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

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Supplier selection is one of the key decisions in supply chain management. Companies need not only to make the "make" or "buy" decisions but also differentiate across potential suppliers in order to improve operational performance. Product design is an engineering based activity that realizes the customer requirements into functions of a new product. Many studies have pointed out that the integration of product and supply chain is a key factor for profitability and efficiency. However, most studies address supply chain performance after freezing the design of the product; only a few studies discuss when and how to incorporate supply chain decisions during product design. This paper presents a graph theory based optimization methodology to tackle this problem. The supplier selection issue is considered by evaluating its impact on both internal (e.g., ease of assembly) and external (e.g., transportation time) enterprise performances, which are aggregated as supply chain performance at the conceptual design stage. A case study in the bicycle industry demonstrates the advantages of this methodology. The presented mathematical programming formulation enables simultaneous optimization of both product design and supply chain design during the early design stages. [DOI: 10.1115/1.4003289]

Keywords: product design, supply chain design, transition matrix, design repository

1 Introduction

Product development is an innovative process that transforms and realizes the potential market opportunities into a product according to product and process technologies [1]. The product design process is an iterative and complex process, which includes defining, conceptualizing, refining, and eventually commercializing a product into a new or existing market. During this process, product size, shape, functions, processes, components, materials, etc., need to be decided under budget and time constraints. These product development decisions can be organized into four categories: concept development, supply chain design, product design, and production ramp-up and launch [1].

The supply chain council defines a supply chain as "every effort involved in producing and delivering a final product or service, from the supplier's supplier to the customer's customer" [2]. Accordingly, a supply chain consists of the supply chain network structure, the supply chain business processes, and the supply chain management components. A representation of a supply chain structure is provided in Fig. 1 [3], where the focal company is the center of the supply chain along with multitier suppliers to its left and multitier customers on the other side.

Up to 70% of product cost [4] and 80% of product quality [5] are decided during the design stage. Meanwhile, product flexibility (e.g., color, shape, materials, etc.) drops sharply during this stage as design decisions are made with irrevocable consequences or implications. The importance of this stage is reflected in its tie to the company bottom line. New products might account for 33% of company sales [6], which have a high association with the profitability and growth of a company. New products here are those that are introduced to the market within 5 years. Besides high profitability, new product development is also known to have high risk. The new product failure rate (NPFR), which is a statistical datum that computes the success percentage of new products, showed that only 40% of new products survived in 2004 [7].

Despite the above mentioned significance of product design and the need to coordinate between product and supply chain designs [3,6,8], only a few methods concurrently consider product design and its supply chain. The objective of this research is to develop a method that can combine and streamline the decision making for product design and supply chain configuration problems. 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 influences of a new product. Consequently, potential limitations of a supply chain can be reviewed early in the product development stage.

In this paper, the next section provides a review of the relevant literature on supplier selection methods and criteria, 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, design for assembly (DfA), and supply chain perspectives simultaneously during the product design stage. A case study is presented in Sec. 4 to demonstrate the proposed methodology. Finally, Sec. 5 presents conclusions.

2 Literature Review

2.1 Supplier Selection: Proposed Methods and Criteria. Currently, most supply chain systems are decentralized. Among the advantages of decentralization in supply chains, or outsourcing, competition among suppliers, external economies of scale, responsiveness to variability in demand, immediate access to capabilities, and minimization of financial investment are commonly cited (e.g., Ref. [9]). This implies that enterprises seldom internally produce all components of a product, and "make and buy" decisions need to be made when considering supply chain effi-

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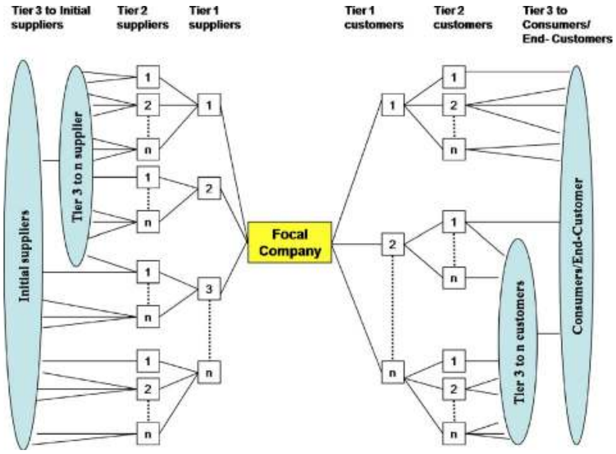

Fig. 1 Supply chain framework [3]

ciency [9], and appropriate suppliers need to be selected.

In order to gain an understanding of the state-of-the-art on supplier selection methodologies, 49 papers were evaluated by Aamer and Sawhney [10]. Overall, the studied methods are categorized as appraisal methods and mathematical methods, as shown in Fig. 2. Appraisal methods compare suppliers using criteria ranking or cost to evaluate their performance. By contrast, mathematical methods involve evaluating trade-offs among selection criteria by linear weighting, optimization, statistical, and neural network techniques. Appraisal methods and mathematical methods can be combined, resulting in hybrid methods.

The purpose of measuring supply chain performance is to determine the optimal component acquisition alternative that will be most beneficial to the focal company and its customers. The benefits can be measured using quantitative or qualitative terms. Cost, resource utilization, quality, flexibility, visibility, trust, and innovativeness are among these metrics [11]. Another study presented quality, cost, technology, production capacities, research and development (R&D), delivery and location, performance, and service as selection criteria [9].

A supplier selection model might include strategic, operational, tangible, and intangible measures and consider the short-term and long-term planning horizons [12]. Suppliers are evaluated based on organizational factors as well as strategic performance matrices. Organizational factors cover culture, technology, and relationship, and strategic performance metrics contain cost, quality, time, and flexibility. In addition, a supplier selection study with a managerial vantage point addressed cost, resource utilization, quality, flexibility, visibility, trust, and innovativeness as evaluation indicators [11]. Cost includes manufacturing, distribution, inventory, and overhead cost. Resources cover labor, machine, capacity, and energy utilization. Quality might involve customer dissatisfaction,

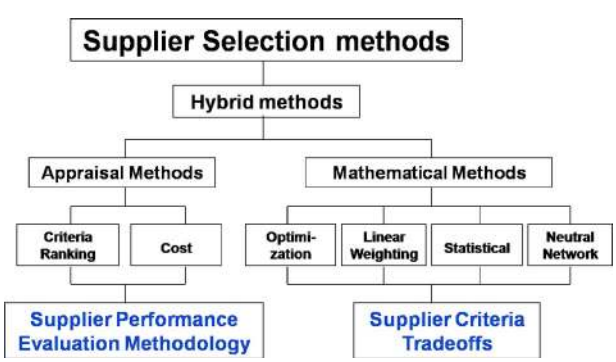

Fig. 2 Supplier selection categories [10]

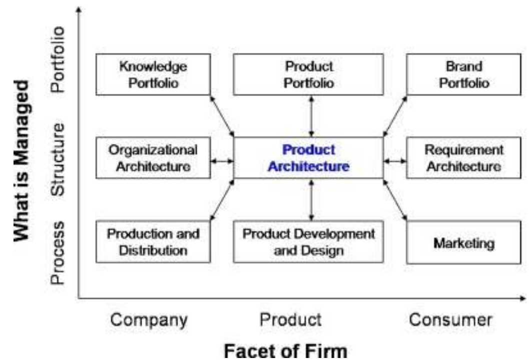

Fig. 3 The implications of product architecture [13]

response time, on-time delivery, fill rate, stock-out probability, and accuracy. Flexibility is the ability of a company to respond to diversity or change. There are four types of flexibility: input, process, output, and improvement. Visibility measures the degree of information sharing in the supply chain in terms of time and accuracy. Trust is an index representing the reliability and consistency between the supplier and the focal company. Finally, innovativeness reflects the technological and engineering capabilities of suppliers such as the launch of new products and creative use of new technology.

Based on the above review, we assert that there is a void in the literature as no study relates supplier selection criteria to product architecture. There is a need to integrate supply chain decisions at the product design phase so that the optimal component acquisition and possible alternatives can be evaluated and determined. The supply chain consideration aims to achieve a win-win situation at the supply chain level, which can benefit all practitioners in the supply chain in terms of performance.

2.2 Product Architecture. A product can be viewed as a physical organization that performs specified functions or provides services. Its components are functional segments that cooperate to accomplish these distinct purposes. Product architecture is the schema of these functional segments showing the physical building blocks 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 (see Fig. 3 [13]). Product architecture serves as the kernel that connects the customer and the enterprise; it impacts process and portfolio design that direct the change, variety, performance, and manufacturability of the product [13–15].

Two main typologies of product architecture are the modular product and the integral product [15]. 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) [16], which emphasizes reducing the quantity of components and creating multifunctional parts. However, the modification of one component usually impacts other related components potentially resulting in a significant redesign effort. This may result in longer design time and renders integral product architecture uncompetitive when compared with modular product architecture in current diverse market segments.

On the contrary, modular products decompose the overall functionality of a product into subfunctions embodied in separate product 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 [17,18]. 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, which eases 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. In addition to component modularity, the standardization of the interface is necessary [15,19]. Despite the advantages, there are potential drawbacks of modular product architecture, such as performance optimization, under or over design, and a considerable design investment. In recent years, however, modular product architecture has become the mainstream in product design due to the advantages in development time, cost, and economy of scale [15].

