complements, and subsequently linearizing the resulting problem through appropriate variable transformations. Sherali and Adams [28] defined a polynomial factor $F_n(J_1, J_2)$ in following form:

$$F_n(J_1, J_2) = \left\{ \begin{array}{l} \left(\prod_{j \in J_1} y_j \right) \left(\prod_{j \in J_1} (1 - y_j) \right), J_1, J_2 \subseteq N_y \equiv 1, \ldots, n_y \\ \text{s.t.} \qquad J_1 \cap J_2 = \phi, |J_1 \cup J_2| = n_y \end{array} \right\}. \tag{18}$$

$$Y_{\mathrm{IN}} = \left\{ y : \sum_{j=1}^{n} g_{rj}(x) y_j \leq \beta_r, r = 1, \ldots, R_1, \quad \sum_{j=1}^{n} h_{rj}(x) y_j = b_r, r = 1, \ldots, R_2, \quad y : \text{binary} \right\} \tag{17}$$

Using this polynomial factor, the convex hull of the inner problem Y_{IN} is obtained as follows:

Step 1 (Reformulation): The original y is a binary variable, which defines a discontinuous feasible region. It should be transformed into continuous variables to form a convex hull. Following equations are added as two inequality constraints of the form such that

$$y^2 - y \leq 0 \quad \forall j = 1, \ldots, n_y \tag{19}$$

$$-y^2 + y \leq 0 \quad \forall j = 1, \ldots, n_y \tag{20}$$

where $0 \leq y \leq 1$. Note that the constraint is valid only at two points: $y = 0$ or $y = 1$. Every constraint is multiplied, including $0 \leq y \leq 1$, with every factor defined in (18). The resulting set of polynomial relationships includes the constraints representing nonnegativities on all possible factors of degree n_y (i.e., $F_n(J_1, J_2) \geq 0$) for all (J_1, J_2) of order n_y).

Step 2 (Linearization): Linearize the resulting polynomial constraints by substituting z_j for the nonlinear $\prod_{j \in J} y_j$ for each element of set J where $|J| \geq 2$. The linearized expression of any factor $F_n(J_1, J_2)$ is denoted as $f_n(J_1, J_2)$. The following polyhedral set results:

$$Y_{\mathrm{IN}} = \left\{ \begin{array}{c} (y, w) : \left(\displaystyle\sum_{j \in J_1}^{n} g_{rj}(x) y_j - \beta_r \right) f_n(J_1, J_2) \geq 0, \\ r = 1, \ldots, R_1, \\ \left(\displaystyle\sum_{j \in J_1} h_{rj}(x) y_j - b_r \right) f_n(J_1, J_2) = 0, \\ r = 1, \ldots, R_2, \\ f_n(J_1, J_2) \geq 0, \forall (J_1, J_2) \\ (J_1 \cup J_2) \equiv N_y, J_1 \cap J_2 = 0 \end{array} \right\}. \tag{21}$$

The constraint set is defined as

$$\mathrm{conv}(Y_{\mathrm{IN}}) = \{(y, w) : f_n(J_1, J_2) \geq 0 \quad \forall (J_1, J_2) \text{ of order } n_y\}. \tag{22}$$

Equation (22) describes a polytope with all vertices defined by binary values, and characterizes the convex hull of feasible solutions for any linear or polynomial 0–1 programming problem.

Step 3 (Introduce KKT optimality conditions and complementarity): The inner problem is now continuous and linear for the inner variables. As the feasible region of the inner problem can be represented as a convex hull, it can be subjected to KKT conditions. Satisfying KKT conditions is an important step that replaces the objective function of the inner problem with the KKT equations. Hence, the bilevel programming problem is transformed into a single-level problem. KKT condition holds when there is a feasible point y^* in x to be an optimal solution of the inner problem, and there exists (λ^*, μ^*) that satisfy

$$\frac{\partial f}{\partial y*} + \sum_{j=1}^{J} \lambda_j^* \frac{\partial g_j}{\partial y*} + \sum_{i=1}^{I} \mu_i^* \frac{\partial h_j}{\partial y*} = 0 \tag{23}$$

