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An investigation on the impact of product modularity level on supply chain performance metrics: an industrial case study

Ming-Chuan Chiu · Gül Okudan

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Abstract The benefit of integrating product design decisions and supply chain design decisions has been recognized by researchers. Such integration can facilitate better communication between design teams and operations groups. Consequently, potential supply chain risks can be highlighted and addressed before the launch of a new product. Modularization is one of the most critical elements for both product design and supply chain design decisions as it impacts the assembly sequence and hence the selection of component and module suppliers. However, the impact of modularity level on supply chain performance is still unclear, and thus is the focus of this study. The proposed analytical method incorporates both product design and supply chain design functions, and hence, enables simultaneous consideration of these decisions. The supply chain performances of all two-module and three-module design concepts are fully investigated in an effort to explore the impact of modularity level on supply chain performance. Results show that increased modularity is advantageous for the time-based performance of a supply chain network, whereas decreased modularity yields superiority in terms of cost performance.

Keywords Product design · Supply chain design · Modularity · Supplier selection

Introduction

A supply chain consists of all parties involved both directly and indirectly in fulfilling a customer's product request. The players include not only the manufacturer and suppliers but also the transporters, warehousers, retailers, and customers themselves (Chopra and Meindel 2006). Supplier selection also plays a critical role in supply chain management. Companies not only need to decide whether to "make" or "buy" but also to be able to differentiate among potential suppliers in order to improve supply chain performance.

We propose that product and supply chain design decisions should be integrated within the initial product design phase because there are interdependent implications between the product structure and its associated supply chain. As noted by Krishnan and Ulrich (2001), product development is an innovative process that transforms potential market opportunities into products according to product and process technologies. Product design, in general, is an iterative and complex process, which includes defining, conceptualizing, and eventually commercializing a product into a new or existing market. According to a survey published during the past decade (Adams 2004), less than 60 % of new products are launched successfully. Researchers have pointed to a lack of coordination between a product and its supply chain as a key reason for this failure (Appelqvist et al. 2004; Fisher 1997; Fine et

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al. 2005). Despite this, most research on the design and management of the supply chain emphasizes production and distribution, with only limited efforts made toward integrating product and supply chain design decisions at the early design stage (Blackhurst et al. 2005; Fine et al. 2005; Lamothe et al. 2006). Indeed, roughly 70 % of product cost (Appelqvist et al. 2004) and 80 % of product quality (Dowlatshahi 1992) are decided during the design stage. Logically, therefore, the incorporation of supply chain issues as early as possible into the design phase should be given importance, so that potential product architecture options as well as the supplier options can be studied to assess their impact on supply chain performance metrics.

Although products can have integral, modular, or hybrid (combined integral and modular) architectures, modular architecture has gained popularity in recent decades. Modular product architecture is advantageous to the efficiency of enterprise performance as it relates to design, production, operations, and logistics (Fixson 2005; Jiao et al. 2007; Lee and Sasser 1995; Martin and Ishii 1996). However, the way in which different levels of modularity influence supply chain performance has not previously been studied. We address this void in the literature by comparing levels of product modularity on the supply chain performance. Our goal is to better match both product architectural design and supply chain design in order to improve supply chain performance metrics. In addition, we intend to show that uncovering supply chain related information early (at conceptual design stage) will benefit an enterprise in terms of increased flexibility as well as providing a longer time to prepare and respond to potential impacts downstream.

Literature review

Product architecture refers to the schema of physical building blocks in a product and the ways in which they interact (Ulrich and Eppinger 2004). It has broad implications for engineering design, process design, systems engineering, marketing, and organizational science perspectives (Fixson 2005; Ulrich and Eppinger 2004). Product architecture serves as the kernel that connects the customer and the enterprise; it impacts process and portfolio design, and it directs the change, variety, performance, and manufacturability of the product (Fixson 2005; Jiao et al. 2007; Lee and Sasser 1995; Martin and Ishii 1996; Yigit et al. 2002; Ulrich and Eppinger 2004; Su et al. 2010).

Since the early 1990s, traditionally standard, uniform customer requirements have become more divergent and variant. This trend has necessitated the demand for mass customization, the goal of which is to produce customized goods at mass production efficiency by means of providing outstanding service while meeting customers' needs at low cost. Studies have developed designs for variety (Martin and Ishii 1996) and product platform methodologies (Jiao et al. 2007; Martin and Ishii 1996) based on modular architecture due to its superior ability to reduce design efforts. Modular architecture can also enable postponement, since production can be simplified by assembling common components during a front-end process, and the assembly of variant components (which represent variety for customization) can be delayed. In this way, postponement and differentiation can be achieved at a lower cost. Table 1 summarizes the advantages and drawbacks of modular architecture derived from our review of the literature.

In essence, the purpose of modular product design is to effectively group components into a set of sub-systems according to function, process, technology and/or design intention. Two of the key factors of modularity are the degree of independence across modules and the standardization of modular interfaces. A high degree of independence results in easily configuring new product variants, while the standardization of interfaces enables both substitutability and interchangeability as a product demands maintenance and upgrades.

Gershenson et al. (2003) classified modular product design methodology into four main categories: checklist methods, design rules, matrix manipulations, and step-by-step measure and re-design methods; among these, matrix manipulations and step-by-step measure and re-design methods are the most prevalent. The decomposition approach (DA) (Huang and Kusiak 1998) is a matrix-based methodology that clusters components as modules, maintaining maximum similarity among the functional interactions within a module. Matrin and Ishii (2002) developed the generational variety index (GVI) and the coupling index (CI) to modularize product architectures while considering design for variety. Salhieh and Kamrani (1999) applied a similarity index to cluster components into modules. On the other hand, Stone et al. (2000) developed a step-by-step heuristic method to identify modules based on functional models of products; modules are identified in terms of dominant flow, branching flow and conversion-transmission flow.

These modular product design methods were then extended to modular product family design (Fujita 2002; Salvador et al. 2002; Simpson 2004; Zhang et al. 2006), which considers both common and variant modules within a family of products and aims to reduce manufacturing costs while at the same time maximizing customer satisfaction through variety. Likewise, with an aim at mass customization, Jiao and Tseng (1999) developed a market-based module identification method for construction of product family architecture. In their paper, three types of modularity (i.e., functional modularity, technical modularity, and

Table 1 The advantages and drawbacks of modular architecture (Fixson 2007; Fredriksson 2006; Gershenson et al. 2003; Ishii and Yang 2003; Mokkola 2007; Muffatto 1999; Simpson 2004; Ulrich and Eppinger 2004)

Advantages
Design
(a) Design time and cost reduction
(b) Upgradeability
(c) Adaptability
(d) Enabler of product family
Production
(a) Decrease in set-up time, WIP, tools and jigs, factory floor space
(b) Ease of rework, testing, maintenance
(c) Shorter learning curve and higher productivity
Operations
(a) Increased purchasing power due to economies of scale
(b) Decreased lead-time and inventory due to common components
(c) Ease of supplier management when diversity of components decreases
(d) Ease of time and form postponement
(e) Increased flexibility and predictability
Logistics/ support
(a) Improvement of responsiveness
(b) Ease of service
(c) Spare parts reduction
(d) Decrease in management loading and complexity
Drawbacks
Overall
(a) Performance degradation compared to an integral product
(b) Huge investment to small or medium size company
(c) Static product architecture due to reuse of components, which may create problems when breakthrough innovation happens
(d) Hinder further innovation due to (b) and (c)
(e) Over-design in low-end products and indistinctiveness in high-end products
(f) Smaller volume disadvantages on variant and unique components

physical modularity) were studied. The goal of functional modularity is to map customer needs in different market segments, while technical modularity addresses the technical feasibility of design, physical modularity tackles the manufacturability. Consequently, customer needs, technical feasibility and manufacturability can be concurrently considered.

