

Integration of Product Structure and Supply Chain Decisions at the Conceptual Design Stage: A Repository Enabled Decision Tool

Ming-Chuan Chiu¹, Saraj Gupta¹ and Gül E. Okudan^{2,1}
¹Department of Industrial and Manufacturing Engineering
²School of Engineering Design
The Pennsylvania state University
University park, PA, 16802, USA

Abstract

The mission of a supply chain is to serve as a bridge that connects product suppliers, manufacturers as well as customers with managerial efficiency. Meanwhile, product design emphasizes the engineering efficiency of a product. Both supply chain management and product design have been drawing attention from numerous researchers. However, there has been only limited research on the integration of product design and supply chain. Despite this fact, there is a significant potential for synergy in the integration of engineering considerations to supply chain management as well as managerial concepts into product design. The proposed methodology first generates functional requirements of a product. A design repository is then utilized to synthesize potential components of all sub-functions, providing multiple options for the potential conceptual designs. These concepts are screened by using a design for assembly (DFA) index and then a Design for Supply Chain (DfSC) index to select the best concept. A case study from bike industry is presented to demonstrate the benefit of supply chain considerations at the conceptual design.

Keywords: Design Repository, Product Design, Supply Chain Design

1 Introduction

Product development is an innovative process that transforms and realizes the potential market opportunities into a specific product according to product and process technologies. The product design process is an iterative and complex one, which includes defining, conceptualizing, refining and eventually commercializing a product into a new or existing market. Product size, shape, functions, processes, components and materials need to be decided during a short period of time. Product development decisions are organized in four categories: concept development, supply chain design, product design, and production ramp-up and launch [1].

The supply chain council [2] defines 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*”. A framework of supply chain consists of supply chain network structure, the supply chain business processes, and the supply chain management components [3]. In supply chain network structure, the focal company is the center of the supply chain along with multi-tier suppliers to its left and multi-tier customers on the other side. Supply chain business processes are comprised of customer relationship management, customer service management, demand management, order fulfillment, manufacturing flow management, procurement, product development and commercialization and return process.

Around 70% of product cost is decided in design stage at this one-time activity [4]. In addition, new products account for a staggering 33% of company sales [5], which have high association with the profitability and growth of a company. New products are those, which have been introduced into the market within five years. Besides the high profitability, the new product development is also well known to have high risk. New Product Failure Rate (NPFR), which is a statistical datum that computes the success percentage of a new product, shows only 40% of new products survived in 2004 [6]. Although the

coordination between product and supply chain is one of the key reasons, [4-6], only a few methods simultaneously considered supply chain and product structure.

Below, Section 1 introduces product design and supply chain concepts; Section 2 presents product architecture, supply chain index and the importance of coordination between the two. Section 3 proposes a method that can consider engineering and managerial perspectives simultaneously during the product design stage. In Section 4, we present a case to illustrate the proposed method. Finally, conclusions are provided in Section 5.

2 Literature Review

2.1 Product Architecture and supply chain coordination

Product architecture is the organization structure of the functional elements of a product. It shows the physical building blocks, and the ways in which they interact. The product architecture has broad implications on: product change, product variety, product performance and manufacturability [7]. Two main typologies of product architecture are modular product and integral product [7]. Modular product architecture has become the mainstream one due to the advantages in development time, cost and economies of scale. Modular products decompose the overall functionality of a product into sub-functions, embodied in separate product modules. These modules are designed to be independent, standardized and interchangeable.

There are two main types of components in modular designs, namely, common and variant components. While common components are static portion of the product architecture which are reusable and hence saves design efforts, a product variant fulfills dynamic customer requirements within a given specific service level. Modular product architecture is widely used due to its advantages in development time, cost and economy of scale [6, 7]. This study applied modularity as the basis for the product structure.

The engagement of product type and supply chain property has attracted attention from researchers. The products can be categorized into two types: “functional” and “innovative”. In the same manner, supply chains can be accordingly classified as “efficient”, or “responsive” supply chains. A functional product has stable demand, low profit margin and many competitors, such as staple items. In contrast, an innovative product refers to a newly introduced and differentiable product with versatile demand. Accordingly, supply chains can be classified as “efficient” and “responsive” supply chains. Efficient supply chains emphasize making and delivering a product with low cost, with cost as the major concern, while responsive supply chains aim for delivering a variety of products quickly to achieve high level of customer service. The right coordination between supply chain type and product type, for example, functional product and efficient supply chain, can assure a high possibility of success [8].