$$h_i(x, y*) = 0 \quad i \in I \tag{24}$$

$$g_j(x, y*) + s_j^* = 0 \quad j \in J \tag{25}$$

$$\lambda_j^* s_j^* = 0 \quad j \in J \tag{26}$$

$$\lambda_j^*, s_j^* \geq 0 \quad j \in J \tag{27}$$

where λ^* and μ^* are the KKT multiplier vectors of the inequality and equality constraints, respectively. The number of constraints and variables increase after the RLT and KKT transformation. The feasible region of the new single-objective problem might not be convex, thus making it very difficult to solve the transformed problem. The complementarity condition constraints involve binary decisions on the set of inner problem active constraints. The set changes when at least one inequality function and its Lagrange multiplier are equal to zero, making it very difficult to solve the transformed problem. To overcome this difficulty, the active set strategy [29] is employed. Based on the underestimation of every term, a convex underestimator for any given differentiable function can be obtained. The purpose of the underestimation is to avoid local optimum. Therefore, the global optimization can be effectively found.

IV. Industrial Case Study

The goal of the proposed methodology is to simultaneously optimize product and supply chain design decisions during the early design stages. There are three overall stages in the outlined method. The first stage generates the design concepts, evaluates assemblability, and modularizes these concepts to possible product architectures. Then, the second stage constructs a centralized supply chain using a MIP model. Finally, the third stage develops a decentralized supply chain with a bilevel programming model based on the centralized supply chain model. In applying the bilevel model, the focal company determines its module suppliers, who in turn select their component suppliers. The outputs of centralized and decentralized supply chain scenarios are compared using the bootstrap technique.

We adopt an industrial case based investigation to test the potential impacts of integrating product design and supply chain design decisions. We begin our discussion of the case later with an overview of bicycle types and usages. A simplified bicycle product structure and the resulting supply chain network are then illustrated. Background information on the focal company (X-bike) and the scope of this design project are introduced in Section IV-A. Product design functions of the proposed methodology are presented in Section IV-B. An EMS model is constructed and design concepts are generated based on it; these are discussed, evaluated using DfA values, and modularized using the decomposition approach. Section IV-C analyzes the supply chain design functions of the proposed methodology and calculates the supply chain performance of three distinct phases. Section IV-D compares the outputs and discusses the implications.

A. Background of the Case Study

The bicycle was first introduced in the eighteenth century for the purpose of transportation. Based on modern functions and usage, bicycles can be divided into five different types:

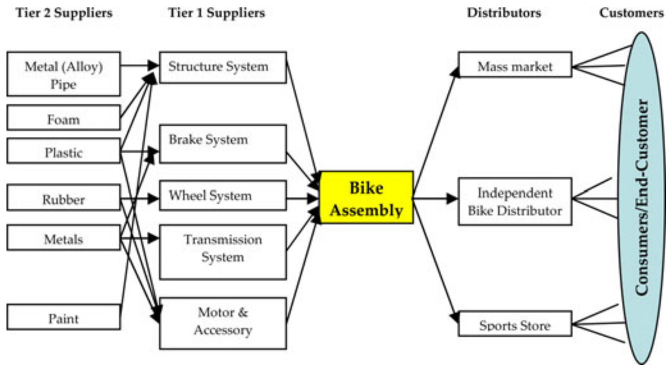

Fig. 3. Bicycle supply chain structure.

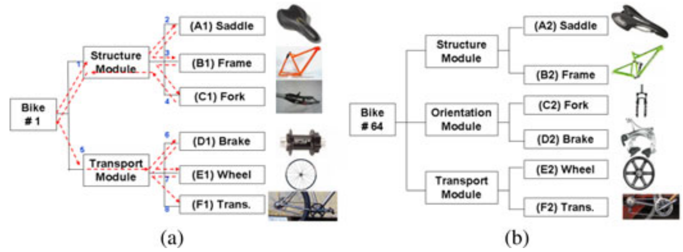

Fig. 4. (a) Two-Module and (b) Three-Module product architectures.

road, mountain, city and path, child, and bicycle motocross (BMX) [31]. The general architecture of a bicycle can be broken down as the structure (comprised of three subsystems: fork, frame, and saddle), the braking system, the transmission system, and the wheel system. We conducted an analysis to validate the importance of each component. A questionnaire was sent to industry experts to confirm the content validity [32] for the bicycle in this study. The first item on the questionnaire asked experts to identify the components of the bicycle as: 1) essential, 2) useful but not essential, or 3) not necessary. The questionnaire results showed that the six components selected for this research comprise 83% of a bike's essential components.