As summarized above, the product architecture has implications for the overall operations of a company, and it should be decided taking into account these implications to arrive at an appropriate structure (integral versus modular) for a specific product.

2.3 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. Products can be categorized into two classes: "functional" and "innovative." In this categorization, 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. Similarly, supply chains can be classified as "efficient" and "responsive" supply chains [8]. Efficient supply chains emphasize making and delivering a product with a low cost (cost-based competition) while responsive supply chains aim for delivering a variety of products quickly to achieve a high level of customer service (time-based competition). The right coordination between supply chain type and product type—for example, a functional product and an efficient supply chain—can increase the likelihood of success.

Vonderembse et al. [20] extended Fisher's framework [8] with a hybrid product type along with a hybrid supply chain. Hybrid product here refers to a product that has some of the standard product's characteristics as well as some of the 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. While an efficient (lean) supply chain focuses on reducing lead-time, increasing efficiency, expanding manufacturing flexibility, and cost cutting, a responsive (agile) supply chain aims to respond to rapidly changing, continually fragmenting markets by being dynamic, context specific, and growth-oriented. Hybrid supply chains combine the capabilities of lean and agile chains to create a network that meets the needs of hybrid products.

Fine et al. [21] presented the idea of modular supply chain and integral supply chain. In an integral supply chain network, members of the chain are in close proximity with each other, where proximity can be measured along four dimensions of geography, organization, culture, or electronic connectivity. Integral supply chains have high formalization, centralization, and complexity. Conversely, the modular supply chain can be geographically dispersed to a relatively higher extent, with few close organizational ties and modest electronic connectivity. Fine et al. [21] recommended associating an integral product with an integral supply chain and a modular product with a modular supply chain to ensure efficiency. They also developed a goal programming model, which is indeed one of the first quantitative models that connected the product, processes, and the supply chain. This model highlighted the relation that an integral product should map with an integral supply chain while a modular product with a modular supply chain.

One other framework of supply chain decision making was proposed by Appelqvist et al. [4], who considered the product design and supply chain design concurrently. In the framework, the case for aligning a new product with a new supply chain (i.e., breakthrough) is mentioned as the most challenging situation to achieve. If a supply chain is new for an existing product, the supply chain should be re-engineered to fit the product attributes. On the other hand, a new product design should consider design for logistics (DfL) to fit within an existing supply chain. For both an existing supply chain and product, continuous improvement is the choice with minimum efforts, and perhaps the minimum investment. These cases are illustrated in Table 1. It should be noted that the scope of DfL was broadened to design for supply chain management (DfSCM) [22], which aims at designing products and processes to more effectively manage supply chain-related cost and performance. DfSCM utilizes product line structure, bill of material (BOM), and customization processes of a product in order to optimize the logistics costs and customer service performance.

Table 1 Framework for supply chain decision making [4]

Supply chain	Product: Existing	Product: New
New	Re-engineering	Breakthrough
Existing	Continuous improvement	Design for Logistics

Based on the summary above, we assert that the supply chain structure is highly related to product design and that the improvement of supply chain performance can be possible 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.

2.4 Previous Supplier Selection Methods at the Product Design Stage. Supplier involvement at the product design stage has recently drawn much attention from researchers. Design stages can be classified into five phases [23]: problem definition, conceptual design, preliminary design, detailed design, and production design. Table 2 illustrates the potential supplier involvement activities [24] during these phases. As it can be seen in the table, product architecture is one such activity to be completed during conceptual design stage.

A robust supplier set selection method was presented to support

Table 2 Supplier involvement in product design stages [23,24]

Design stages	Supplier involvement
Problem definition	Establish specification
	Avoid ambiguity and information distortion
	Identify early changes
Concept design	Key product and process technologies
	Product architecture
	Contribute key ideas/concepts/critical components
	Establish interfaces between product subsystems
Preliminary and detailed design	Selection of proprietary parts and components
	Tolerance design
	Prototype testing and demonstration
	Design for manufacturability
	Material selection
Production design	Tooling design
	Design for manufacturability
	Quality control and assurance
	Raw materials

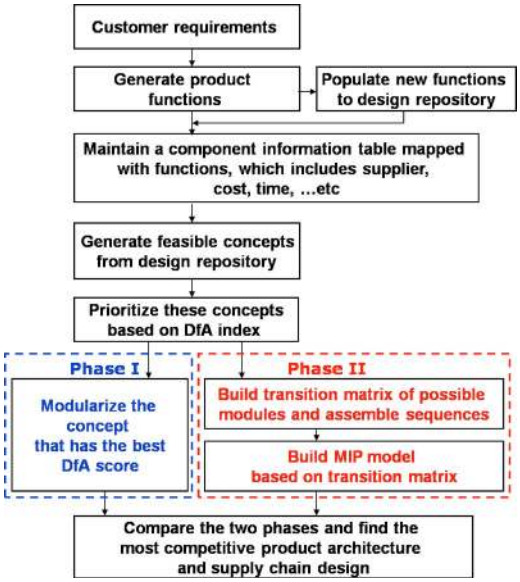

Fig. 4 Flow of the proposed method

various needs of product architecture over a planning horizon in response to the challenge of mass customization [25]. In this method, Taguchi's quality loss function and ant colony optimization (ACO) method were applied to evaluate various product architectures for minimum total acquisition costs while selecting suppliers. In another study, a mixed-integer program was developed to consider supply chain decisions relevant to cost, lead-time, and demand satisfaction to achieve an overall profit maximization at the detail design stage [26]. However, the product architecture is taken into account only as a set of components; the interactions among components and the multi-echelon supply chain structure that might result in different possible product architectures and supply chain configurations are not considered.

Some researches (e.g., Refs. [14,27]) claimed that integral product 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 as the component technology, design, and management of specifications are performed within one company under a vertical integration strategy. As the product matures and customers are satisfied, a modular product 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 the profit, the focal company needs to keep control of the core capability, however.

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 an integration of supply chain decisions at the product design phase so that the optimal component acquisition and possible supply chain alternatives can be determined 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 stage and compare the supply chain performance results (lead-time and cost) when this simultaneous optimization is done versus not done. Figure 4 presents an overview of the methodology. One critical aspect of the methodology presented is the use of energy-material-signal (EMS) functional model, a design repository, and a DfA concept filtering algorithm to complete a preliminary concept selection. This process allows unbiased selection of the product components to be used in the following methodology phases.

First, the functional requirements of a product are defined and decomposed into the most basic subfunctions to form an EMS functional model. Second, a repository is utilized to synthesize potential components of all subfunctions, providing multiple options for the conceptual design. These concepts are evaluated using a DfA index and then modularized with the decomposition approach (DA). The final step contains two phases with two different design concepts. The design concept with the best DfA score is selected as the phase I output. This design concept and the relevant supply chain performance, achieved to minimize the component costs, will be compared with the output of phase II. In phase II, the proposed graph theory based method, which consists of a transition matrix and mixed-integer programming model, is implemented using a mathematical model that will optimize the best product architecture as well as the supply chain (Table 3).

In this study, a software framework developed with JAVA SWING within the NETBEANS IDE 6.1 programming environment [28] 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. The transition matrix and nonlinear optimization model is then solved with LINGO 9. Below we provide information relevant to critical components of the proposed methodology.

3.1 Functional Requirements. The EMS functional model was applied to present the functions of the whole product. This model is obtained by decomposing the overall function into simpler subfunctions and flows, which are generally described in a

Table 3 The transition matrix of all possible disassembly sequences

	A												
S	0	1	2	3	4	5	6	7	8	9	10	11	12
ABCD	+1	−1	−1	−1									
ABD		+1			−1	−1							
ACD			+1				−1	−1					
BCD				+1					−1	−1			
AD					+1		+1				−1		
BD						+1			+1			−1	
CD								+1		+1			−1
A				+1		+1		+1			+1		
B			+1		+1					+1		+1	
C		+1					+1		+1				+1
D											+1	+1	+1

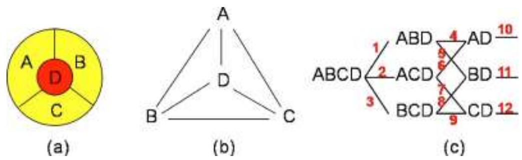

Fig. 5 Simple assembly (*a*), its connection diagram (*b*), and its disassembly graph (*c*) [36]

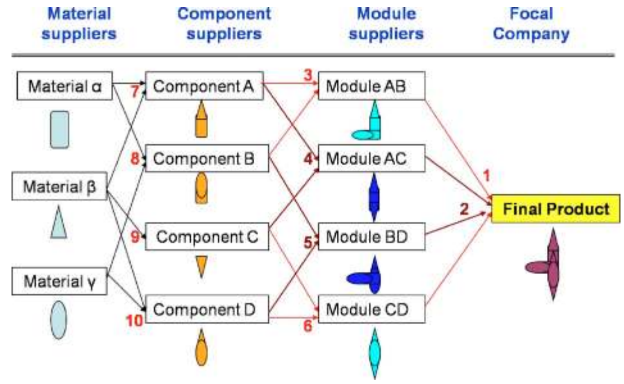

Fig. 6 Possible supply chain network and product structure

verb-object form. These subfunctions and flows are obtained from a standard set of vocabulary referred to as a functional basis [29].