Fisher (1997) was one of the first to recognize the importance of coordination between product and supply chain. As per his analysis, innovative products should have responsive supply chains, and functional products should be arranged with efficient supply chains. More recently, Lau et al. (2010) empirically demonstrated the positive relationship between product modularity and supply chain integration in selected Hong Kong manufacturing industries. Bush et al. (2010) pointed out that product design modularity enhances supply chain responsiveness, and thereby improving the performance of the supply chain.

Fine et al. (2005) investigated the interdependencies among products, processes and the supply chain and developed a goal-programming model—the first quantitative model to analyze the tradeoffs among product architecture alternatives, assembly processes, and supply chain selection decisions. Other methods such as those presented by Blackhurst et al. (2005) and Lamothe et al. (2006) integrated product and supply chain design decisions based on the Bill of Materials (BOM). The research scope of these studies starts from the detail design phase of product design, when the design concepts have already been generated and the specifications for a product have been determined; hence, decisions flowing from them have only limited impact. Chiu and Okudan (2011a) developed an integrative methodology that can simultaneously connect and harmonize product design and supply chain decisions at conceptual design stage. Nepal et al. (2011) applied weighted goal programming model to optimize both supply chain compatibility and total costs. The supply chain performance of integral and modular product architectures are compared and discussed. Ulku and Schmidt (2011) found that modular architectures are more likely in supply chain network when adversarial relationships exist. On the contrary, long term trusted based relationships incubate integral product architectures. Despite their contributions, however, previous studies (Blackhurst et al. 2005; Fine et al. 2005; Lamothe et al. 2006; Chiu and Okudan 2011a; Nepal et al. 2011; Ulku and Schmidt 2011) failed to provide comprehensive analysis for all design concept alternatives along with their supply chain performance.

Indeed, a comprehensive analysis can give decision makers insight that might not otherwise be obvious. If an analysis is provided at the product design stage, company management will have a longer time horizon in which to respond and solve potential issues related to supply chain execution. Accordingly, in this paper, we present a methodology that is applied to an industrial case study to allow an examination of the impact of modularity level on supply chain performance. Below we present the methodology, followed by an introduction to the industrial case study.

Methodology

We investigated the impact of the level of product modularity (operationalized as the number of modules in a product) on supply chain performance using a realistic case study involving a bicycle company located in central Pennsylvania. The partner company sponsored factory visits, provided component cost and time information, made suggestions and verified the feasibility of various modular architectures for a new bicycle design. First, we conducted a series of interviews with the bicycle company management and technical experts. Then, a questionnaire was designed to collect cost and time information, to validate the selection of a bicycle's critical components, and to gather suggestions on modularity allocation. We analyzed the questionnaire responses and then computed the cost and lead-time for the sub-assembly and final assembly using a reverse engineering technique. The data gathered provided the basis—that is, the case study context and parameters—for investigations undertaken to address the original research question. The investigation also involved the use of product architecture design software (Design-ADAPS.1) in conjunction with a mixed integer programming model (Chiu and Okudan 2011a) to enable the integration of product design and supply chain design functions into a cohesive method. Using these methodologies in the case study context along with the values, a set of comparisons was developed to answer the research question.

To use Design-ADAPS.1, product design starts with interpreting customer needs and transforming them into functional requirements. These are then defined and decomposed into the most basic sub-functions to form an Energy-Material-Signal (EMS) functional model. After that, a repository synthesizes the potential components of all sub-functions and provides multiple options for the conceptual design. These concepts are evaluated using a set of Design for Assembly (DfA) criteria (Rampersad 1995). 13 different criteria are collected and evaluated. 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 as follows, where design concepts with lower DFA index values are preferred.

$$\text{DfA index} = 10\left(\sum \mathrm{P_i} - \sum \mathrm{V_{min,i}}\right) \Big/ \left(\sum \mathrm{V_{max,i}} - \sum \mathrm{V_{min,i}}\right) \qquad (1)$$

Here,
P_i : point value for each criterion, $i = 1, \ldots, 13$
$\mathrm{V_{min,i}}$: minimum value for each criterion
$\mathrm{V_{max,i}}$: maximum value for each criterion

Product architecture options are determined through the implementation of the following three steps:

1. Concepts are sorted in increasing DfA index values. Consideration of DfA ensures ease of assembly, although assembly sequences are not taken into account at this step.
2. Suitability analysis of components for possible bundling in a module is done. This analysis requires evaluation of potential modules by industry experts for technical feasibility along with advantages and disadvantages.
3. Design concepts (from step 1) are modularized using decomposition approach (DA).Two matrices are developed under this approach: an interaction matrix and a suitability matrix. Suitability matrix is developed based on the information from step 2. Modular structures are identified after implementing Huang and Kusiak (1998) seven steps for DA: triangularization, rearrangement, combination, deletion, duplication, classification, and termination. Possible assembly sequences are also analyzed.

Next, supply chain information about the modularized design concepts such as suppliers, processes, transportation methods, inventory levels, costs, and lead-times are collected and formulated into Chiu and Okudan's mixed integer program-

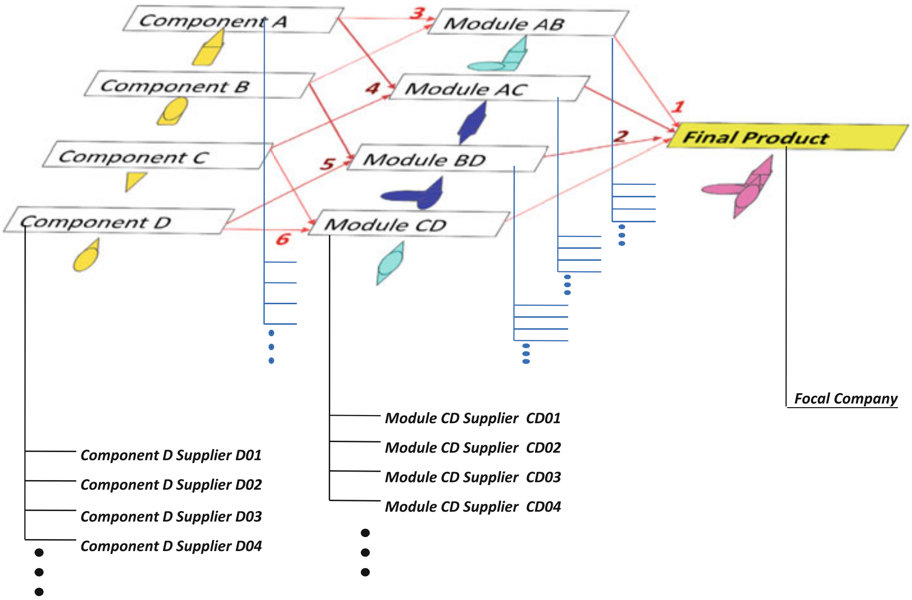


Fig. 1 The relationship between product architecture and supply chain network

ming (MIP) model (Chiu and Okudan 2011a). Corresponding process time and cost information of suppliers should be gathered from credible sources. The MIP program then computes the different combinations of assembly sequences that can complete a final product based on minimized lead-time or minimized cost objectives.

The relationship between product architecture and supply chain model can be illustrated as shown in Fig. 1 below. The final product is assembled either using modules AB and CD, or modules AC and BD. It should be noted; however, technical capabilities of suppliers will include or exclude them as suppliers of a module, or a component. For module CD, candidate suppliers are listed along with their process time and cost information.

The feasible candidate suppliers for each component/module are determined based on the product architecture, and hence, facilitate determination of the all possible configurations of the supply chain network. Transition matrix and MIP identify the supply chain performance of all possible combinations so that the most cost effective or responsive supply chain network and product architecture can be determined simultaneously. Below is a brief description of this model.