A framework for supply chain decision making was presented while considering the product design and supply chain design [4]. Breakthrough is the most challenging situation to achieve, when both the product and supply chain are newly developed. If a supply chain is new for an existing product, the supply chain should do re-engineering 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 which requires the minimum effort. The matrix is illustrated in Figure 1. The scope of design for logistics was broadened to Design for Supply Chain Management (DfSCM) [9] with the aim of designing products and processes to more effectively manage supply chains in terms of cost and performance. DfSCM utilizes product line structure, bill of materials and customization processes of a product in order to optimize the logistics costs and customer service performance.

From the above research, the product architecture is highly related to supply chain structure. We assert that improvement of supply chain performance can be possible through simultaneous consideration of product structure and supply chain attributes. However, only limited studies addressed this relationship. In this paper, we present a methodology, which utilizes a design repository and a design for supply change index, to simultaneously optimize design and supply chain management decisions.

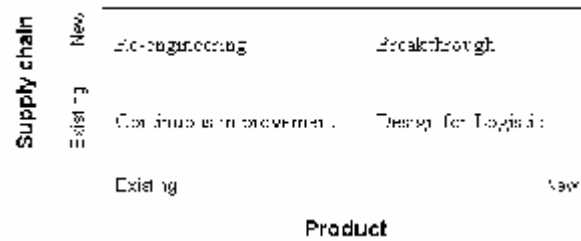


Figure 1: Framework for supply chain decision making [4]

2.2 Supplier Selection: Methods and Criteria

The purpose of measuring supply chain performance is to determine the optimal component acquisition alternative that can be most beneficial to the focal company and its customers. The benefit can be measured using quantitative or qualitative terms. Cost, resource utilization, quality, flexibility, visibility, trust, and innovativeness are among these metrics [10]. Cost includes manufacturing, distribution, inventory and overhead cost. Resources cover labor, machine, capacity, and energy utilization. Quality might involve customer dissatisfaction, 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 five types of flexibility: input, process, output and improvement. Visibility measures degree of information sharing in the supply chain. It relates to time and accuracy. Trust is an index presenting the reliability and consistency between supplier and focal company. Finally, innovativeness reflects the technological and engineering capability of suppliers such as new launch of products and new use of technology.

In order to gain an understanding of the state-of-the-art, 49 papers were evaluated focusing on supplier selection [11]. Overall, the studied methods are categorized as appraisal methods and mathematical methods. Appraisal methods compare suppliers using criteria ranking or cost to evaluate their performance. On the other hand, mathematical methods involve trade-offs among selection criteria by linear weighting, optimization, statistical or neural network techniques. Appraisal methods and mathematical methods can be combined resulting in hybrid methods.

Supplier selection criteria include product market position, product development strategies and six types of modularity. Quality, cost, technology, production capacities, R&D, delivery and location, performance and service are used as selection criteria [12]. A strategic supplier selection model [13] that includes strategic, operational, tangible and intangible measures considers short term and long term planning horizon. Suppliers are evaluated by organizational factors and strategic performance matrices. Organizational factors cover culture, technology and relationship and strategic performance metrics contain cost, quality, time and flexibility.

3 Proposed Method

In the methodology, first of all, functional requirements of a product are defined and decomposed in the most basic sub-functions. Secondly, a repository is utilized to synthesize potential components of all sub-functions, providing multiple options for the conceptual design. These concepts will be evaluated by a Design for Assembly (DFA) index, modularized with the Decomposition Approach. Finally, these concepts are evaluated using a design for supply chain index to select the best concept.

In this study, a software framework has been developed using Java Swing within the NetBeans IDE 6.1 programming environment. 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. Below we explain major sections of the software.

An Energy Material Signal (EMS) functional model was applied to present the function of whole product. This model is obtained by decomposing the overall function into simpler sub-functions and flows, which are generally described in a verb-object form. The function to be performed is mentioned inside the boundary of the box, while input energies, materials and signals flows are identified to the left of the box.