3.2 Design Repository. The purpose of a design repository is to record and reuse the best design practices at a later stage. It can be used for storing and retrieving design knowledge. A design repository could be defined as a heterogeneous product design database in which various design solutions can be searched and reused. Design repositories are employed extensively in research involving the development of computer-aided design (CAD) tools [30].

3.3 DfA Index, Decomposition Approach, and the Supply Chain Considerations. Over the years, numerous "design for X" (DfX) concepts/methods have been developed in order to increase the efficiency at the design stage and reduce the total cost and lead-time of the product. Design for manufacture, assembly, quality, maintenance, environment, obsolescence, recyclability, etc., are among these [31]. This research focuses on DfA and design for supply chain (DfSC).

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 [32,33] are collected and evaluated from the perspectives of the assembly, component, and process properties. These include (1) weight, (2) number of unique components, (3) stiffness, (4) length, (5) presence of the base component, (6) vulnerability hardness, (7) shape, (8) size, (9) composing movement, (10) composition direction, (11) symmetry, (12) alignment, and (13) jointing method. The formula for calculating the DfA index is provided below [33]. 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.

$$\text{DfA index} = 10\left(\sum \mathrm{P}_i - \sum \mathrm{V}_{\min,i}\right) \Big/ \left(\sum \mathrm{V}_{\max,i} - \sum \mathrm{V}_{\min,i}\right) \quad (1)$$

Here, P_i is the point value for each criterion, $i=1,\ldots,13$, $\mathrm{V}_{\min,i}$ is the minimum value for each criterion, and $\mathrm{V}_{\max,i}$ is the maximum value for each criterion.

Afterward, the DA, which is a matrix based methodology [34], 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 concept that has the best DfA score is selected for further comparisons.

3.4 Transition Matrix. The transition matrix was developed to solve the disassembly sequence with the purpose of optimizing the profit of the product at the end-of-life stage [35–39]. Product architecture is viewed as a graph where nodes are components and vertices are connections between components, as shown in Figs. 5(*a*) and 5(*b*). While disassembling the product, all possible status of subgraph or subassemblies are denoted as a stage set (set ***S***). The disassembly process or action that results in transferring between two subassemblies is represented as the vertex (set ***A***). The whole disassembly sequence will generate a new directed graph, as provided in Fig. 5(*c*). An $\boldsymbol{S}\times\boldsymbol{A}$ size transition matrix is summarized to describe this from-to relationship of subassemblies and matching processes in Table 4. In this table, each of the columns corresponds to an action and each of the rows to a subassembly. Destruction of an original subassembly status will create two new different subassemblies. The destructed subassembly is assigned the value of −1, while newly created subassemblies are +1. These

Table 4 Transition matrix of Fig. 6

	Process									
	Final assembly		Module assembly				Component manufacturing			
Stage	1	2	3	4	5	6	7	8	9	10
Final product	+1	+1								
Module AB	−1		+1							
Module AC		−1		+1						
Module BD		−1			+1					
Module CD	−1					+1				
Component A			−1	−1			+1			
Component B			−1		−1			+1		
Component C				−1		−1			+1	
Component D					−1	−1				+1
Material α							−1	−1		
Material β							−1		−1	−1
Material γ								−1		−1

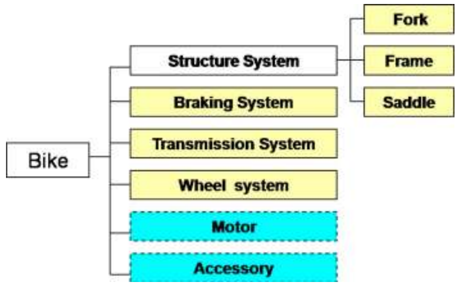

Fig. 7 Simplified bike architecture

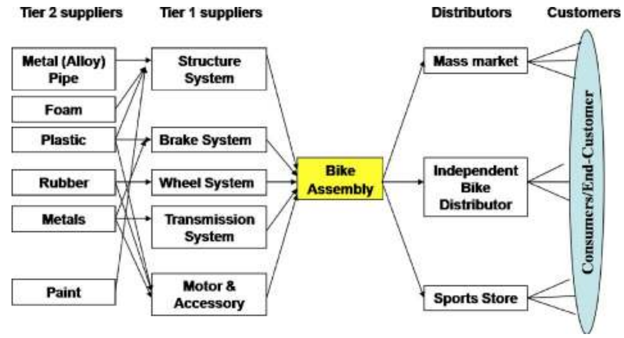

Fig. 8 Bike supply chain structure

values will be put in the column of specific action and all other unrelated states will remain empty or at zero. For example, action 3 is a disassembly process that destructs assembly (state) ABCD and creates two subassemblies, A and BCD. Hence, a value of −1 is put for state ABCD, and +1 is inserted for states A and BCD. These values are only arranged in column 3 because action 3 is the process connecting these subassemblies.

In this study, the transition matrix is applied in a reverse manner. During the product design stage, the functions of a product are generated based on customer requirements. Components are physical elements that execute these functions. Accordingly, suppliers are the manufacturers of these components. We provide an example supply chain network as well as product architecture in Fig. 6 to explain this idea. In the example network, there are a total of ten processes from upstream to downstream. The transition matrix is shown in Table 4 to indicate the manufacturing/assembling processes and their corresponding status changes. In this table, upstream status is denoted as value −1 due to the destruction in the assembly process. Accordingly, downstream status will be marked as value +1 since it is created. It must be noted that selection of different processes will generate different supplier groups as well as product architectures. In Table 4, there are two process groups, which are 1-4-5 and 2-3-6. Their product architecture is different, and the process technology, cost, and time will certainly vary. Cost is the unit expense of a process that a supplier can provide. Process time is the time required for manufacturing/assembling this process. When a supplier is not able to provide this service, the cost and process time will be taken as infinite in our calculations. We use geographic coordinates as location attributes to make it easier to compute the transport distance while assigning suppliers. Process time and transportation time are indicators of inventory level control for downstream players. For example, process 1, in Table 4 and Fig. 6, represents the final assembly process that modules AB and CD are assembled as the final product. Hence, the value of modules AB and CD is −1 because they are destructed and the value of created final product is +1. A mixed-integer optimization model is constructed to measure the supply chain performance.

3.5 Mathematical Formulation

3.5.1 Notation. The index sets are as follows:

$P=\{1,\ldots,N_p\}$ are the possible processes of a product, $p\in P$
$S=\{1,\ldots,N_s\}$ are the possible states of a product manufacture and assembly, $s\in S$
$I=\{1,\ldots,N_k\}$ are the potential component suppliers, $i\in I$
$J=\{1,\ldots,N_j\}$ are the potential subassembly suppliers, $j\in J$
$K=\{1,\ldots,N_k\}$ are the potential final assembly suppliers, $k\in K$

The decision variables are as follows:

X_{pi} is the variable indicating that component supplier i is selected for process p (binary variable)
X_{pj} is the variable indicating that subassembly supplier j is selected for process p (binary variable)
X_{pk} is the variable indicating that final assembly location k is selected for process p (binary variable)