The braking system, as its name implies, is responsible for decelerating a bicycle's speed. The transmission system defines the functions and usage of the bike. The wheel system enables the bike to move by creating friction with the ground. Together with the structure, these subsystems are modular designs, which are mutually independent but cooperate as a whole product. Two optional subsystems are an electric motor with a battery and accessories that save physical effort and take into consideration the environment in which the bicycle will be used. The EMS model considers a total of seven components and functions, and it excludes the motor.

The supply chain structure of a bike can be arranged in four layers. The upstream layer in Fig. 3 consists of subsuppliers (Tier 2) who provide raw materials. The second layer (Tier 1) is made up of suppliers who produce the components of the bike. The next layer is the focal company, which focuses on the assembly process and manufacturing key components. Finally, the last layer is the distributors who set up the market channels and provide services to customers. Further subdividing the last category, there are three major distributors in the bicycle supply chain. Mass-market distributors include Wal-Mart and Target, which emphasize the mass-market segment with unit prices lower than $250 [33]. Both independent bike distributors and sports stores sell specialized bikes in niche market areas. The U.S. bicycle business was a $6 billion industry in 2008 [33]. Of interest to this study, road bike sales occupied 30.6% of the market share in 2005 [34], which is the largest segment of the market.

In our case study, X-bike is a bicycle company located in central Pennsylvania, and it is currently a high-end product leader. However, the size of the high-end market is small, and management has decided to extend the company's business to the mid-market products. The purpose of the product design function is to create a road bike with a price range of $400 to $1,000 USD and a production quantity of 10,000 per month. Company managers would like to have an acceptable lead-time interval to ensure responsiveness to market dynamics. The lead-time target is 130 days, beginning with component manufacturing and ending with completion of the final assembly process. The mission of the design team is to develop one or more design concepts that satisfy both product design and supply chain considerations regarding cost and time.

B. *Product Design*

The design team generated an EMS model of a road bike according to customer requirements. 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 inputting all functional rules and components, design concepts can be generated and placed in a design repository. The user must input the EMS model of a complete product. In this case study, the design team had six components and each component had two alternatives. The resultant twelve alternatives were: (A1) comfortable saddle, (A2) light weight saddle, (B1) steel frame without suspension, (B2) steel frame with suspension, (C1) steel fork without suspension, (C2) steel fork with suspension, (D1) single speed transmission, (D2) transmission with six fly wheels, (E1) reverse brake rotor, (E2) braking system with brake shoes, (F1) wheels with steel spokes, and (F2) wheels with plastic spokes. Hence, the design repository generates $2^6 = 64$ possible design concepts. These design concepts were then modularized as various product architectures; Fig. 4 illustrates the two-module and three-module product architectures after modularization. All 64 concepts were further incorporated in a transition matrix, and MIP and bilevel methods were used to evaluate supply chain performance. To address suitability concerns, ten bike industry experts with experience totaling more than 100 years were interviewed.

C. *Supply Chain Design*

There are numerous supply chain configurations possible, and hence, the transition matrix and MIP method were applied to compute supply chain performance for all design concepts. All feasible product architectures were analyzed according to possible assembly processes, as shown in Table II. Bicycle architectures were analyzed in three steps: final assembly, module

TABLE III
GLOBAL SUPPLIERS FOR THE X-BIKE (= ACTUALLY PRODUCE THE COMPONENT)

ID	Supplier	(A)	(B)	(C)	(D)	(E)	(F)	(AB)	(BC)	(CD)	(EF)	(ABC)	(DEF)	(ABCDEF)
1	X-Bike		√	√				√	√	√	√	√	√	√
2	ADK		√	√				√	√			√		
3	Advanced			√				√	√			√		
4	Campagnolo				√					√	√		√	
5	DT Swiss					√								
6	Easton			√										
7	Formula					√								
8	HB				√									
9	Mavic					√					√			
10	Velo	√												
11	Selle Royal	√												
12	Shimano				√	√	√				√		√	
13	Sram				√		√			√			√	
14	Tektro				√					√				
15	Ten-Tech		√				√							
16	Tien Hsin													
17	Topkey		√	√				√	√			√		
18	Viscount	√												