Indices

p	Possible processes of a product with $p = 1, 2, \ldots, m$
s	Possible states of a product manufacture and assembly with $s = 1, 2, \ldots, n$
i	Potential component suppliers with $i = 1, 2, \ldots, x$
j	Potential sub-assembly suppliers with $j = 1, 2, \ldots, y$
k	Potential final assembly suppliers with $k = 1, 2, \ldots, z$

Parameters

m	Number of processes
n	Number of possible states
x	Number of potential component suppliers
y	Number of potential sub-assembly suppliers
z	Number of potential final assembly suppliers
T_{sp}	Entity value of transition matrix
CC_{pi}	Unit cost of component supplier i in process p
CS_{pj}	Unit cost of sub-assembly supplier j in process p
CF_{pk}	Unit cost of final assembly k in process p
LCC_{pi}	Duration of stay of component at supplier i in process p
LCS_{pj}	Duration of stay of a module at supplier j in process p
LCF_{pk}	Duration of stay of a product at final assembly supplier k in process p
$LEAD$	Total lead-time of the supply chain
$TRANCSX_iX_j$	Transportation cost between component supplier i and sub-assembly supplier j
$TRANCFX_jX_k$	Transportation cost between sub-assembly supplier j and final assembly location k
$TRANTSX_iX_j$	Transportation time between component supplier i and sub-assembly supplier j
$TRANTFX_jX_k$	Transportation time between sub-assembly supplier j and final assembly location k

L_MAX	Longest acceptable lead-time of supply chain provided by the decision maker
L_MIN	Shortest acceptable lead-time of supply chain provided by the decision maker
C_MAX	Highest acceptable cost of product provided by the decision maker
α	Percentage of component cost viewed as inventory cost
β	Percentage of transportation cost viewed as inventory cost

Variables

$$CCX_{pi} = \begin{cases} 1 \text{ if component supplier } i \text{ is selected} \\ \text{ for process} p \\ 0 \quad \text{otherwise} \end{cases}$$

$$CSX_{pj} = \begin{cases} 1 \text{ if subassembly supplier } j \text{ is selected} \\ \text{ for process } p \\ 0 \quad \text{otherwise} \end{cases}$$

$$CFX_{pk} = \begin{cases} 1 \text{ if final assembly supplier } k \text{ is selected} \\ \text{ for process } p \\ 0 \quad \text{otherwise} \end{cases}$$

$$Y_p = \begin{cases} 1 \text{ if process } p \text{ is performed} \\ 0 \text{ otherwise} \end{cases}$$

There are two objective functions in this study. The first one is to minimize the total cost of supply chain so that the efficient supply chain can be achieved. The second objective is to perform a responsive supply chain with minimized lead-time. It should be noted that when one objective function is selected, the other objective function is taken as a constraint.

For the first objective function, the overall cost is composed of three components: process cost, C_1; transportation cost, C_2; and inventory cost, C_3. As shown in (2), process cost (C_1) summarizes the process costs of selected supplier(s) i, j, k in the process p. Transportation cost (C_2) is the expense between the upstream (Input state) suppliers and downstream suppliers (Output state) for all processes in Eq. 3. Inventory cost (C_3) 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 at module suppliers, and module inventory at the final assembly supplier. After interviewing several engineers at the bike company, we ascertained that the inventory cost has a positive relationship with the component and the transportation costs (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); it is provided in Eq. 4.

Objective Function 1

$$\textbf{min Total Cost} = C_1 + C_2 + C_3$$

$$C_1 = \sum_p \sum_i CC_{pi} * CCX_{pi} + \sum_p \sum_j CS_{pj} * CSX_{pj} + \sum_p \sum_k CF_{pk} * CFX_{pk} \tag{2}$$

$$C_2 = \sum_p \sum_i \sum_j TRANCSX_i X_j * CCX_{pi} * CSX_{pj} + \sum_p \sum_j \sum_k TRANCFX_j X_k * CSX_{pj} * CFX_{pk} \tag{3}$$

$$C3 = \alpha C_1 + \beta C_2 \tag{4}$$

Lead-time 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 the supply chain network's agility. Lead-time calculation includes: component lead-time, component transportation time, module lead-time, module transportation time, and lead-time of final product assembly. The mathematical formulation is as provided in Eq. 5.

Objective Function 2

$$\textbf{min } LEAD$$

$$LEAD = \text{Max}\, \{CCX_{pi} * LCC_{pi} + TRANTSX_i X_j + CSX_{pi} * LCS_{pj} + TRANTFX_j X_k + CFX_{pk} * LCF_{pk}\} \tag{5}$$

Subject to

$$\sum_p T_{sp} * Y_p \geq 0 \, \forall \, s \in S \tag{6}$$

$$\sum_s T_{sp} \leq 0 \, \forall \, p \in P \tag{7}$$

$$\sum_i CCX_{pi} = 1 \, \forall \, p \in P \tag{8}$$

$$\sum_j CSX_{pj} = 1 \, \forall \, p \in P \tag{9}$$

$$\sum_k CFX_{pk} = 1 \, \forall \, p \in P \tag{10}$$

$$LEAD \leq L\_MAX \tag{11}$$

$$LEAD \geq L\_MIN \tag{12}$$

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

$$Y_p, CCX_{pi}, CSX_{pj}, CFX_{pk} \in \{0, 1\} \tag{14}$$

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

The rationale for Eqs. 6 and 7 originates from a transition matrix (Lambert 2002), which views product architecture as a graph where the nodes are components and the vertices are connections between components. Transition matrix describes from-to relationships among components, modules, and final product during assembly sequence. All possible states of the sub-graphs or sub-assemblies are denoted as a stage set (***P***). The assembly process or action that results in a transfer between two sub-assemblies/components is represented as a vertex (Set ***S***). The whole assembly sequence will generate a new directed graph. A ($\boldsymbol{P} \times \boldsymbol{S}$) transition matrix is summarized to describe the relationship of sub-assemblies and related processes. Destruction of two or more original component states will create one new sub-assembly. The destructed component states are assigned a T_{sp} value of -1, while created sub-assembly is denoted by T_{sp} of $+1$. These values will be put into columns of a specific action, while all other unrelated states will remain empty or at zero. The outflow will be the same as or smaller than the inflow, since the number of components decreases during the assembly process.

The advantages of a transition matrix are: (1) its ability to present all possible assembly sequences of a 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 components/modules are correctly assembled into module/final product and only assembled once. Each process is assigned to only one supplier capable of process p. The supplier that provides the process will be marked as 1; otherwise 0 is used. Equations (8–10) denote this property.

Equations 11 and 12 serve as regular constraints for decision makers. 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. The cost constraint of the supply chain can be expressed as provided below. Equation 13 comes from the assumption that the process cost has a positive relation with customer satisfaction. The decision maker might want to maintain a minimum level of customer satisfaction when the budget allows. All variables in Eq. 14 are binary variables. Other variables in Eq. 15 are positive values.

Case study

X-bike is the bicycle company analyzed in this case study. Located in central Pennsylvania, 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 strength to mid-market products. The purpose of this research is to help create a relatively low-end road bicycle with a price range of $400–$1,000 USD and a production quantity of 10,000 per month. Company managers would like an acceptable lead-time interval to allow for a response to market dynamics. The lead-time target is 130 days, beginning with component manufacturing and ending with the completion of the final assembly process. The current supplier network contains worldwide module suppliers and components. X-bike is considering whether to outsource or manufacture these modules and components. The mission of the design team is to develop design concepts that satisfy both product design and supply chain considerations regarding cost and time. Importantly, the company would like to investigate the potential benefit of increased modularity on the supply chain performance metrics before the bike design is frozen for production.

In the following sections, the use of Design-ADAPS.1 software for design alternative generation and the subsequent supplier selection via the MIP model are explained.

Product design

The bicycle architecture contains the structure, the braking system, the transmission system, and the wheel system. The structure is composed of three sub-systems: saddle, frame, and fork. The braking system, as its name implies, is responsible for decelerating the bicycle speed. The wheel system enables the bicycle to move by creating friction against the ground. The transmission system defines the functions and usages of the bicycle.