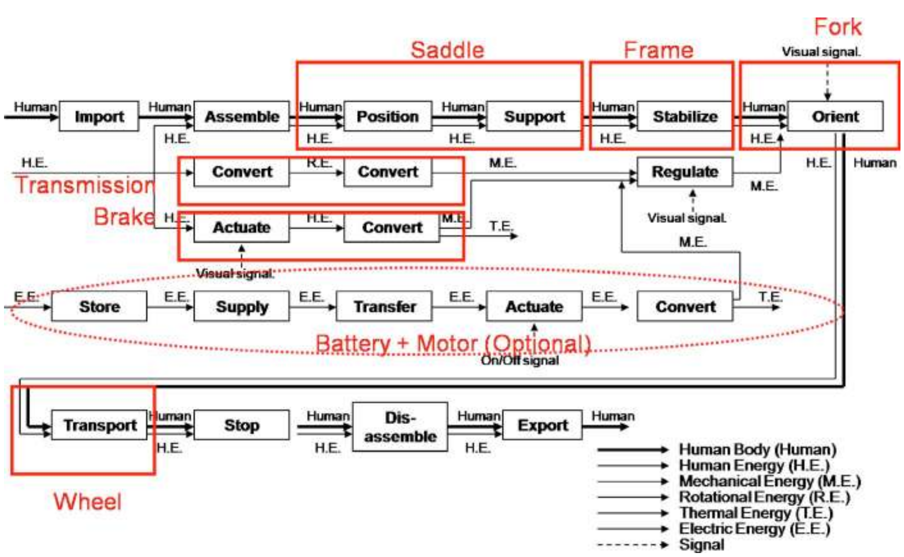

Fig. 9 EMS diagram of a bike with mapping components

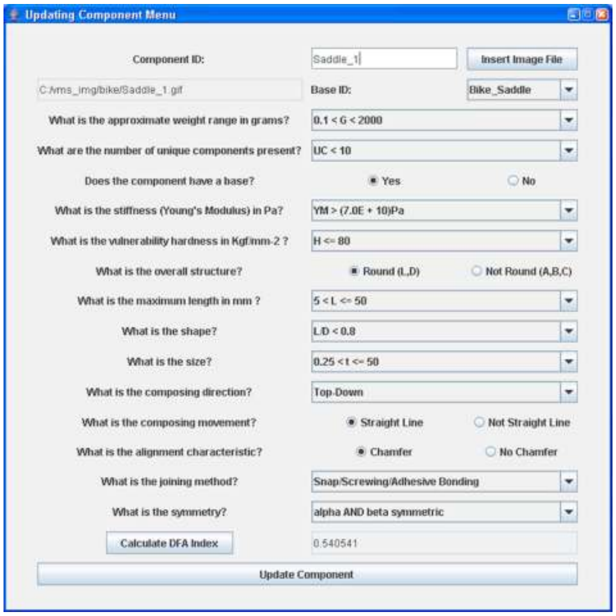

Fig. 10 The DfA index calculation

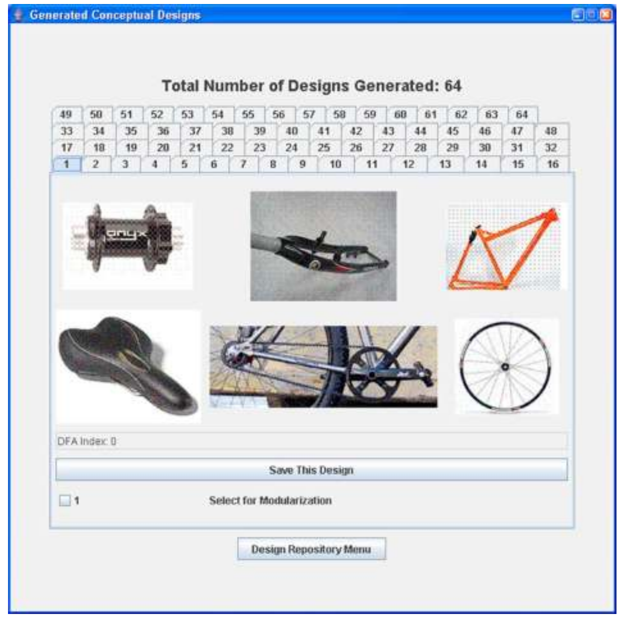

Fig. 11 64 concepts generated from the design repository

Y_p is the variable indicating that process p is performed (binary variable)
L_MAX is the longest acceptable lead-time of supply chain
L_MIN is the shortest acceptable lead-time of supply chain
C_MAX is the highest acceptable cost of product

The parameters are as follows:

T_{sp} is the entity value of transition matrix
C_{pi} is the unit cost of component supplier i in process p
C_{pj} is the unit cost of subassembly supplier j in process p
C_{pk} is the unit cost of final assembly k in process p, L_{pi} is the time of a component staying at supplier i in process p
L_{pj} is the time of a module staying at supplier j in process p
L_{pk} is the time of a product staying at final assembly supplier k in process p, LEAD is the total lead-time of the supply chain,
$TRANCX_iX_j$ is the transportation cost between component supplier i and subassembly supplier j
$TRANCX_jX_k$ is the transportation cost between subassembly supplier j and final assembly location k
$TRANTX_iX_j$ is the transportation time between component supplier i and subassembly supplier j
$TRANTX_jX_k$ is the transportation time between subassembly supplier j and final assembly location k
α is the percentage of component cost that will be viewed as inventory cost, and β is the percentage of transportation cost that will be viewed as inventory cost

3.5.2 Objective Function. Min {process costs (C_1) + transportation cost (C_2) + inventory cost (C_3)}. All cost items are expressed mathematically in Eqs. (2)–(4) below.

Process cost summarizes the process cost of selected supplier i, j, k in the process p.

$$C_1 = \sum_p \sum_i C_{pi} * X_{pi} + \sum_p \sum_j C_{pj} * X_{pj} + \sum_p \sum_k C_{pk} * X_{pk} \tag{2}$$

Transportation cost is the expense between the upstream (input state) suppliers and downstream (output state) suppliers for all processes.

$$C_2 = \sum_p \sum_i \sum_j TRANCX_iX_j * X_{pi} * X_{pj} + \sum_p \sum_j \sum_k TRANCX_jX_k * X_{pj} * X_{pk} \tag{3}$$

Inventory cost includes the front-end inventory of selected suppliers due to the lead-time and other issues (e.g., order processing time). Two inventory types are considered: component inventory

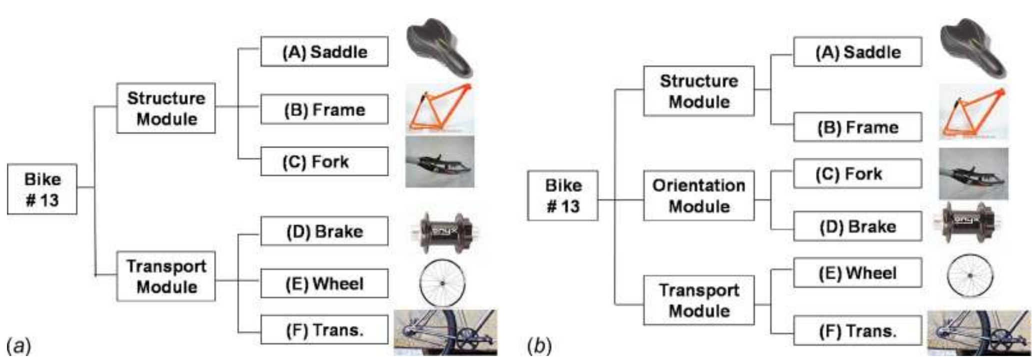

Fig. 12 Two-module product architectures (*a*) and three-module case (*b*)

Table 5 The transition matrix with possible assembly processes

	Process														
	Final assembly		Module assembly							Component process					
State	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Final product	+1	+1													
Module ABC	−1		+1		+1										
Module DEF	−1			+1		+1									
Module AB		−1			−1		+1								
Module CD		−1						+1							
Module EF		−1				−1			+1						
Component A			−1				−1			+1					
Component B			−1				−1				+1				
Component C			−1		−1			−1				+1			
Component D				−1		−1		−1					+1		
Component E				−1					−1					+1	
Component F				−1					−1						+1

at module suppliers and module inventory at final assembly supplier. After interviewing several engineers from a bike company, we ascertained that the inventory cost has a positive relationship with the component and the transportation cost (i.e., when the component has a higher cost, the inventory cost is greater). Accordingly, since the transportation expense is considerable, a company will increase the inventory level to reduce the transportation frequency. Hence, the inventory cost is modeled as a percentage of the component cost (α) and a percentage of the transportation cost (β).

$$C_3 = \alpha C_1 + \beta C_2 \tag{4}$$

3.5.3 Constraints. For the assembly process, some processes and states are mutually exclusive. For example, final assembly process 1 in Table 4 is mutually exclusive with process 2 since they represent different product architectures with different modules. In the same manner, the supporting subassembly process of processes 1 and 2 will differ. In the sample, subassembly processes 3 and 6 will support final assembly process 1. Accordingly, final assembly process 2 is supported by subassembly processes 4 and 5. To avoid the incoherent sequences, Eq. (5) is required; it presents the condition of coexistence in inflow and outflow of component, module, and final product stages.

$$\sum_p T_{sp} * Y_p \geq 0, \quad \forall p \in P \tag{5}$$

The number of parts will decrease during assembly processes. Therefore, the summary of the entity value will be smaller than 0 in every process. Equation (6) is the mathematical formulation to ensure this.

$$\sum_s T_{sp} \leq 0, \quad \forall s \in S \tag{6}$$

Each process is assigned to only one supplier that is capable of process p. The supplier that provides the process will be marked as 1, otherwise 0. Equations (7)–(9) denote this property.

$$\sum_i X_{pi} = 1, \quad \forall p \in P \tag{7}$$

$$\sum_j X_{pj} = 1, \quad \forall p \in P \tag{8}$$

$$\sum_k X_{pk} = 1, \quad \forall p \in P \tag{9}$$

The lead-time here refers to the total time required to manufacture a bike including component manufacturing, module assembly, final assembly, transportation, work-in-process wait times, etc. The maximum lead-time is the maximum value that exists across all possible suppliers. Lead-time serves as a measure of agility of the supply chain network. The pseudocode expression is provided below.

$$\begin{aligned} \text{Total lead-time} = \text{Max} \{ & \text{component lead-time} \\ & + \text{component transportation time} \\ & + \text{module lead-time} \\ & + \text{module transportation time} \\ & + \text{final product lead-time} \} \end{aligned}$$

Table 6 Worldwide component supplier survey results

ID	Supplier	(A) Saddle	(B) Frame	(C) Fork	(D) Brake	(E) Wheel	(F) Trans	Location
1	X-bike		√	√				USA East
2	2-HIp	√	√					USA West
3	BBB	√			√	√	√	Holland
4	Bombshell		√	√		√	√	USA West
5	ATOM Lab	√	√		√	√	√	USA West
6	Axxis		√					USA West
7	SRAM			√	√		√	USA East
8	Velo	√						Taiwan
9	Tektro				√			Taiwan
10	Shimano				√	√	√	Japan
11	ALEX					√		Taiwan
12	Spinner			√				Taiwan
13	Falcon				√		√	Taiwan

Table 7 Worldwide module supplier survey results

ID	Supplier	(AB)	(CD)	(EF)	(ABC)	(DEF)	(ABCDEF)	Location
1	X-bike				√		√	USA East
2	2-HIp	√						USA West
3	BBB			√		√		Holland
4	Bombshell		√	√	√			USA West
5	ATOM Lab	√		√		√		USA West
6	Axxis							USA West
7	SRAM		√					USA East
8	Velo							Taiwan
9	Tektro							Taiwan
10	Shimano			√		√		Japan
11	ALEX							Taiwan
12	Spinner							Taiwan
13	Falcon							Taiwan

The mathematical formulation is provided in Eq. (10):

$$\mathrm{LEAD} = \mathrm{Max}\{X_{pi} * L_{pi} + \mathrm{TRANTX}_i X_j + X_{pi} * L_{pj} + \mathrm{TRANTX}_j X_k + X_{pk} * L_{pk}\} \tag{10}$$

$$\mathrm{LEAD} \le \mathrm{L\_MAX} \tag{11}$$

$$\mathrm{LEAD} \ge \mathrm{L\_MIN} \tag{12}$$

Equations (11) and (12) serve as constraints. When there is a trade-off between cost and time, decision maker can regulate the acceptable total lead-time range to find the corresponding total cost.