TABLE IV
SAMPLE PROCESS COSTS AND TIME

		(A) Saddle	Process ID: 12	
Type	No.	Supplier	Unit Cost	Time
A1	1	(10) Velo	$ 7.75	45
A2	2	(11) Selle Royal	$ 32.86	40
A1	3	(18) Viscount	$ 6.15	45

		(B) Frame	Process ID: 13	
Type	No.	Supplier	Unit Cost	Time
B2	1	(1) X-Bike	$ 320.00	30
B1	2	(2) ADK	$ 290.00	45
B2	3	(15) Ten-Tech	$ 380.00	45
B1	4	(17) Topkey	$ 278.60	35

		(C) Fork	Process ID: 14	
Type	No.	Supplier	Unit Cost	Time
C2	1	(1) X-Bike	$ 120.00	15
C1	2	(2) ADK	$ 53.00	10
C1	3	(3) Advanced	$ 22.66	15
C1	4	(6) Easton	$ 93.45	8
C2	5	(17) Topkey	$ 90.00	12

	(AB) Module	Process ID: 8	
No.	Supplier	Unit Cost	Time
1	(1) X-Bike	$ 18.00	0.5
2	(2) ADK	$ 5.00	0.8
3	(3) Advanced	$ 8.00	0.7
4	(15) Ten-Tech	$ 6.00	1.2

	(BC) Module	Process ID: 9	
No.	Supplier	Unit Cost	Time
1	(1) X-Bike	$ 10.00	0.3
2	(2) ADK	$ 5.00	0.5
3	(3) Advanced	$ 5.20	0.4
4	(17) Topkey	$ 6.20	0.5

	(CD) Module	Process ID: 10	
No.	Supplier	Unit Cost	Time
1	(1) X-Bike	$ 20.00	1.2
2	(4) Campagnolo	$ 9.00	3
3	(13) Sram	$ 7.00	2.6
4	(14) Tektro	$ 8.00	4.8

assembly, and component process. The assembly processes varied based on product architectures. For example, processes 1, 3, 4, 5, 6, and 7 (marked in shaded columns) were possible processes for a two-module architecture. Process 1 denotes that Module ABC and Module DEF are assembled as a final product.

The relationship among X-bike and its suppliers in the bike industry is similar to conditions in the computer industry. Suppliers are responsible for the design of components, and their brand names are shown both on the components and on the product specifications. The core technology of an X-bike is in the frame and fork design. Due to overhead costs and seasonal demands, X-bike has released some of the low-end frames and forks to their suppliers. Based on X-bike's data analysis, the capabilities of 18 suppliers are listed in Table III. Among them, 11 suppliers are from Taiwan, 2 are from Italy, 1 is from France, 1 is from Japan, and 3 are from the United States.

The planned total quantity for the final product was 10,000 per month. X-bike provided the process cost, transportation cost, inventory cost, and lead time for the components. This study estimated the cost and time for subassembly and final assembly. For the estimation of manufacturing and assembly processes, an actual bike was disassembled, and relevant component dimensions and weight information were captured. The total estimated process costs and time for all components and modules are summarized in Table IV. The assembly costs and times were calculated using methods developed by Boothroyd and Dewhurst [35] and Ulrich and Eppinger [3].

The default transportation method across the ocean is by ship. For purposes of this study, if two suppliers were on the same continent, the transportation time was estimated based on the distance. The estimated transportation times among these players in the supply chain network are calculated according to industrial quotations [36]. These data were input into the MIP and bilevel programming models. There were 145 variables and 125 constraints in the MIP model; the bilevel programming model had 239 variables and 257 constraints. The extra variables and constraints resulted from the reformulation, linearization and KKT complementarity procedures.