In this case study, the components of the bicycle are as follows: (A) saddle, (B) frame, (C) fork, (D) brake, (E) wheels, and (F) transmission systems. Product design function starts with an Energy-Material-Signal (EMS) model. Figure 2 shows the EMS model, which starts with the human body climbing on the saddle. This action contains "import" and "assemble" functions. The saddle provides "position" and "support" functions. The frame "stabilizes" the human body and the fork "orients" the direction based on the visual signal. The transmission system (drivetrain) "converts" human energy into rotational energy, and then the rotational energy is converted to mechanical energy on the wheel to move forward. The braking system is "actuated" by a visual signal and the "converted" human energy to mechanical energy which slows down the bicycle when needed. The mapping of functions and physical components allows construction of a simple but complete bicycle architecture.

In addition to data from the EMS diagram, the potential components from suppliers serve as input information for use with the Design-ADAPS.1 software. The component database includes graphical elements and 13 assembly related items (Rampersad 1995) such as weight range, shape, size and composing direction that can be used to evaluate a DfA index value. Based on the EMS diagram and the component database, Design-ADAPS.1 can generate feasible design concepts that may fulfill customer requirements. For all six

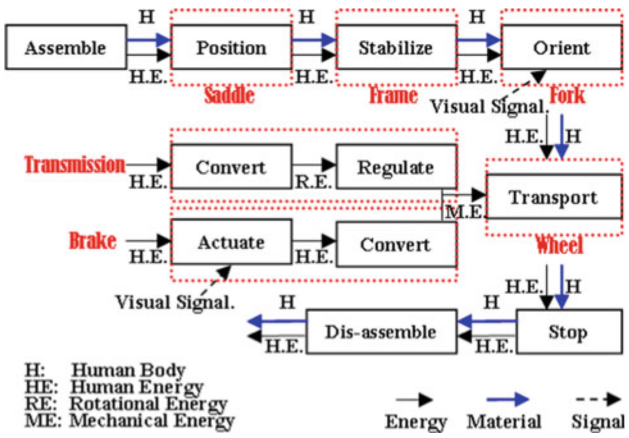
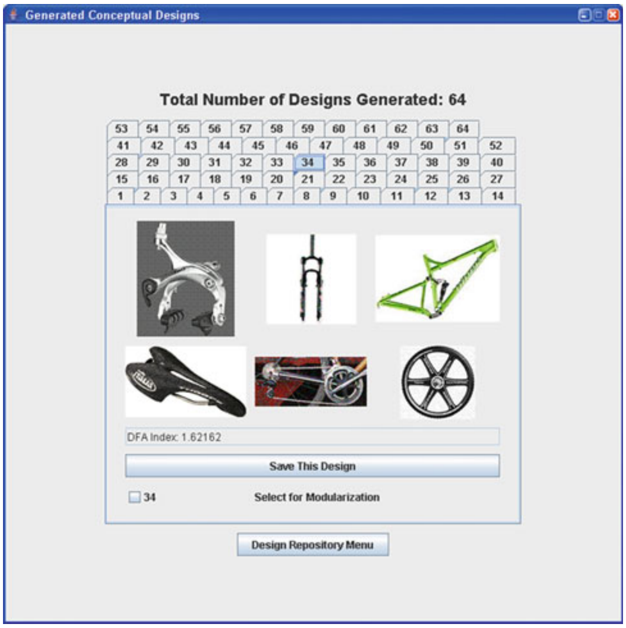


Fig. 2 EMS diagram of bike with mapping of components

sub-functions in this case study, each function has two candidate components. Accordingly, as illustrated in Fig. 3, the design repository generates $2^6 = 64$ design variants. These concepts are further modularized, taking into account the feasibility of the assembly processes. In addition to the predefined interaction matrix, the Fig. 4 depicts the suitability matrix using the decomposition approach (DA) and its resulting suggested modules. After modularization, two dominant product architectures are chosen, based on the validation of nine experts in the bicycle industry. These are the two-module (ABC and DEF) and three-module (AB, CD, and EF) architectures as shown in Figs. 5 and 6, respectively. Components (A) saddle and (B) frame are always assigned in the same module because they are physically connected. Components (E) wheel and (F) transmission are paired since they can be assembled together for a further assembly process.

Comparison of supply chain scenarios

To investigate the differences of supply chain performance between two-module and three-module product architectures, those candidate suppliers with the ability to produce the requisite components are searched for, along with their estimated process time, manufacturing cost, and geographic location. Based on actual data from the industrial partners, the MIP model was used to calculate the supply chain performances under two objective scenarios: (1) minimizing the total supply chain cost, and (2) minimizing the total supply chain lead-time. The former scenario can explore how efficient the supply chain performance of this design variant is under stable market demand. The latter scenario can examine the responsiveness/agility under the burden of volatile demand dynamics. In analysis, the mathematical model was executed 128 times (each design variants was applied once for cost minimization and once for lead-time minimization) in LINGO 9.0 to comprehensively investigate all design variants as shown in Table 2. It should be noted that all index



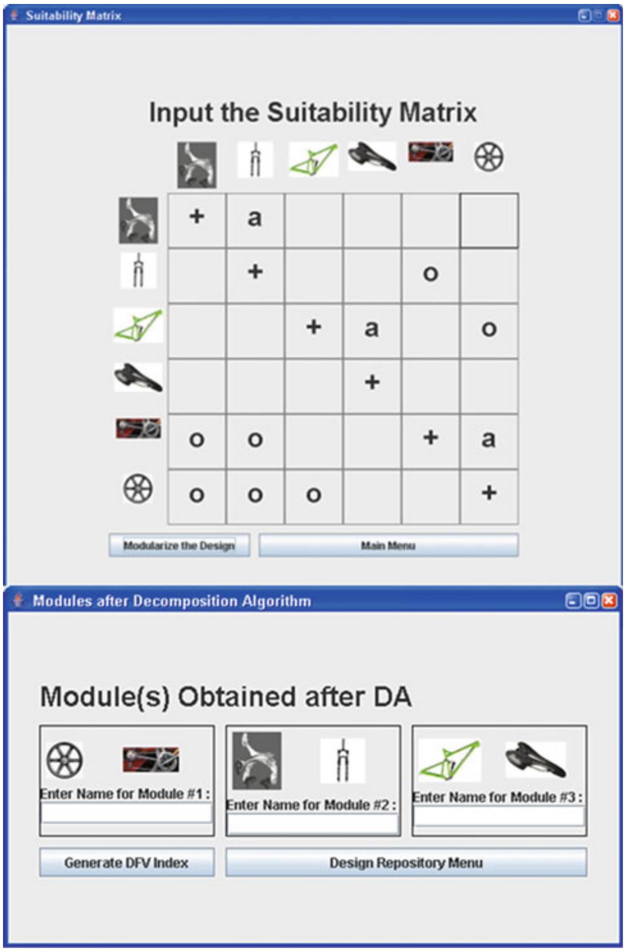
Total Number of Designs Generated: 64

53 54 55 56 57 58 59 60 61 62 63 64
41 42 43 44 45 46 47 48 49 50 51 52
28 29 30 31 32 33 34 35 36 37 38 39 40
15 16 17 18 19 20 21 22 23 24 25 26 27
1 2 3 4 5 6 7 8 9 10 11 12 13 14

DFA Index: 1.62162

☐ 34 Select for Modularization

Fig. 3 Feasible concepts in Design-ADAPS.1



Input the Suitability Matrix

+	a				
	+			o	
		+	a		o
			+		
o	o			+	a
o	o	o			+

Module(s) Obtained after DA

Enter Name for Module #1 :
Enter Name for Module #2 :
Enter Name for Module #3 :