The cost constraint of the supply chain can be expressed as provided below. Equation (13) comes from the assumption that the process cost has positive relation with customer satisfaction. The decision maker might want to maintain a minimum level of customer satisfaction when budget allows.

$$C_1 + C_2 + C_3 \le \mathrm{C\_MAX} \tag{13}$$

All variables in Eq. (14) are binary variables. Other variables in Eq. (15) are positive values.

$$Y_p, X_{pi}, X_{pj}, X_{pk} \in \{0,1\} \tag{14}$$

$$\mathrm{L\_MAX}, \mathrm{L\_MIN}, \mathrm{C\_MAX} \ge 0 \tag{15}$$

The best concept using the transition matrix and the mixed-integer programming model is selected as the output of phase II.

4 Application

We demonstrate the methodology using a bicycle case study. Based on the functions and usages, bicycles can be divided into five different types: the road bike, the mountain bike, the city and path bike, the children's bike, and bicycle motocross (BMX) [40]. In this case study, the city and path bike is chosen as our focus.

The general architecture of a bike can be broken down, as shown in Fig. 7. The components of the first level are structure, braking system, transmission system, and wheel system. Structure is composed of three subsystems: fork, frame, and saddle. The braking system, as its name implies, is responsible for decelerating the bike speed. Another important subsystem 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 subsystems are modular designs, which are mutually independent but cooperate as a whole product. Other two subsystems 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 six components and functions, excluding the motor and accessories.

The supply chain structure of a bike can be described in four layers. The upstream layer in Fig. 8 is subsuppliers, which provide raw materials. The second layer is suppliers who produce components of the bike. The next one is the focal company, which focuses on the assembly process and the manufacturing of key components. Finally, the last layer includes distributors who set up the market channels and provide services to customers. 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 [41]. 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 [41]. In addition, road bike sales occupied 30.6% of the market share in 2005 [42], which is the biggest segment of the market.

In this case study, X-bike is a 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–$100 USD. According to prior experience, the inventory cost is around 3% of component cost plus 50% of transportation cost. In addition, the planned total quantity of the final product will be 10,000 units per month. The management of the company would like to have an acceptable lead-time that can respond to market

Table 8 Estimated key processes

Process	Key Processes
(A) Saddle	Stamping/foam molding/profile shearing/sewing
(B) Frame	Cutting/welding/heat treatment/shaving/painting
(C) Fork	Welding/bending/shaving/annealing/paint
(D) Brake	Shearing/injection molding/fastening
(E) Wheel	Extrusion/roll forming/drilling/polish/rubber molding
(F) Transmission	Injection molding/stressing/precise forging/finish grinding
(AB)	Module-assembly
(CD)	Module-assembly
(EF)	Module-assembly
(ABC)	Module-assembly
(DEF)	Module-assembly
(ABCDEF)	Final assembly

Table 9 Estimated lead-time of all suppliers

Process conditions	Process No.	Lead-time formulation (L_{pi}, L_{pj}, L_{pk})
<4 days	1–3, 5, and 7–9	Uniform (2,4)+process time
>4 day but <10 days	4, 6, 10, 13, and 15	Uniform (3,7)+process time
>10 days	11, 12, and 14	Uniform (5,10)+process time

Table 10 Estimated cost and time of processes (U refers to uniform distribution)

No.	Supplier	Cost	Time	Lead-time
	(A) Saddle	Process ID: 10		
1	(2) 2-HIp	9	6.5	U(3,7)+process time
2	(3) BBB	8	6	U(3,7)+process time
3	(5) ATOM LAB	6	5	U(3,7)+process time
4	(8) Velo	6	3.5	U(2,4)+process time
	(B) Frame	Process ID: 11		
1	(1) X-Bike	12	18	U(5,10)+process time
2	(2) 2-HIp	10	18	U(5,10)+process time
3	(4) Bombshell	11	26	U(5,10)+process time
4	(5) ATOM LAB	13	17	U(5,10)+process time
5	(7) Axxis	10	21	U(5,10)+process time
	(C) Fork	Process ID: 12		
1	(1) X-Bike	10	10.8	U(5,10)+process time
2	(4) Bombshell	11	8.8	U(3,7)+process time
3	(7) SRAM	14	7.5	U(3,7)+process time
4	(12) Spinner	16	6	U(3,7)+process time
	(D) Brake	Process ID: 13		
1	(3) BBB	5	3	U(2,4)+process time
2	(5) ATOM LAB	5.2	2.6	U(2,4)+process time
3	(7) SRAM	6	4.8	U(3,7)+process time
4	(10) Shimano	6.6	2.5	U(2,4)+process time
5	(12) Falcon	6.8	2.2	U(2,4)+process time
	(E) Wheel	Process ID: 14		
1	(3) BBB	9	11.4	U(5,10)+process time
2	(4) Bombshell	8	12.2	U(5,10)+process time
3	(5) ATOM LAB	8.5	10.4	U(5,10)+process time
4	(10) Shimano	8.5	10.6	U(5,10)+process time
5	(11) ALEX	8	9.8	U(3,7)+process time
	(F) Trans.	Process ID: 15		
1	(3) BBB	8	5.5	U(3,7)+process time
2	(4) Bombshell	10	5	U(3,7)+process time
3	(5) ATOM LAB	12	4.5	U(3,7)+process time
4	(7) SRAM	14	4	U(2,4)+process time
5	(10) Shimano	15	3.5	U(2,4)+process time
6	(13) Falcon	13	3	U(2,4)+process time
	(AB) Module	Process ID: 7		
1	(2) 2-HIp	5	2	U(2,4)+process time
2	(5) ATOM LAB	8	1.7	U(2,4)+process time
	(CD) Module	Process ID: 8		
1	(4) Bombshell	9	0.4	U(2,4)+process time
2	(7) SRAM	7	0.5	U(2,4)+process time
	(EF) Module	Process ID: 9		
1	(3) BBB	3	2.5	U(2,4)+process time
2	(4) Bombshell	4	2.3	U(2,4)+process time
3	(5) ATOM LAB	5	2.1	U(2,4)+process time
4	(10) Shimano	6	2	U(2,4)+process time
	(ABC) Module	Process ID: 3, 5		
1	(1) X-Bike	10	3	U(2,4)+process time
2	(4) Bombshell	12	2.5	U(2,4)+process time

Table 10 (*Continued.*)

No.	Supplier	Cost	Time	Lead-time
	(A) Saddle	Process ID: 10		
	(DEF) Module	Process ID: 4, 6		
1	(3) BBB	8	4	U(2,4)+process time
2	(5) ATOM LAB	11	3.4	U(2,4)+process time
3	(10) Shimano	13	3	U(2,4)+process time
	(ABCDEF) Module	Process ID: 1, 2		
1	(1) X-Bike	10	2	U(2,4)+process time

dynamics. Current lead-time target is 75 days starting from components manufacturing and ending 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 in terms of cost and time.

4.1 EMS Model and Component Mapping. The design team generates the EMS model of the road bike according to customer requirements. As provided in Fig. 9, the EMS model starts with the human body climbing on the saddle. This action contains "import" and "assemble." The saddle provides "position" and "support" functions. The frame "stabilizes" the human body and the fork will "orient" the direction based on the visual signal. The transmission system will "convert" human energy into rotational energy, and then the rotational energy "converts" to mechanical energy on the wheel to move forward. Accordingly, the braking system is "actuated" by a visual signal and converts human energy to mechanical energy to slow down the bike. The mapping of components and functions is also shown in Fig. 9.

4.2 Design Repository and Modularization. The functional rules in the EMS model are input separately into the design repository [30]. Every component is associated with a functional rule and evaluated using the DfA index (as shown in Fig. 10). After all functional rules and components have been input, design concepts can be generated in the design repository. The user needs to input the EMS model of a complete product. All possible design concepts are generated automatically. In this case, 64 concepts with good DfA scores are generated for the transition matrix method, as shown in Fig. 11. The concept with the best DfA score is chosen. This concept is considered for the component cost optimization as part of phase 1 of the proposed methodology. DfA index serves as a filter that screens for the better design concepts. The optimal design concept along with its suppliers and total cost is then compared with phase II output, where the supply chain structure is also considered.