D. Comparison of Supply Chain Scenarios

After modularization, the main product architecture of a bicycle is either a two-module or a three-module architecture. Supply chain performances of all design concepts are comprehensively analyzed. The differences between a centralized supply chain network (MIP) and a decentralized supply chain network (bilevel) are investigated in this section. In the centralized scenario, focal company selects its tier 1 module suppliers and tier 2 component suppliers so as to optimize the overall supply chain costs. On the other hand, decentralized scenario presents that focal company (leader) selects tier 1 module suppliers and optimize the total costs from tier 1 module suppliers; then, tier 1 module suppliers (follower) choose their component suppliers with an aim to optimize tier 1 module suppliers' total costs. As shown in Table V, the average cost of a decentralized supply chain is 3% higher than a centralized supply chain for both two-module and three-module architectures, but the lead times are 11% and 21% shorter, respectively. Further, a centralized chain has cost advantages, on average, for both two-module (3%) and three-module (3%) architectures, while a decentralized chain has better time performance for both two-module (11%) and three-module (21%) architectures. As we analyze the cost structure, we also find that while the component cost and transportation cost of both scenarios remain about the same, the decentralized supply chain has higher assembly and inventory costs as illustrated in Table VI.

To investigate the statistical significance of the results, the bootstrap technique is used. Normally, this technique generates a new, large-scale population randomly from the same data source, which might increase the probability of getting at least one significant result purely by chance. To solve that issue, this study applies the Bonferroni correction [37], which divides significance level α by n to obtain a more conservative number. As a result, the noise can be eliminated. Further, this experiment only performs a one-sided test; accordingly we divide the corrected number by two to get $\alpha/2n$ as the new significance level. We test the differences between MIP model and bilevel model at a significance level of $\alpha = 0.05$, $n = 4$, and a sample size of $N = 1000$. The bootstrap results show that a centralized network has cost advantages, while a decentralized network has time benefits (see Table VII).

The results exhibit the benefit of the design for supply chain (DfSC) at the product design stage and show how different product architectures shape various supply chain networks. As mentioned in Literature Review A, efficient supply chains emphasize making and delivering a low-cost product, while agile supply chains focus on delivering a variety of products quickly in order to achieve a high level of customer satisfaction. Given these definitions as well as the case study results, we conclude that a centralized network would be more efficient, while a decentralized one would be more agile. In addition, the two-module product architecture has cost advantages in both types of supply chain networks. Company managers can make decisions on whether they should order components for their module suppliers (centralized) or allow module suppliers to search for their own component suppliers (decentralized) according to time and cost constraints.

After analyzing the tradeoffs between two-module and three-module product architectures under minimized cost, minimized lead-time, and centralized versus decentralized supply chain conditions, this study calculated the areas of efficient supply chain configurations as shown in Fig. 5. Here, X-axis is the time performance, and Y-axis is the cost performance. The efficient area is located in the bottom-left corner of the chart, where both cost and time are competitive. The DfA index can be further assigned as the Z-axis. The marked area with a circle indicates the concepts that are both efficient in product and supply chain performance.

E. Discussion

Traditional efforts to improve the product development efficiency and to reduce the supply chain risk consisted of early supplier involvement [38]–[40]. For example, the Japanese auto industry selected suppliers as business partners and built long-term relationships with them before designing a new product. This created the competitive advantage of Japan's auto industry from the 1970s to the 1990s [40]. However, since this effort might freeze the supply chain network, and thus limit the network's agility and product variety, reducing its ability to effectively tackle the mass customization and globalization trend. Our motivation is to develop a method that can simultaneously accomplish "design for" supply Chain and "design of" supply chain, where the efficiency of supply chain performance can be improved by probing earlier at the product design stage. Further, scenario analyses can highlight possible issues of supply chain operations; thus, decision makers can develop solutions that can solve or mitigate these issues in a timely manner. The method proposed in this study can survey and involve suppliers at the conceptual design stage, and thus provide flexibility in constructing the supply chain network. Our result validated the cost advantage of centralized supply chains [54] and the superior lead-time performance of decentralized supply chains [55], [56] with real industrial data.

The case study also provides evidence that a modular product architecture should be coordinated with an appropriate modular supply chain design [18]. Indeed, prior published work has analyzed similar issues. For example, Mikkola and Skjtt-Larsen [41] analyzed the interrelated and complementary strategies among mass customization, postponement, and modularization while managing supply chain integration; Lau and Yam [42] examined the relationship between product modularization and supply chain design in coordination with an industrial case study; and Ro *et al.* [43] pointed out that modularity, accompanied by a reorganization of enterprises and supply chain structures, was adopted by the U.S. auto industry. However, one of the major drawbacks of modular product architecture combined with a lean supply chain network is a lack of flexibility, generating a less than optimum response to the burden of market demand. Through consideration of different levels of