The output energy, material and signal flows are indicated to the right of the box, which identifies the remainder flows obtained after the overall function has been executed. A design repository used within the software for the purpose of recording and reusing the best design practices at later stages. A design repository is [14] defined as a heterogeneous product design database in which various design solutions can be searched and reused.

The purpose of Design for Assembly is to consider the manufacturing and assembly problems in the early phases of product design which can increase the productivity significantly without any investment. In this study, 13 criteria [19] are collected and evaluated. These include: 1) weight, 2) number of unique component, 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. Afterward, Decomposition Approach (DA) [15], which is a matrix based methodology, is applied to modularize the design concepts. There are two matrices inside this method: interaction matrix and suitability matrix. 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.

Five criteria are introduced to form the supply chain index: 1) Number of suppliers, 2) quality level, 3) cycle time, 4) cost, and 5) supplier capability. Amount of suppliers tally the total number of suppliers in one product concept. Lower is better because suppliers can sub-assemble components before shipped. Quality level will impact the yield of the product and after service cost. Time refers to manufacturing, transportation and assembly time. Time is an important factor because it impacts the response speed of supply chain. In addition, the design with less total cycle time will result in lower WIP level. Cost is a universal indicator that the design with lower total cost absolutely has higher priority. Cost items include raw material, manufacturing, transportation and assembly. The criteria include the capacity information. For quality, time cost, and supplier capability, it will be ranked with Borda count [18]. On contrary to the quality, cost and time, supplier capability considers long term capability such as technology, capacity, partnership, etc.

$$\text{Supply chain index} = \sum W_i Q_i \quad \text{where,}$$

Q_i : point value for each criterion, $i = 1 \dots 5$; and W_i : weight of each criterion, $i = 1 \dots 5$

4 Case Study

4.1 Bicycle Product Structure and Supply Chain Structure

In this case study, a leisure bike is chosen as our target product which aims for comfort daily cycling. The architecture of a bike and supply chain structure can be simplified into four subsystems. The components of first level are structure system, braking system, transmission system, and wheel system. Structure is composed of three sub structures: fork, frame and saddle. Braking system, as its name, is responsible for decelerating the bike speed. Another important sub-system is transmission system, which defines the functions and usages of the bike. Wheel system enables bike to move by creating friction with ground. These four sub systems are modular designs which are mutually independent but cooperative as a whole product. Another two sub-systems are electric motor with battery set and accessory which are optional equipment for saving physical effort and environment consideration. The EMS model will consider a total of seven components and functions, but motor will be excluded temporarily.

The supply chain structure of a bike can be described in four layers. The upstream layer is sub-suppliers which provide raw materials. The second layer is suppliers who produce components of the bike. The next one is focal company which focuses on assembly process and manufacturing of key components. Finally, the last layer is 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 mass market segment with unit prices lower than \$250 [16]. On the other hand, independent bike distributors and sport stores sell specialized bikes in niche market areas.

4.2 EMS model and Design Repository

From Figure 2, the EMS model with mapping components of the bike and design concepts generated by design repository is presented. EMS model starts from human body climbing on the saddle. This action contains “import”, and “assemble”. The saddle provides “position” and “support” functions. Frame

“stabilize” human body and 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 convert into mechanical energy on wheel to move forward. On the other hand, the braking system is “actuated” by visual signal and “converts” the human energy to mechanical energy to slow down the bike. In this case study, design repository [17] generates $2^6 = 64$ combinations with DFA values.