The above chosen concept is 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 without suspension, (C) steel fork without suspension, (D) single speed transmission, (E) reverse brake rotor, and

Table 11 Dimension and weight information for bike components

Component	Dimension (mm^3)	Volume (cm^3)	Volume (M^3)	Weight (g)
Saddle	$130\times280\times50$	1,820	0.00182	220
Frame	$1000\times600\times120$	72,000	0.072	3500
Fork	$450\times45\times120$	2,430	0.00243	1200
Brake	$80\times120\times120$	1,152	0.001152	1290
Wheel	$700\times700\times50$	24,500	0.0245	3200
Trans.	$200\times200\times50$	2,000	0.002	625

Table 12 Transportation costs of bike components

Components	Freight class	Sea shipping cost (USD)	CA– >PA (USD)	IL– >PA (USD)	NY Dock– >PA (USD)
Saddle	70 (fabrics)	0.10	0.293	0.139	0.218
Frame	60 (steel pipe)	3.95	0.402	0.187	0.932
Fork	60 (steel pipe)	0.13	0.974	0.476	0.457
Brake	70 (tools-non-electric)	0.06	1.163	0.584	0.546
Wheel	60 (steel pipe)	1.34	2.066	1.007	0.934
Trans.	85 (transmission)	0.11	0.689	0.319	0.357

(F) wheels with steel spokes. Two- and three-module product architectures are considered in this application, which are shown in Fig. 12.

4.3 Transition Matrix and Mixed-Integer Programming. After analyzing all feasible product architectures, possible assembly processes are shown in Table 5. For the overall bike architecture, the processes can be classified into three groups: final assembly, module assembly, and component process. The assembly processes vary based on product architectures. For example, processes 1 and 3–6, which are values in boldface, are possible processes of the two-module architecture. Meanwhile, processes 2 and 7–9 are for the three-module architecture.

In addition, possible bike suppliers are surveyed worldwide [43–45]. For this case study, 12 suppliers were carefully selected as candidates for the supply chain partners based on their technological capability. Tables 6 and 7 present their manufacturing and assembly capacity with a "√" mark. The locations of these suppliers are marked as a key factor for the transportation time. The physical addresses and contact information of suppliers are provided in the Appendix.

The planned total quantity of the final product is 10,000 units per month, and the cost structure includes engineering cost, material cost, and manufacturing cost [46]. Due to mass production, manufacturing costs dominate the cost structure. The cost drivers of the manufacturing cost contain batch setup cost, processing cost, and the overhead cost. As for the process time, the key manufacturing processes of every stage are identified (see Table 8) and estimated as per guidelines in Refs. [47–49]. In addition to manufacturing time, order processing time, work in process (WIP) time, etc., can influence the lead-time. In order to account for these, we have added "other time" components to the manufacturing time to yield the lead-time. The other time is modeled using a uniform distribution to estimate the overall lead-times of all suppliers, as was done in Ref. [21]. As shown in Table 9, if the maximum process time of a process ID is smaller than 4 days (e.g., processes 1–3, 5, and 7–9), the total lead-time is calculated as the sum of process time, and the uniform (2, 4). When the maximum process time is between 4 days and 10 days (i.e., for processes 4, 6, 10, 13, and 15), we add uniform (5, 10) to the process time. The assumption here is that the total lead-time is impacted by the number of processes, and the relevant WIPs wait in between processes.

The estimated process cost, process time, and lead-time for all components and modules are listed in Table 10 [15,50]. For (A) saddle, the process ID is 10 in the transition matrix (Table 5). There are four potential suppliers that have the required manufacturing capability. For example, the process cost of supplier 2-HIp is $9 USD, the process time is 6.5 days, and the total lead-time is the sum of process time and uniform (3, 7) under mass production conditions.

In addition to manufacturing cost, transportation cost is also taken into account in our model. To estimate the approximate transportation cost, we dissected a bike and measured the dimension and weight information for each key component. This information is provided in Table 11. In a global supply chain network, the freight can be shipped by air, sea, or land. Since air shipment is too expensive for a mass produced product, we survey the cost estimation of land [51,52] and sea [53,54] shipments. For land shipment, we assume that the freight is (1) less than a truck-load, (2) the batch size is 1000 units, (3) the location type is business with a dock or a forklift, (4) no extra service and pallet preparation fee is required, and (5) box packed. The inventory policy is (S, s). The capacity of the factory is 10,000 units per month, which means that the production planner of this supply chain network will order components every 3 days. For the sea shipment, we estimate the cost of components according to their volume in a 20 ft standard steel container [53]. Therefore, we can compute the transportation cost of the components as provided in Table 12.

Transportation time is another key performance measure. We used logistics websites [52,54] to estimate the transportation duration via land and sea shipments; our findings are provided in Table 13. The transportation time covers shipping, commodity inspection, paperwork, and other tasks.

There are 122 variables and 100 constraints in this model. LINGO 9 is used to solve this mixed-integer nonlinear mathematical model.

4.4 Results and Discussion

4.4.1 Comparison of the Two Phases. We have compared the supply chain performance of the product concept chosen after the DFA index screening. In our comparisons, we took into account different product architectures through the use of the transition matrix. In phase I of the presented work, we have assumed that designers are not taking into account the supply chain issues (e.g., transportation costs, etc.) but they focus on component cost minimization. Note that available components for selection are from various suppliers with adequate technological capabilities. In phase II, all possible product architectures as well as supply chain issues are taken into account. Table 14 and Fig. 13 present the comparison results.

Table 13 Transportation time of bicycle components (in days)

Area	Taiwan	Japan	Holland	USA East	USA West
Taiwan	1	5	35	40	25
Japan	5	1	40	35	25
Holland	35	40	1	30	40
USA East	40	35	30	1	6
USA West	25	25	40	7	3

Table 14 Comparison of the two phases

	Comparison		
	Phase I	Phase II	
Objective function	Minimum component cost (a) (USD)	Minimum total cost (b) (USD)	Minimum total lead-time (c) (days)
Component cost (USD)	47	48	55.7
Assemble cost (USD)	30	25	31
Transportation cost (USD)	9.58	4.74	4.12
Inventory cost (USD)	6.99	4.46	4.54
Total cost (USD)	93.58	82.20	95.35
Difference	14%	-	16%
Total lead-time (days)	93.23	57.88	33.71
Difference	61%	-	–42%
Number of suppliers	7	5	3
Part type		Supplier (process No.)	
ABCDEF	X-bike (1)	X-bike (1)	X-bike (1)
ABC			X-bike (3)
DEF			ATOM LAB (4)
AB	ATOM LAB (7)	2 Hip (7)	
CD	Bombshell (8)	SRAM (8)	
EF	BBB (9)	BBB (9)	
A	Velo (10)	ATOM LAB (10)	ATOM LAB (10)
B	2 Hip (11)	2 Hip (11)	X-bike (11)
C	X-bike (12)	X-bike (12)	X-bike (12)
D	BBB (13)	BBB (13)	ATOM LAB (13)
E	ALEX (14)	BBB (14)	ATOM LAB (14)
F	BBB (15)	BBB (15)	SRAM (15)

Figure 13(*a*) provides the supply chain network that is the outcome of component cost minimization and Fig. 13(*b*) presents the supply chain network that is the outcome of total cost minimization. Note that for both solutions three-module architectures are chosen; however, the selected suppliers are different. Figure 13(*c*) shows the total lead-time minimization case for the supply chain, where the resultant architecture consists of two modules. These different supply chain structures have different supply chain performance values, which are provided in Table 14. As it would be anticipated, phase I output has the minimum component cost, $47. However, phase II total cost minimization provides the better cost point, $82.20, in comparison with the phase I total cost outcome,

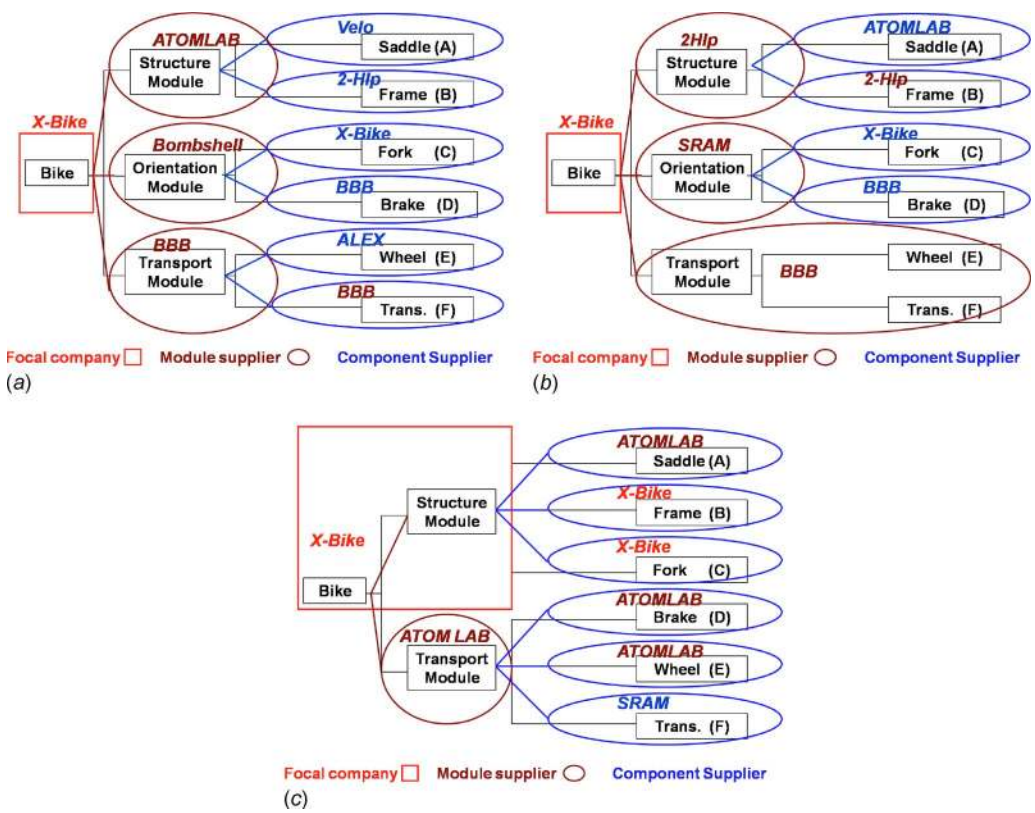

Fig. 13 (***a***) **Phase I: only PD optimization,** (***b***) **both PD and SC optimizations in phase II** (**cost minimization**)**, and** (***c***) **both PD and SC optimizations in phase II** (**lead-time minimization**)