TABLE V
RESULTS FOR TWO-MODULE AND THREE-MODULE ARCHITECTURES IN THE BILEVEL MODEL

		2 module MIP V.S. BI_L				**3 module MIP V.S. BI_L**			
		Cost($USD)		Time (Day)		Cost($USD)		Time (Day)	
Concept #	DfA Score	2 M_MIP	2 M_Bi_L	2 M_MIP	2 M_Bi_L	3 M_MIP	3 M_Bi_L	3 M_MIP	3 M_Bi_L
1	1.08	580.9	609.4	128.2	124.2	592.61	610.188	125	123.5
2	1.08	551.6	579.2	128.2	124.2	561.59	579.96	125	123.5
3	1.17	522.1	549.8	128.2	124.2	531.90	554.897	125	123.5
4	1.17	551.5	580.0	128.2	124.2	562.93	585.125	125	123.5
5	1.22	671.1	701.2	128.2	124.2	685.67	704.667	158	123.5
6	1.22	700.5	729.8	128.2	124.2	716.70	734.895	158	123.5
7	1.26	620.6	647.8	128.2	124.2	630.14	650.734	125	123.5
8	1.26	650.0	678.0	128.2	124.2	661.17	679.312	125	123.5
9	1.31	671.0	700.3	128.2	124.2	687.01	705.438	158	123.5
10	1.31	641.6	670.1	128.2	124.2	655.99	675.21	158	123.5
11	1.31	589.0	606.9	128.2	124.2	589.54	617.99	125	123.5
12	1.31	619.2	635.5	128.2	124.2	619.77	636.211	125	123.5
13	1.35	591.2	635.1	128.2	124.2	600.69	613.869	125	123.5
14	1.35	625.6	648.5	128.5	124.2	631.71	653.677	125	123.5
15	1.40	559.5	575.8	128.2	124.2	559.85	569.118	125	123.5
16	1.40	769.5	798.3	128.2	124.2	785.25	803.447	158	95
17	1.40	740.2	769.7	128.2	124.2	754.23	769.396	158	123.5
18	1.40	589.7	609.1	128.2	127.2	590.08	626.26	125	123.5
19	1.44	738.7	755.8	128.2	124.2	743.85	756.523	158	123.5
20	1.44	708.5	727.2	128.2	124.2	713.62	732.34	158	123.5
21	1.49	710.7	740.3	128.2	124.2	724.77	743.762	158	123.5
22	1.49	740.1	768.8	128.2	124.2	755.79	780.736	158	86.5
23	1.49	657.5	673.8	128.2	124.2	658.09	676.757	125	123.5
24	1.49	687.7	704.0	128.2	124.2	688.32	709.158	125	123.5
25	1.53	679.0	696.1	128.2	124.2	683.93	691.08	158	123.5
26	1.53	709.3	726.3	128.2	124.2	714.16	721.746	158	123.5
27	1.53	477.3	497.1	93.2	89.2	479.88	496.188	99.1	88.5
28	1.53	506.6	525.7	115.2	89.2	510.90	532.387	112.8	88.5
29	1.58	628.0	644.3	128.2	124.2	628.63	649.472	125	123.5
30	1.58	658.3	674.6	128.2	124.2	658.86	679.7	125	123.5
31	1.62	471.7	496.2	115.2	89.2	481.21	503.594	112.8	88.5
32	1.62	442.4	466.0	91.2	89.2	450.19	472.775	93	88.5
33	1.62	777.1	794.1	128.2	124.2	782.17	799.242	158	123.5
34	1.62	807.3	824.3	128.2	124.2	812.40	829.47	158	123.5
35	1.67	596.8	615.8	93.2	89.2	603.96	620.895	158	88.5
36	1.67	626.2	660.0	115.2	95	634.98	651.123	158	95
37	1.71	777.8	810.0	128.2	124.2	782.94	830.556	158	123.5
38	1.71	747.6	764.6	128.2	124.2	752.72	769.784	158	123.5
39	1.71	546.3	565.6	93.2	89.2	548.43	565.312	95	88.5
40	1.71	575.7	594.2	115.2	89.2	579.45	595.54	112.8	97
41	1.76	566.4	586.3	155.5	89.2	574.27	596.204	158	88.5
42	1.76	595.8	616.5	155.5	89.2	605.30	623.906	158	86.5
43	1.76	544.9	551.7	93.2	89.2	538.06	554.413	99.1	94.5
44	1.80	511.4	550.2	91.2	89.2	518.97	553.719	96.1	88.5
45	1.80	540.8	574.3	115.2	116.7	550.00	572.718	112.8	88.5
46	1.85	665.9	700.0	93.2	89	672.51	691.097	158	95
47	1.85	479.8	492.0	89.2	89.2	478.14	528.355	93	88.5
48	1.85	695.3	714.5	115.2	89.2	703.54	729.895	158	95
49	1.85	509.97	522.2	90.5	89.2	508.37	529.8	93.0	99.1
50	1.89	634.22	635.9	93.2	93.2	631.91	648.6	158.0	95.0
51	1.89	664.45	686.0	93.2	87.2	662.14	672.8	158.0	88.5
52	1.92	514.66	523.1	93.2	89.2	507.83	546.6	99.1	95.0
53	1.94	664.87	685.0	155.5	89.2	674.08	693.0	158.0	86.5
54	1.94	635.49	670.5	155.5	89.0	643.06	690.8	158.0	87.5
55	1.94	613.44	634.3	93.2	89.2	606.61	639.4	96.1	88.5
56	1.94	583.21	590.0	93.2	89.2	576.38	607.0	96.1	95.0
57	1.98	634.06	642.5	155.5	89.2	632.45	652.1	158.0	94.5
58	1.98	609.74	612.3	193.9	89.2	602.22	619.1	158.0	88.5
59	2.03	560.56	576.2	89.2	89.2	546.92	565.7	96.1	88.5
60	2.03	578.53	590.8	90.5	89.2	577.15	598.7	96.1	88.5
61	2.07	733.00	740.6	93.2	89.2	730.69	745.7	158.0	88.5
62	2.07	702.77	712.0	93.2	89.2	700.46	715.5	158.0	95.0
63	2.16	672.38	680.89	155.5	89.2	671.00	707.9	158.0	94.5
64	2.16	702.61	723.4	155.5	90.7	701.23	720.3	158.0	96.5
Avg.	**1.62**	**627.02**	**647.82**	**120.88**	**107.32**	**631.55**	**652.84**	**135.30**	**106.31**
Dif.		--	**103%**	--	**89%**	--	**103%**	--	**79%**
STD		**84.6295**	**85.3968**	**21.9825**	**17.4701**	**86.3514**	**84.9369**	**24.8226**	**16.4981**