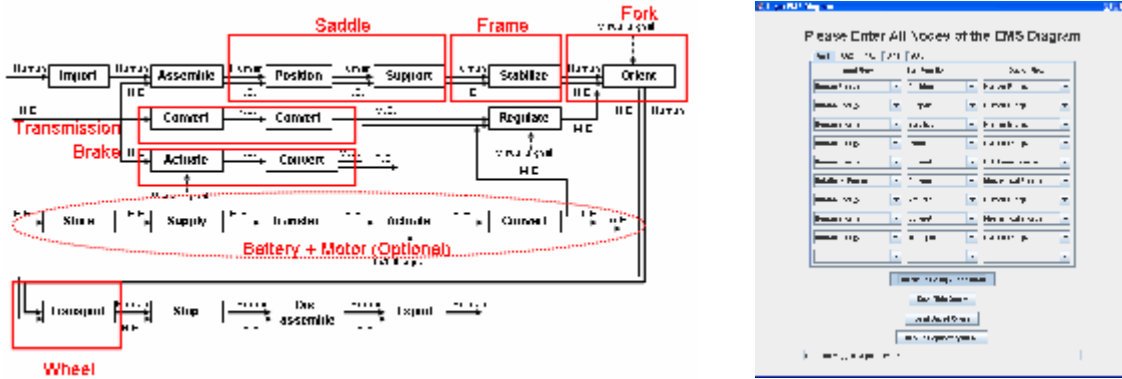


Figure 2. EMS diagram of bike with mapping components (left) and in design repository (right)

4.3 Modularization and Supply Chain Index

Two design concepts, #13 and #54, with best DFA scores are selected and modularized using DA. #13 has the comfortable saddle, steel frame without suspension, steel fork without suspension, single speed transmission, reverse brake rotor, and wheel with steel spoke. In the meantime, #54 has light weight saddle, steel frame with suspension, steel fork with suspension, transmission with six fly wheels, braking system with brake shoes, and wheel with plastic spoke. From Figure 3, the concept #13 has two modules according to suitability matrix while #54 has three modules.

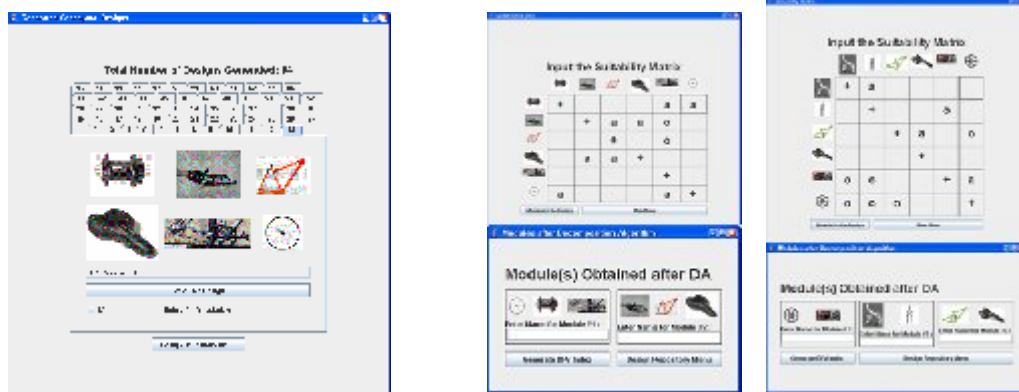


Figure 3. design concepts from repository (left), Modularization of #13 and #54 (right)

Table 1. Supply chain index calculation

Index item	Actual value		Index value	
	# 13	# 54	# 13	# 54
Number of Suppliers	4	6	2	1
Quality level	4	4	3	3
Cycle Time (day)	3.5	4.2	2	1
Cost (\$)	42	80	2	1
Supplier capability	3	6	2	3
Total score	$\sum W_i Q_i$		11	9

In the case study, the actual values are equally clustered into three groups between the maximum and the minimum. As shown in Table 1, Concept #13 is chosen because it has only four suppliers and it has cost advantages. The weights of all indices are equal. Decision maker can adjust the weights based on the

product characteristics and preference. The way to aggregate the total score can be modified according to the preference as well. In addition, other indexes can be incorporated to reflect the priorities of the focal company.

5. Conclusion and Recommendations for Future Work

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 to demonstrate the whole picture of a product. A graphical design repository is then applied to generate possible design concepts and these concepts are evaluated with a DFA index and modularized. Two of the most competitive concepts are selected to further evaluate with supply chain index. The final optimal design is elected, which has advantages both in manufacturing and supply chain management.

This research currently only considers single road bike product. With the support of design repository and modular components, it will be further populated to handle a family of products that can cover all market segments with commonality and economic of scale. Another research direction is the modification of supply chain index. It will be beneficial for management if it can provide scenario analysis for supply chain strategy.

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