Fig. 4 Modularization of concepts in Design-ADAPS.1

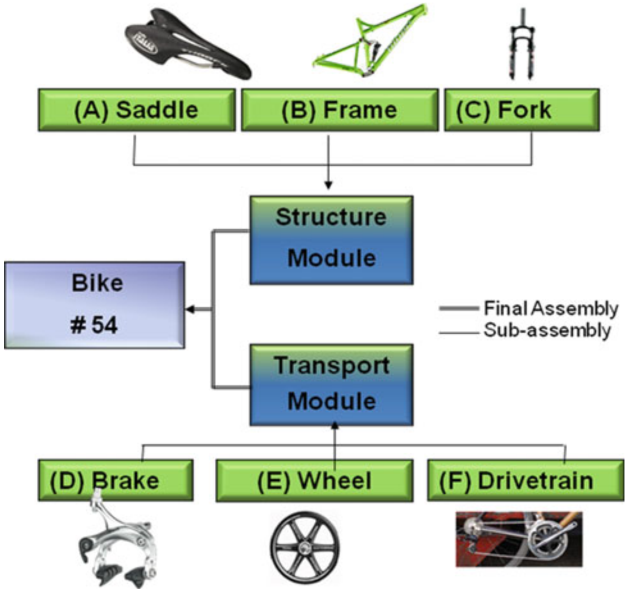


Fig. 5 Two-module product architecture

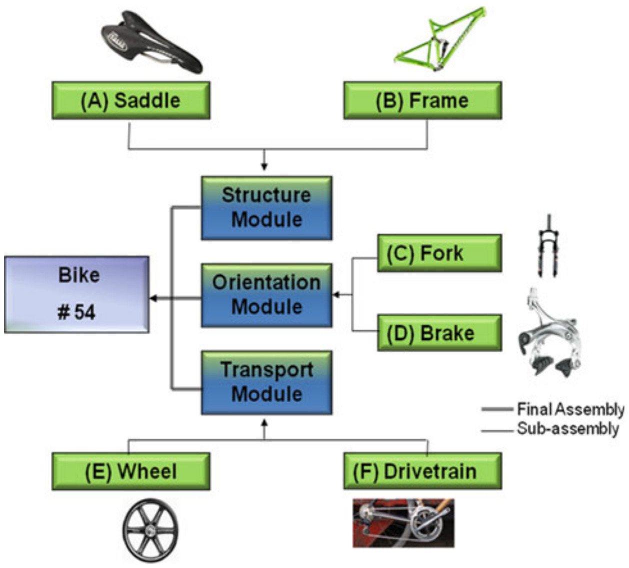


Fig. 6 Three-module product architecture

values (i.e., cost, lead-time and DfA) represent better performance as their values decrease.

Under minimized cost conditions, a two-module product architecture exhibits both cost (1 %) and time (12 %) advantages on average. However, the three-module product architecture performs better in terms of total lead-time (1 %) under minimized lead-time conditions. These values can be seen in the bottom three rows of Table 2, where the average value of the DfA index and the average value of cost and lead-time values for all concept combinations are provided. The final two rows present the difference in terms of percentage of improvement and the standard deviation, respectively.

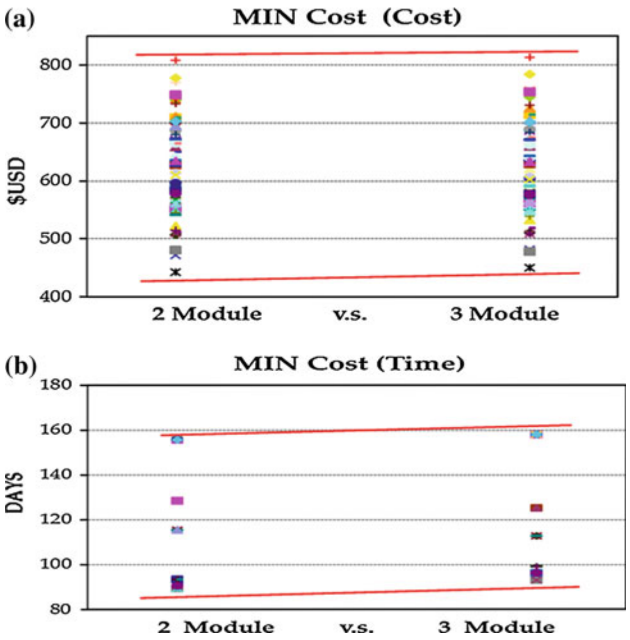


Fig. 7 **a** The cost comparison of MIP two-module and three-module architectures under minimized cost conditions of 64 design concepts. **b** The time comparison of MIP two-module and three-module architectures under minimized cost conditions of 64 design concepts

Below we present the information from Table 2 in graphic form across a number of figures. Figure 7a shows the cost information of these 64 design variants across two-module and three-module designs. It may be seen that the cost range of a three-module architecture is smaller than the range for a two-module architecture under cost minimization conditions. This depiction agrees with the information in Table 2 showing that the value of the standard deviation of two-module architectures is smaller than that of the three-module architectures. In Fig. 7b, we can see that the three-module architecture has a higher lead-time, but the difference in lead-time variation is not obvious.

In a lead-time minimization situation, the cost range for a three-module architecture is almost the same as that for a two-module architecture as shown in Fig. 8a; however, the lead-time range for the three-module architecture appears to be smaller, as shown in Fig. 8b. For the same design concept (dot), the three-module product architecture appears to have a better lead-time performance than does the two-module architecture. The time advantage is distinctly obvious for this case study.

To investigate the statistical significance of the results, the bootstrap technique is used. Typically, 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 (Cutrin and Schulz 1998), which divides significance level α by n to obtain a more conservative number. As a result, the noise can

Table 2 The supply chain performance of 64 design concepts in the MIP model

ID#	DfA score	MIN cost				MIN lead-time			
		Two-module		Three-module		Two-module		Three-module	
		Cost ($USD)	Time (Day)	Cost ($USD)	Time (Day)	Cost ($USD)	Time (Day)	Cost ($USD)	Time (Day)
1	1.08	580.92	128.2	592.61	125	919.92	89.5	935.91	88.5
2	1.08	551.55	128.2	561.59	125	923.54	90.7	905.68	88.5
3	1.17	522.09	128.2	531.90	125	885.63	89.2	920.32	88.5
4	1.17	551.46	128.2	562.93	125	911.99	89.2	936.40	88.5
5	1.22	671.10	128.2	685.67	158	1,024.75	90.7	1,086.33	88.5
6	1.22	700.48	128.2	716.70	158	1,045.34	89.2	1,036.09	88.5
7	1.26	620.61	128.2	630.14	125	984.48	90.7	980.98	88.5
8	1.26	649.99	128.2	661.17	125	990.66	89.2	979.55	88.5
9	1.31	671.02	128.2	687.01	158	1,022.61	89.2	1,022.64	88.5
10	1.31	641.64	128.2	655.99	158	956.06	89.2	990.96	88.5
11	1.31	588.95	128.2	589.54	125	970.41	89.2	957.33	88.5
12	1.31	619.17	128.2	619.77	125	972.84	89.2	941.80	88.5
13	1.35	591.15	128.2	600.69	125	960.98	89.5	939.20	88.5
14	1.35	625.58	128.5	631.71	125	1,011.04	90.7	976.19	88.5
15	1.40	559.49	128.2	559.85	125	928.70	89.2	924.05	88.5
16	1.40	769.54	128.2	785.25	158	1,125.57	90.7	1,116.33	88.5
17	1.40	740.17	128.2	754.23	158	1,036.95	89.2	1,075.20	88.5
18	1.40	589.72	128.2	590.08	125	888.13	89.2	880.13	88.5
19	1.44	738.73	128.2	743.85	158	1,021.64	89.2	1,022.39	88.5
20	1.44	708.50	128.2	713.62	158	1,084.75	89.2	1,123.01	88.5
21	1.49	710.72	128.2	724.77	158	1,086.56	89.2	1,078.33	88.5
22	1.49	740.09	128.2	755.79	158	1,102.03	89.2	1,094.27	88.5
23	1.49	657.50	128.2	658.09	125	1,069.50	89.2	1,042.45	88.5
24	1.49	687.73	128.2	688.32	125	1,063.70	89.2	1,052.59	88.5
25	1.53	679.04	128.2	683.93	158	973.89	89.2	1,006.00	88.5
26	1.53	709.27	128.2	714.16	158	1,086.73	89.2	1,076.76	88.5
27	1.53	477.26	93.2	479.88	99.1	576.63	89.2	590.46	88.5
28	1.53	506.64	115.2	510.90	112.8	617.59	90.7	600.31	88.5
29	1.58	628.04	128.2	628.63	125	971.37	92.2	995.79	88.5
30	1.58	658.27	128.2	658.86	125	995.45	89.2	982.08	88.5
31	1.62	471.72	115.2	481.21	112.8	572.19	89.2	594.83	88.5
32	1.62	442.35	91.2	450.19	93	564.81	89.2	546.60	88.5
33	1.62	777.05	128.2	782.17	158	1,202.36	89.5	1,192.90	88.5
34	1.62	807.28	128.2	812.40	158	1,167.76	89.2	1,142.36	88.5
35	1.67	596.82	93.2	603.96	158	632.02	87.2	661.75	87.5
36	1.67	626.20	115.2	634.98	158	670.31	87.2	665.17	86.5
37	1.71	777.82	128.2	782.94	158	1,091.28	89.2	1,096.42	88.5
38	1.71	747.60	128.2	752.72	158	1,138.95	89.2	1,117.73	88.5
39	1.71	546.33	93.2	548.43	95	636.54	89.2	608.43	88.5
40	1.71	575.70	115.2	579.45	112.8	625.28	90.4	633.53	88.5
41	1.76	566.43	155.5	574.27	158	648.69	87.2	686.56	87.5
42	1.76	595.80	155.5	605.30	158	698.96	87.2	685.59	86.5
43	1.76	544.89	93.2	538.06	99.1	698.15	89.2	697.32	88.5
44	1.80	511.41	91.2	518.97	96.1	572.70	89.2	542.49	88.5