*2M= Two-module product architecture; *3M= Three-module product architecture; MIP= mixed integer model; and Bi_L = bi-level model.

modularity and supply scenarios presented in this research, we overcome that drawback (reduced flexibility) by imposing a modular architecture on both products and supply chain networks. The newly proposed supply chain is a vertical specialization network between a focal company and suppliers. It forms a virtual organization that keeps costs low while maintaining quick response times. Selldin and Olhager [10] described this situation as a supply chain frontier, where a company can design its supply chain to be both physically efficient and responsive to the market while maintaining its profitability.

TABLE VI
COST AND LEAD TIME COMPARISON FOR MIP VERSUS BILEVEL MODEL UNDER 2M PRODUCT ARCHITECTURE

Comparison Item	MIP	Bi-Level	Diff
Component Cost ($USD)	547.41	547.41	0.00%
Assemble Cost ($USD)	36.70	55.00	49.85%
Transportation Cost ($USD)	26.22	25.98	-0.89%
Inventory Cost ($USD)	16.69	19.43	16.41%
Total Cost ($USD)	627.02	647.82	3.32%
Lead time (Day)	120.88	107.32	-11.22%

TABLE VII
BOOTSTRAP RESULTS FOR MIP VERSUS BI-LEVEL MODEL

MIP vs. Bi-Level ($\alpha/2n$, $1-\alpha/2n$)	Two Modules	Three Modules
Cost (0.625%, 99.375%)	Significant (-23.967, -18.061)	Significant (-24.085, -18.653)
Time (0.625%, 99.375%)	Significant (6.637, 19.753)	Significant (21.314, 37.874)