Table 15 Supplier information

Supplier	Physical address	Website	Location
2-HIp	P.O. Box 462, Santa Cruz, CA 95062	http://www.2hip.com/	USA West
BBB	P.O. Box 1297, 2302 BG Leiden, Holland	http://www.bbbparts.com/	Holland
Bombshell	9565 Pathway St., Ste. B, Santee, CA 92071	http://www.bombshellparts.com/	USA West
ATOM LAB	26370 Diamond Place, #505, Santa Clarita, CA 91350	http://www.atomlab.com/	USA West
Axxis	328 A. Malbert St., Perris, CA 92570	http://www.axxisbicycles.com/	USA West
SRAM	1333 N. Kingsbury, 4th Floor, Chicago, IL 60622	http://www.sram.com/	USA East
Velo	1012, Sec. 1, Chung Shan Rd., Tachia, Taichung Hsien, Taiwan	http://www.velosaddles.com	Taiwan
Tektro	No. 138, Minzhu St., Xiushui Township, Changhua County, Taiwan	http://www.tektro.com	Taiwan
Shimano	3-77 Oimatsu-cho, Sakai-ku, Sakai, Osaka 590-8577, Japan	http://corporate.shimano.com/	Japan
ALEX	No. 21-2, Pel-Shi Chou, Min-Ho Village, Shan-shang Hsiang, Tainan, Taiwan	http://www.aclass-wheels.com	Taiwan
Spinner	34 Chia-Hou Rd., Liu Feng Tsuen, Waipu Hsiang,Taichung County, Taiwan	http://www.spinner-usa.com	Taiwan
Falcon	P.O. Box 1-57, Feng Yuan, Taichung, Taiwan		Taiwan

$93.58. The total cost under the lead-time minimization case for phase II is $95.35. Total lead-time differences across the two phases (and three different supply chains) are different as well. Clearly, the phase II lead-time minimization case provides the shortest lead-time solution, 33.71 days. Phase I output has a lead-time of 93.23 days, which is ~2.8 times longer than the optimum. Total cost minimization case of phase II yields a lead-time of 57.88 days. In addition, the lead-time of phase I is longer than the original target lead-time of 75 days and hence is not acceptable. This might result in iterations in the design process.

We found that (E) wheel is manufactured in ALEX, which is located in Taiwan. It is shipped to BBB in Holland to be assembled as a module (EF). After that, module (EF) needs to travel to X-Bike in the USA. A similar case is true for the structure module (AB). While the component costs are very competitive in these locations, extra shipments cause the increase in total cost and lead-time. From the management vantage point, phase I solution has to manage seven suppliers. At the same time, phase II solution requires five suppliers (for the total cost minimization case) or as little as three suppliers (for the lead-time minimization case). The reduction in suppliers can also limit the operational complexity. These results disclose the significant difference of considering supply chain decisions at the product design stages.

4.4.2 Discussion. One of the traditional efforts for improving the product development efficiency and reduction of supply chain risk is the early supplier involvement [55]. This, in fact, has built the competitive advantage of Japanese auto industries around 1970s–1990s. However, this strategy not only limits the supply chain flexibility but also its diversity, which might reduce the potential of being responsive for mass customization purposes. The case presented above demonstrates the advantages of coordination between product and supply chain. The bike is positioned as a functional product since it has (1) a stable market demand and (2) a long product life. In addition, the dominant design of a bicycle has been established for more than one century attesting to the mature phase of its life cycle. According to Vonderembse et al. [20], designing a lean supply chain that focuses on low cost, high quality, and limited flexibility can strongly support mature products. Lean supply chain can conserve the cost of coordination between suppliers and manufacturers, fabrication, inventory, and material handling by eliminating nonvalue added activities. However, the drawback of limited flexibility in a supply chain network might be serious if an unexpected demand burden occurs.

Selldin and Olhager [56] pointed out that the classifications of functional product versus innovative product and efficient versus responsive supply chain are only comparative properties for use while describing the general supply chain characteristics. For companies within an industry, the leader enterprises might be able to achieve the efficient but responsive supply chain performance. The case study presented also is one other evidence that modular product architecture with an appropriate supply chain design and coordination can reduce inventory levels and reduce lead-times. Indeed, prior published works analyzed similar issues. For example, Mikkola and Skjtt-Larsen [57] analyzed the interrelated and complementary strategies among mass customization, postponement, and modularization while managing supply chain integration, Lau and Yam [58] examined the relationship between product modularization and supply chain design and coordination with an industrial case study, and Ro et al. [59] pointed out that modularity accompanied with reorganization of enterprises and supply chain structures is adopted in the U.S. auto industry. However, the case study presented here is much more comprehensive in nature as it includes all possible product architectures (two module and three module) and supply chain configurations. For example, the study of Lau and Yam [58] used a single case firm with specific product architectures across four different products.

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 the focal company and its suppliers. It forms a virtual organization that keeps the low cost level while maintaining a quick response time. Selldin and Olhager [56] 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. With reference to the case study, we note that the selected upstream and downstream suppliers are geographically close to each other. For the cost minimization case, the only non-U.S. location is for BBB (Holland); for the lead-time minimization case, all suppliers are located in the USA. This indicates that an appropriate supply chain design and integration can bring competitive advantages to a company. These observations align well with Michael Porter's clustering effect [60]. Attesting to this, Chen et al. [61] studied the bicycle industry in Taiwan and indicated that 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 a constructive mechanism that enhances the competitive edge of all partners in the network.

As a functional product in the mature phase of its life cycle, product diversity and innovation can stimulate the market demand. The design repository in this research is a platform based database for a company to generate the new product designs with less time and cost. The frame of the current design is made of steel. New materials such as carbon fiber, titanium alloy, aluminum alloy, and magnesium alloy (that are strong, durable, and lightweight) could be considered as future products 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. Another limitation of the current design repository is that it is unsuitable to model much more complex products (i.e., more than 200 components). The possible design concepts will increase exponentially and modularization of this product will be time consuming. However, due to the ever enhancing computational power, we anticipate that this issue is of no major concern. In addition, the interface among components is 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. Future versions of our model will account for this.

5 Conclusion and Future Development

In this paper, the supply chain design is considered 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 a DfA index and then are modularized. Singularly considered DfA and a graph based transition matrix method with supply chain consideration are compared and discussed to demonstrate the benefit of this methodology in design for the supply chain area. The presented model can serve as a decision making support system with which decision makers can analyze, predict, control, and assure the success of both the product and the enterprise at the design stage. At this point, disclosure of supply chain-related information can convey higher flexibility and longer time to prepare and respond to potential impacts. Therefore, a competitive advantage is possible. In addition, this method can be a sensitivity analysis function, which will be a precautionary tool to prevent 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.

In this work, only DfA and DfSC are considered; other DfX factors [31], e.g., sustainability, environment, and recyclability, could be incorporated at the design phase to support a green planet. In the current transition matrix model, most variables (other than lead-times) 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. 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 after incorporation of these criteria

Appendix: Supplier Information

The supplier information is shown in Table 15.