Table 2 continued

ID#	DfA score	MIN cost				MIN lead-time			
		Two-module		Three-module		Two-module		Three-module	
		Cost ($USD)	Time (Day)	Cost ($USD)	Time (Day)	Cost ($USD)	Time (Day)	Cost ($USD)	Time (Day)
45	1.80	540.79	115.2	550.00	112.8	627.86	89.2	626.55	88.5
46	1.85	665.88	93.2	672.51	158	759.58	89	735.68	87.5
47	1.85	479.75	89.2	478.14	93	617.31	89.5	588.45	88.5
48	1.85	695.26	115.2	703.54	158	777.74	87.2	764.26	86.5
49	1.85	509.97	90.5	508.37	93	617.92	89.2	662.66	88.5
50	1.89	634.22	93.2	631.91	158	746.39	89	742.04	87.5
51	1.89	664.45	93.2	662.14	158	783.99	87.2	817.64	86.5
52	1.92	514.66	93.2	507.83	99.1	674.20	89.2	711.76	88.5
53	1.94	664.87	155.5	674.08	158	790.15	88.2	784.69	86.5
54	1.94	635.49	155.5	643.06	158	708.26	88.7	695.81	87.5
55	1.94	613.44	93.2	606.61	96.1	667.05	89.2	675.94	88.5
56	1.94	583.21	93.2	576.38	96.1	620.31	89.2	609.20	88.5
57	1.98	634.06	155.5	632.45	158	763.47	88.7	724.07	86.5
58	1.98	609.74	193.9	602.22	158	738.20	89.5	710.93	87.5
59	2.03	560.56	89.2	546.92	96.1	652.24	89.2	660.17	88.5
60	2.03	578.53	90.5	577.15	96.1	627.30	89.2	626.47	88.5
61	2.07	733.00	93.2	730.69	158	785.14	87.2	790.28	86.5
62	2.07	702.77	93.2	700.46	158	815.92	89	853.39	87.5
63	2.16	672.38	155.5	671.00	158	844.59	89	872.16	87.5
64	2.16	702.61	155.5	701.23	158	743.65	87.2	745.39	86.5
Avg.	1.62	627.02	120.88	631.55	135.30	851.42	89.14	852.17	**88**.13
Dif%		–	–	101	112	–	–	100.7	99
STD	1.702	84.630	21.983	86.351	24.823	186.859	0.958	187.045	0.701

be eliminated. Furthermore, 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 at a significance level of $\alpha = 0.05$, $n = 4$ and sample size $N = 1,000$. The bootstrap results (see Table 3) show that the two-module product architecture has cost advantages in both types of supply chain networks under the minimized cost condition. The three-module product architecture is superior at time performance under the minimized lead-time condition. Figure 9 illustrates the design concept #32 which is two-module supply chain that has the optimal cost ($ USD 442.35), while Fig. 10 depicts design concept #36 that is a three-module supply chain network with minimum lead-time (86.5 days) (The list of suppliers is provided in Appendix along with the relevant cost and time data). Therefore, company managers can base decisions on whether to apply a two-module or a three-module architecture according to the company's cost and time constraints and objectives.

These results exhibit the benefit of product design and supply chain integration at the product design stage and show how the different product architectures (in particular

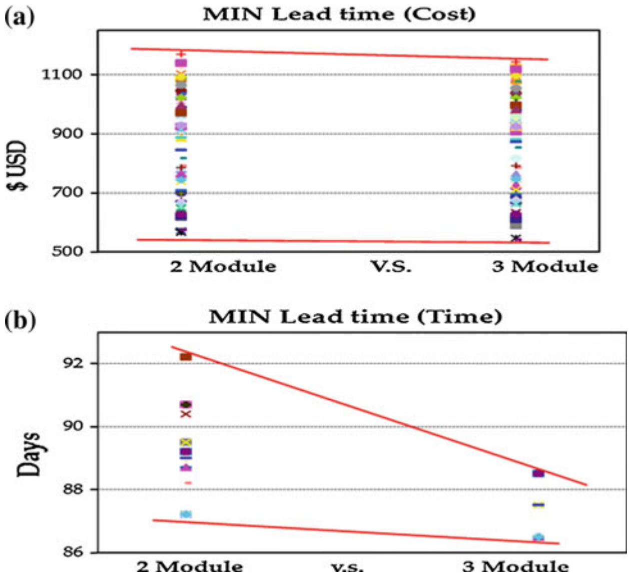


Fig. 8 The cost (**a**) and Time (**b**) comparison of MIP two-module and three-module architectures under minimized lead-time conditions of 64 design concepts

Table 3 Bootstrap results for two-module and three-module architectures in the MIP model

MIP 2M versus 3M ($\alpha/2n$, $1-\alpha/n$)	Cost for two modules versus three modules	Time for two modules versus three modules
Min cost condition (0.625, 99.375 %)	Significant (−6.477, −2.453)	Significant (−21.295, −7.832)
Min lead-time condition (0.625, 99.375 %)	Not Significant (−8.006, 5.841)	Significant (0.813, 1.198)