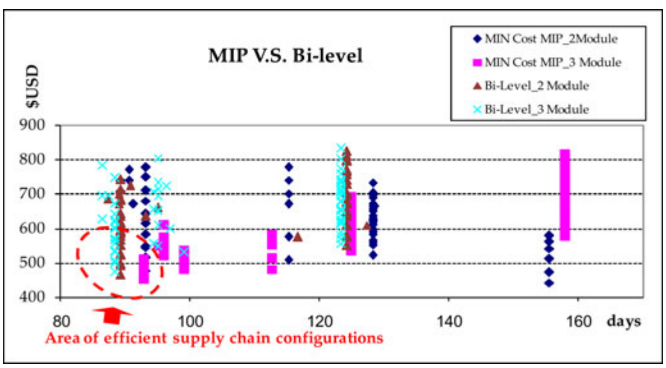

Fig. 5. Area of efficient supply chain configurations.

Vonderembse *et al.* [12] argued that the supply chain network should be reconfigured during different phases of the product life cycle. Enterprises should embrace an agile supply chain during the introduction and growth phases of the product life cycle. After that, enterprises can adjust to a lean or hybrid supply chain according to the degree of demand variation. The studies presented thus far addressed the importance of integrating product design decisions and supply chain design decisions. The coordination of product type and supply chain configuration can ameliorate the strike rate of a new product launch as well as the competitive advantage of the enterprise.

With reference to the case study, we note that the upstream and downstream suppliers were geographically close to each other. The eighteen enterprises can be clustered into three areas: East Asia, the Great Lakes region, and southern Europe. This indicates that the trend of supply chain design and integration can provide competitive advantages to a company, realized through the clustering effect coined by Porter [44]. Attesting to this, Chen *et al.* [45] studied the bicycle industry in Taiwan and indicated that geographical proximity not only reduces transaction costs among firms, but also increases 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.

Our method is applicable to complex products by modeling subassemblies or modules, and then modeling components for each module. Take airplane as an example: the overall product can be divided into fuselage, wings, landing gear, main body, and power modules. The fuselage module can be further broken down to cockpit, cabin, etc. Such a systematic and hierarchical decomposition allows consideration of key suppliers at the design stage. But for most of the noncritical suppliers (e.g., screw or paint suppliers), airplane manufacturer does not have to spend effort. Thus, the modeling complexity can be reduced. The proposed method integrates product design functions with a three-tier supply chain network and we believe this framework can satisfy most of companies' needs while managing their supply chain network.

This study can be extended in several directions. Ulku and Schmidt [47] examined the link between product architecture and supply chain configuration and pointed out that supply chain structure, firms, market, and product characteristics play important roles in the selection of product architecture. Future research will address these factors so as to better align the product design and supply chain design decisions. Another research direction is the robustness of the supply chain network. Xie *et al.* [53] implemented Nash's noncooperative game to analyze the quality improvement strategies under different supply chain structures. The competition intensity has significant impact on selection of supply chain structure and vertical integration is a dominant strategy in quality improvement. Zhao *et al.* [48] developed randomized local rewiring approach to enhance the robustness of supply chain networks during disruptions. Such an approach can be implemented to investigate the robustness of the network in the studies of supply chain scenarios. Xie *et al.* [52] developed a mathematical model to compare the quality investment and pricing decisions in different supply chain strategies and suggested that centralized decision making is an effective way to achieve high quality in products.

V. CONCLUSION

In this paper, a methodology that connects and harmonizes product design and supply chain design decisions is presented. With the proposed approach, the supply chain cost and time performance is investigated, and inefficiencies in supply chain execution can be detected at the conceptual design stage. Centralized and decentralized supply chain network scenarios are analyzed for insight that could aid decision making related to supply chain execution. By incorporating supply chain considerations, this method effectively allowed a clearer view of the influences of the manufacturing process, transportation costs and the lead time. Therefore, it can support planning for financial investments in facilities and equipment. In addition, the proposed method can also provide a scenario analysis function. Under the analysis of centralized and decentralized supply chain scenarios, enterprises and suppliers can better understand the impact of different conditions and determine which scenario to apply as market situations vary. Hence, agility of the supply chain is improved. While other studies focus on later aspects of the design stage, this innovative method explores the supply chain during early design stages. This method establishes the potential competitiveness of enterprises leading to a win–win situation for both the focal company and its cooperative suppliers.

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