References

[1] Krishnan, V., and Ulrich, K. T., 2001, "Product Development Decisions: A Review of the Literature," Manage. Sci., **47**(1), pp. 1–21.
[2] Supply Chain Council, 2009, http://www.supply-chain.org/
[3] Lambert, D. M., and Cooper, M. C., 2000, "Issues in Supply Chain Management," Ind. Mark. Manage., **29**(1), pp. 65–83.
[4] Appelqvist, P., Lehtonen, J. M., and Kokkonen, J., 2004, "Modeling in Product and Supply Chain Design: Literature Survey and Case Study," Journal of Manufacturing Technology Management, **15**(7), pp. 675–686.
[5] Dowlatshahi, S., 1992, "Purchasing's Role in a Concurrent Engineering Environment," Int. J. Purch. Mater. Manage., **28**(1), pp. 21–25.
[6] Cooper, R. G., 2001, *Winning at New Products: Accelerating the Process From Idea to Launch*, 3rd ed., Perseus Publishing Ltd., Cambridge, MA.
[7] Adams, M., 2004, *PDMA Foundation New Product Development Report of Initial Findings: Summary of Responses From 2004 CPAS*, Product Development and Management Association, Mount Laurel, NJ.
[8] Fisher, M., 1997, "What is Right Supply Chain for Your Product?," Harvard Bus. Rev., **75**(2), 105–116.
[9] Ulrich, K. T., and Ellison, D. J., 2005, "Beyond Make-Buy: Internalization and Integration of Design and Production," Prod. Oper. Manage., **14**(3), pp. 315–330.
[10] Aamer, A. M., and Sawhney, R., 2004, "Review of Suppliers Selection From a Production Perspective," Proceedings of the IIE Annual Conference and Exhibition 2004, pp. 2135–2140.
[11] Chan, F. T. S., 2003, "Performance Measure in a Supply Chain," Int. J. Adv. Manuf. Technol., **21**, pp. 534–548.
[12] Sarkis, J., and Talluri, S., 2002, "A Model for Strategic Supplier Selection," The Journal of Supply Chain Management, **38**(1), pp. 18–28.
[13] Yassine, A. A., and Wissmann, L. A., 2007, "The Implications of Product Architecture on the Firm," Systems Engineering, **10**(2), pp. 118–137.
[14] Itoh, M., 2004, "Product Competitive Advantage and Product Architecture—Value Creation and Value Capture in the Digital Camera Industry," Proceedings of the 2004 IEEE International Engineering Management Conference, pp. 263–268.
[15] Ulrich, K. T., and Eppinger, S. D., 2004, *Product Design and Development*, 3rd ed., McGraw-Hill, New York.
[16] Boothroyd, G., 1994, "Product Design for Manufacture and Assembly," Comput.-Aided Des., **26**(7), pp. 505–520.
[17] Gershenson, J. K., Prasad, G. J., and Zhang, Y., 2003, "Product Modularity: Definitions and Benefits," J. Eng. Design, **14**(3), pp. 295–313.
[18] Jiao, J., Simpson, T. W., and Siddique, Z., 2007, "Product Family Design and Platform-Based Product Development: A State-of-the-Art Review," J. Intell. Manuf., **18**(1), pp. 5–29.
[19] Mikkola, J. H., 2007, "Management of Product Architecture Modularity for Mass Customization: Modeling and Theoretical Considerations," IEEE Trans. Eng. Manage., **54**(1), pp. 57–69.
[20] Vonderembse, M. A., Uppal, M., Hunag, S. H., and Dismukes, J. P., 2006, "Designing Supply Chains: Toward Theory Development," Int. J. Prod. Econ., **100**, pp. 223–238.
[21] Fine, C. H., Golany, B., and Naseraldin, H., 2005, "Modeling Tradeoffs in Three-Dimensional Concurrent Engineering: A Goal Programming Approach," J. Operations Manage., **23**(3–4), pp. 389–403.
[22] Lee, H. L., and Sasser, M. M., 1995, "Product Universality and Design for Supply Chain Management," Prod. Plan. Control, **6**(3), pp. 270–277.
[23] Ogot, M., and Kremer, G. E., 2004, *Engineering Design: A Practical Guide*, Trafford Publishing, Victoria, BC, Canada.
[24] Zhu, Y., You, J., and Alard, R., 2008, "Design Quality: The Crucial Factor for Product Quality Improvement in International Production Networks," International Conference on Wireless Communications, Networking and Mobile Computing, Dalian, China, Oct. 12–14.
[25] Tenneti, B., and Allada, V., 2008, "Robust Supplier Set Selection for Changing Product Architectures," Int. J. Comput. Appl. Technol., **31**(3/4), pp. 197–214.
[26] Gökhan, N. M., Needy, K. L., Norman, B. A., and Hunsaker, B., 2008, "Benefits of Incorporating Supply Chain Decisions Into the Product Design via Design for Supply Chain," Proceedings of the IIE Annual Conference and Expo 2008, pp. 390–395.
[27] Fixson, S. K., and Park, J.-K., 2008, "The Power of Integrality: Linkages Between Product Architecture, Innovation, and Industry Structure," Res. Policy, **37**(8), pp. 1296–1316.
[28] Gupta, S., and Okudan, G. E., 2008, "Computational Modularized Conceptual Designs With Assembly and Variety Considerations," J. Eng. Design, **19**(6), pp. 533–551.
[29] Stone, R. B., and Wood, K. L., 2000, "Development of a Functional Basis for Design," ASME J. Mech. Des., **122**(4), pp. 359–370.
[30] Bohm, M. R., Vucovich, J. P., and Stone, R. B., 2005, "Capturing Creativity Using a Design Repository to Drive Concept Innovation," Proceedings of the 2005 ASME IDETC and CIE Conference, Paper No. DETC2005-85105.
[31] Chiu, M.-C., and Okudan, G. E., 2010, "An Investigation of the Applicability of DfX Tools During Design Concept Evolution," Journal of Product Development, to be published.
[32] Rampersad, H. K., 1995, *Integrated and Simultaneous Design for Robotic Assembly*, Wiley, London.
[33] Hsu, W., Fuh, J. Y. H., and Zhang, Y., 1998, "Synthesis of Design Concepts From a Design for Assembly Perspective," Comput.-Integr. Manuf. Syst., **11**(1–2), pp. 1–13.
[34] Huang, C.-C., and Kusiak, A., 1998, "Modularity in Design of Product and Systems," IEEE Trans. Syst. Man Cybern., **28**(1), pp. 66–77.
[35] Lambert, A. J. D., 1999, "Linear Programming in Disassembly/Clustering Sequence Generation," Comput. Ind. Eng., **36**(4), pp. 723–738.
[36] Lambert, A. J. D., 2001, "Automatic Determination of Transition Matrices in Optimal Disassembly Sequence Generation," Proceedings of the 2001 IEEE International Symposium on Assembly and Task Planning, pp. 220–225.
[37] Lambert, A. J. D., 2002, "Determining Optimum Disassembly Sequences in

Electronic Equipment," Comput. Ind. Eng., **43**(3), pp. 553–575.
[38] Lambert, A. J. D., 2007, "Optimizing Disassembly Processes Subjected to Sequence-Dependent Cost," Comput. Oper. Res., **34**(2), pp. 536–551.
[39] Min, J. K., Yoo, S. H., and Nam, W. C., 2007, "Eco-Architecture Analysis as a Method of End-of-Life Decision Making for Sustainable Product Design," Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 3, pp. 499–511, Paper No. DETC2007-35882.
[40] Wu, S., 2004, "A Study on Computer Aided Design System—With the Mountain Bike Design as an Example," MS thesis, Huafan University, Taipei, Taiwan.
[41] National Bike Dealers Association, 2009, http://nbda.com
[42] Market Share Reporter, 2007, *Market Share Reporter: An Annual Compilation of Reported Market Share Data on Companies, Products, and Services*, Gale Research, Inc., Detroit, MI.
[43] Bike Net-Bike Manufacturer Directory, 2009, http://www.bicycle.net/resources/bicycle-manufacturer-directory
[44] Bicycle Manufacturers Association of America, 2009, http://www.ftc.gov/opp/jointvent/madeusa/ftp/usa/086.txt
[45] Best Bike Buys-Bike Manufacturer, 2009, http://www.bestwebbuys.com/bikes/browse/t/manufacturer/
[46] Chang, T.-C., Wysk, R. A., and Wang, H.-P., 2005, *Computer-Aided Manufacturing*, 3rd ed., Prentice Hall, Upper Saddle River, NJ.
[47] Ballantine, R., and Grant, R., 1998, *Ultimate Bicycle Book*, DK Publishing Inc., New York.
[48] Taiwan Bicycle Exporter's Association, 2009, http://www.tbea.org/english/all.htm
[49] Bike Pro.com, 2009, http://www.bikepro.com/products/rims/rimover.shtml
[50] Boothroyd, G., Dewhurst, P., and Knight, W., 2002, *Product Design for Manufacture and Assembly*, 2nd ed., Marcel Dekker, New York.
[51] How to Calculate Truckload Cost, 2010, http://www.ehow.com/how_5714906_calculate-truck-shipping.html
[52] Freight Center Quick Quote, 2010, http://www.freightcenter.com/QuickQuote.aspx
[53] Sea Freight Calculations, 2010, http://www.exporthelp.co.za/modules/16_logistics/sea_freight_calculations.html
[54] Sea rate.com, 2010, http://www.searates.com
[55] Wasti, N. S., and Liker, J. K., 1999, "Collaborating With Suppliers in Product Development: A U.S. and Japan Comparative Study," IEEE Trans. Eng. Manage., **46**(4), pp. 444–461.
[56] Selldin, E., and Olhager, J., 2007, "Linking Products With Supply Chains: Testing Fisher's Model," Supply Chain Management: An International Journal, **12**(1), pp. 42–51.
[57] Mikkola, J. H., and Skjøtt-Larsen, T., 2004, "Supply-Chain Integration: Implications for Mass Customization, Modularization and Postponement Strategies," Prod. Plan. Control, **15**(4), pp. 352–361.
[58] Lau, A. K. W., and Yam, R. C. M., 2005, "A Case Study of Product Modularization on Supply Chain Design and Coordination in Hong Kong and China," Journal of Manufacturing Technology Management, **16**(4), pp. 432–446.
[59] Ro, Y. K., Liker, J. K., and Fixson, S. K., 2007, "Modularity as a Strategy for Supply Chain Coordination: The Case of U.S. Auto," IEEE Trans. Eng. Manage., **54**(1), pp. 172–189.
[60] Porter, M. E., 1990, *The Competitive Advantage of Nations*, The Free Press, New York.
[61] Chen, Y.-S., Lin, M.-J., Chang, C.-H., and Liu, F.-M., 2009, "Technological Innovations and Industry Clustering in the Bicycle Industry in Taiwan," Technol. Soc., **31**(3), pp. 207–217.