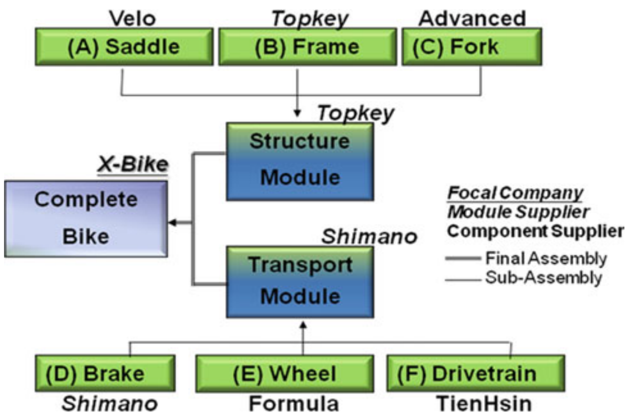


Fig. 9 Two-module supply chain network with optimal cost

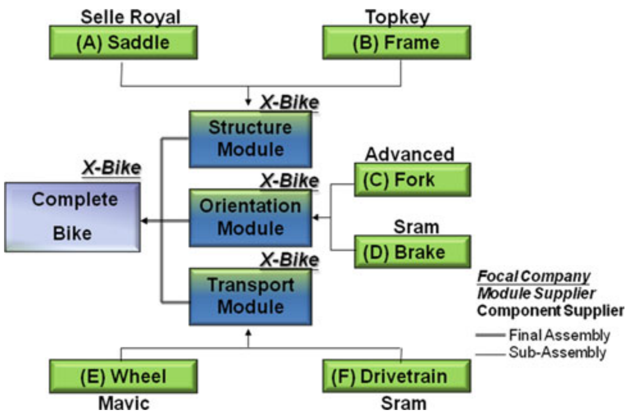


Fig. 10 Three-module supply chain network with minimum lead-time

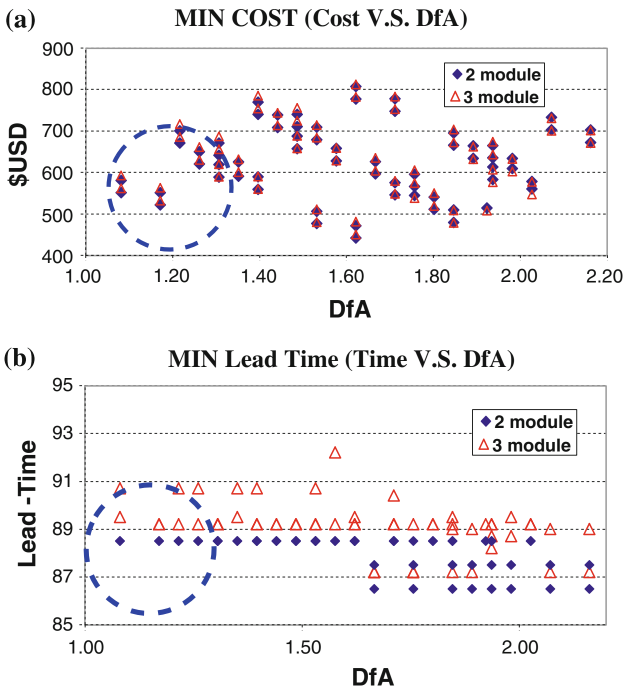


Fig. 11 **a** Efficient design variants in cost and Assemblability under minimized cost condition. **b** Efficient design variants in cost and Assemblability under minimized lead-time condition

the level of modularity) can shape various supply chain performances. Decision makers can select and develop design variants that have advantageous in cost and assemblability (Fig. 11), time and assemblability (Fig. 12), or time and cost (Fig. 13). By observing Fig. 8a, we can see there is an inverse trend between (a) cost and assemblability, and (b) time and assemblability; this implies that there is a trade-off between them. In Figs. 11b, 12a and b, we observe that although lead-time values cluster in a much smaller range, the DfA values have a much larger range. Given these plots, one can select design variants that are much easier to assemble without increasing the lead-time at the supply chain level.

There are some design variants that have high costs and long lead-times as indicated in Fig. 13a, b. These design concepts involve more time and higher cost because they are relatively sophisticated at the component level—for example, they require multiple speed transmissions or a fork with suspension. Figure 14 integrates all three indices to demonstrate design variants that are both efficient product and supply chain network configurations in light of assemblability, cost and time performance. Given the entire spectrum of options, an enterprise can select those design concepts in the circled area (shown in red) to achieve a better product as well as a better supply chain performance.

Discussion

This study applied actual industrial data to test how different levels of modularity can impact the supply chain performance. The results show that certain efficient design concepts are superior in how they affect the time and cost performance in supply chain execution, and can provide decision makers with solid insights into the selection of product designs with a higher potential for success in the competition of the supply chain network. Enterprises can benchmark and enhance

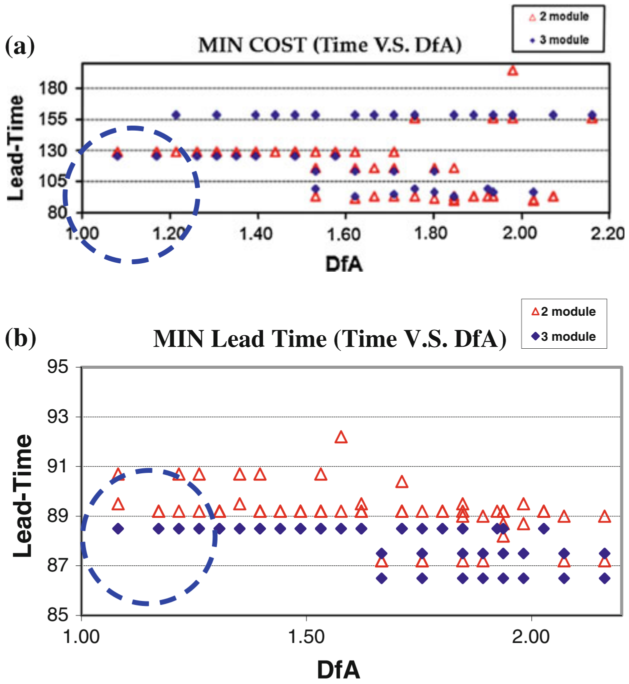


Fig. 12 **a** Efficient design variants in time and Assemblability under minimized cost condition. **b** Efficient design variants in time and Assemblability under minimized lead-time condition

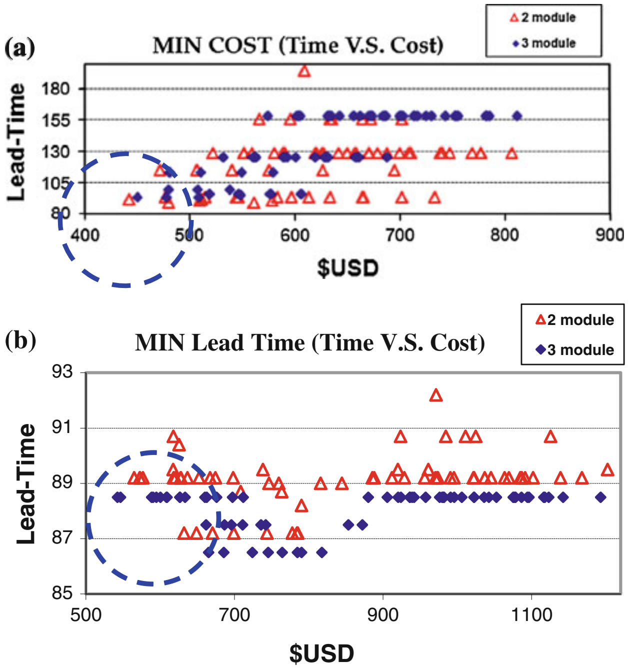


Fig. 13 **a** Efficient design variants in Time and Cost under minimized cost condition. **b** Efficient design variants in cost and Time under minimized lead-time condition

supply chain efficiency simply by re-modularizing the current product architecture. In this way, the product level decisions and the organizational level decisions are coordinated.

Another observation relates to IT support in the supply chain decision making process. This research utilized a design repository to populate all possible design concepts at the conceptual design stage. A well-constructed design repository could aid future product improvement activities (such as an upgrade) with the substitution of a few components/modules. IT can also support effective inventory management and information-sharing in supply chain operations. Bush et al. (2010) confirmed the complementarities between product design modularity and IT infrastructure in supply chain performance; moreover, they suggest that good responsiveness in the supply chain network can also enhance the network's flexibility.

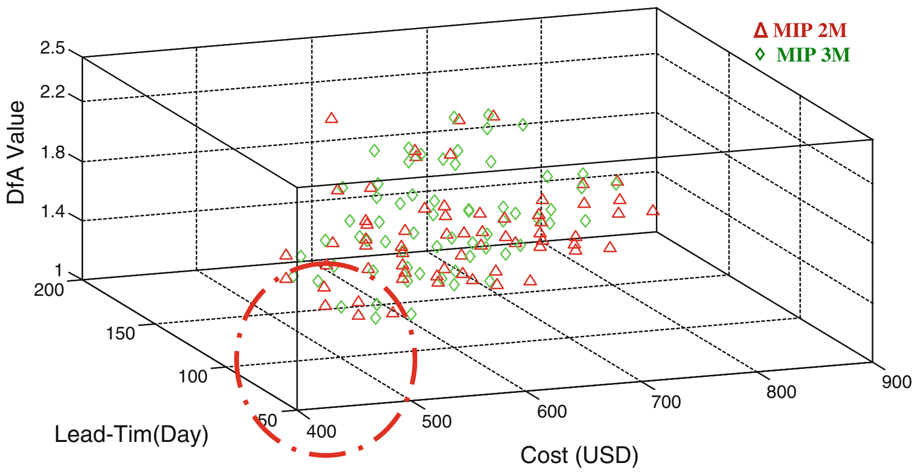
During this study, we found that the bicycle industry has an architecture phenomenon that is modular at the product level but integral at the component level. For example, the transmission module can be assembled easily with the frame module according to a standardized interface. The transmission module includes a derailleur, a crankset, freewheels, and chains. The design of the derailleur is highly integrated, however, to enable both the protection of intellectual property and the competitive advantage of the supplier. This is an example of a simultaneous cooperation/competition relationship within a supply chain network (Fredriksson 2006).

The modularity method applied in this research (decomposition analysis–DA) considers the interaction and suitability among components. Different methods should be taken into consideration. For example, Kusiak's process modularity (2002) which contemplates the line balancing and utilization of production resources could be integrated into performance analysis. In 2006, Voordijk et al. (2006) suggested that supply chain modularity should be considered while designing supply chain networks.

This study can be further extended in several ways. First of all, the current model only considers cost and time. Other managerial criteria such as profit, partnership, and the financial stability of suppliers are not investigated here. The current model could be extended as a multiple criteria model, and the performance measures could be aggregated as a new final output. The methodology would be more practical and complete with the incorporation of these criteria. Furthermore, the current method only considers design for assembly (DfA) and design for supply chain (DfSC); other X factors such as sustainability, environment, and recyclability (Chiu and Okudan 2011b) could be further incorporated to benefit both the enterprise and the planet.

Finally, the supply chain parameters of this study are assigned as single fixed values from our industrial partners, but they will vary in supply chain execution while market demand changes. Taking lead time as an example, rush orders might exist when customers are willing to pay more, or due to the delay of previous processes. Accordingly, suppliers will provide quantity discount as procurement volume grows.

Fig. 14 The design variants of efficient product and supply chain configurations



Area of efficient product and supply chain configurations

One of our future directions is to develop a more sophisticated model to tackle the uncertainty issue within the supply chain network.

Conclusion

In this paper, a methodology has been presented that connects and harmonizes product design and supply chain design decisions. The proposed approach has investigated the supply chain performance regarding cost, and has detected inefficiencies in supply chain execution at the conceptual design stage. Different levels of modularity have been analyzed for insight that could aid decision making related to supply chain execution. The proposed method has effectively allowed a clearer view of the influences of the manufacturing process, transportation costs and the lead-time. Findings indicate that during supply chain execution, rearrangement of an existing supply chain network, based on product characteristics, can markedly improve system performance. Using this approach, enterprises can benchmark and enhance their own supply chain efficiency by simply re-modularizing their current product architecture. In addition, the proposed methodology can provide a comprehensive analysis function; specifically, enterprises and suppliers can better understand the impact of different levels of modularity and determine which product architecture to apply as market situations vary. Hence, the agility of the supply chain is improved. While other supply chain studies have focused on later aspects of the design stage, this innovative method explores analysis during the early design stage. This method can establish the potential competitiveness of an enterprise, leading to a win-win situation for both the focal company and its cooperative suppliers.

Acknowledgments The authors would like to thank Mr. Travis Wright and Mr. Robert Octavio of Cannondale Bicycle Corporation (Bedford, PA) for their assistance with this research.

Appendix

See Tables 4, 5.

Table 4 Supplier Information

ID	Supplier	Location	Website
1	X-bike	PA, USA	
2	ADK Technology, Ltd.	TAICHUNG CITY, TW	www.adktec.com
3	Advanced Int'l Multitech	KAOHSIUNG CITY, TW	
4	Campagnolo	Vicenza – ITALY	http://www.campagnolo.com/
5	DT Swiss	TAICHUNG CITY, TAW	http://www.dtswiss.com/
6	Easton Sports Asia	TAIPEI CITY, TW	http://www.eastonbike.com/
7	Formula Engineering	TAICHUNG CITY, TW	http://www.formulahubs.com/
8	HB Performance Systems	Mequon, WI, USA	http://www.hayesbrake.com/
9	Mavic	Annecy cedex, FR	http://www.mavic.com/
10	Overseas Technology, Ltd. (Velo)	TAICHUNG CITY, TW	http://www.velosaddles.com
11	Selle Royal, SPA	Verona Area, ITALY	http://www.selleroyal.com/About.aspx

Table 4 continued

ID	Supplier	Location	Website
12	Shimano	Osaka, JAPAN	http://corporate.shimano.com/
13	Sram	Chicago, IL, USA	http://www.sram.com/
14	Tektro Technology	TAICHUNG CITY, TW	http://www.tektro.com
15	Ten-Tech Composite Technology	TAICHUNG CITY, TW	http://tentechcomp.com
16	TienHsin Industries	TAICHUNG CITY, TW	http://www.thindustries.com.tw/
17	Topkey Corporation	TAICHUNG CITY, TW	http://www.topkey.com.tw/
18	Viscount Ind. Co., Ltd.	TAIPEI CITY, TW	

Table 5 Process costs and time

Type	(A) Saddle		Process ID: 12	
	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	
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	
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
	(D) Brake		Process ID: 15	
D2	1	(4) Campagnolo	$ 82.04	40
D2	2	(8) HB	$ 33.70	60
D1	3	(12) Shimano	$ 8.44	40
D1	4	(13) Sram	$ 56.76	60
D1	5	(14) Tektro	$ 23.00	45
	(E) Wheel		Process ID: 16	
E2	1	(5) DT Swiss	$ 359.13	45
E1	2	(7) Formula engineering	$ 17.50	45
E1	3	(9) Mavic	$ 38.16	40
E2	4	(12) Shimano	$ 98.78	85
	(F) Transmission		Process ID: 17	
F1	1	(12) Shimano	$ 39.65	50
F2	2	(13) Sram	$ 151.33	80
F1	3	(16) Tien Hsin	$ 34.00	45

Table 5 continued

No.	(AB) Module		Process ID: 8
	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
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
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
	(EF) Module		Process ID: 11
1	(1) X-Bike	$ 12.00	1.5
2	(4) Campagnolo	$ 4.00	2.5
3	(9) Mavic	$ 6.00	2.1
4	(12) Shimano	$ 3.00	3
	(ABC) Module		Process ID: 3, 5, 6
1	(1) X-Bike	$ 20.00	2
2	(2) ADK	$ 10.00	3
3	(3) Advanced	$ 12.00	2.5
4	(17) Topkey	$ 8.00	3.2
	(DEF) Module	Process ID: 4, 7	
1	(1) X-Bike	$ 25.00	2.2
2	(4) Campagnolo	$ 8.00	3.9
3	(12) Shimano	$ 11.00	3.5
4	(13) Sram	$ 13.00	3.2
	(ABCDEF) Module		Process ID: 1, 2
1	(1) X-Bike	$ 10.00	2

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