

An Integrated Framework Matching Product Architecture with Supply Chain Design Policies

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Product architecture is the arrangement of the functional elements of a product into physical components. The arrangement defines the way in which the components interact and interface with each other. Product architecture can be classified into two types: open (or modular) and closed (or integral). Modular architecture indicates a one-to-one mapping between functional elements and physical components, whereas integral architecture indicates a one-to-many or many-to-one relationship. Because of openness and standardized modules with greater substitutability, modular architecture allows us to create more product variety at lower costs. Although product architecture is normally established during the early stages of the product development cycle, however, it influences decisions made downstream in domains of product, process and supply chain. While it is widely believed both in engineering and operations management that it is better to consider supply chain concerns during product development stage, however, there are few existing studies that provide a quantitative framework for making such decisions early in the architecture selection stage. This paper tries to fill this gap by proposing a quantitative framework to aid product development engineers and managers in identifying the optimal modules considering multiple design and supply chain objectives. The optimization model will incorporate decision variables so that one can examine the impact of modularity decisions on supply chain policy. It attempts to bring the supply chain decision making into the early stage of the product development cycle.

Key Words: Product architecture, modularity, supply chain structure.

1. Introduction

For many manufacturing firms, the recent increase in competition in the marketplace due to globalization, increase demand in variety and shorter product life cycle has forced them to move from traditional mass manufacturing world to the world of mass customization through flexibility and agility. However, in order to achieve agility, industries must adapt their product design and development processes to accommodate the rapidly changing needs of their customers. However, moving product from the initial design stage to its arrival at the customer requires many decisions on design and operations in the domains of product development, production/manufacturing and supply chain. Traditionally, these decisions were made in a sequential manner. First, a product design is selected out of possible set of feasible designs, driven primarily by marketing objectives and engineering constraints. The chosen design is then transferred to the production and manufacturing planning function to develop an appropriate

manufacturing plan guided mainly by operational objectives like capacity utilization, load balancing and cost minimization. Finally, the product design and manufacturing plan decisions become the constraints for the logistics function that determine the supply chain structure.

This serial method is known to generate solutions that suffer from two major deficiencies (Gunasekaran, 1998). First, it is slow because parallel processing opportunities are often missed. Secondly, it leads to sub-optimal solutions, because each stage can make, at best, sequential locally optimal choices.

Many firms now focus on the value of considering other manufacturing and process concerns during product design and to overlap previously sequential design processes. Simultaneous engineering (SE) is a paradigm aimed at eliminating such flaws found in serial method. SE dictates that product and process decisions are made in parallel as much as possible and that production considerations be incorporated into the early stages of product design.

Over the last two decades, many researchers have worked on this concept of combining production/manufacturing considerations during product design and development stage leading to a fundamental tradeoff. On one hand it reduces the need for re-design and re-work (Fine et al, 2005), thus reducing development time) and increases the chances for smoother production (thus helping to minimize cost and improve quality). On the other hand, SE complicates the design problem as it requires simultaneous optimization of a more complex objective with a larger set of constraints (Wu and O'grady, 1999).

It is estimated that product and process design influences 80% of manufacturing costs, 50% of quality, 50% of order lead time, and 50% of business complexity (Child et al. 1991). More importantly, the decisions made during the conceptual design stage have direct impact on over 70% of the production costs, even though the actual cost of the design phase accounts for only 6% of the total development cost (Shehab and Abdalla 2001). Therefore, optimization of product costs early in the design stage is a pressing need. Moreover, the impact of product architecture decisions is far reaching. It influences decisions in the domains of product, process, and the supply chain. Individual product architecture characteristics such as the degree of commonality, the nature of interactions, and interfaces between components may constrain strategic decisions like postponement and late customization. These characteristics also affect the operational decisions in the supply chain domain such as service level, delivery schedule, and resources planning.

While it is widely believed that both in engineering and operations management that the performance of a supply chain configured for a product is determined by the design decisions of the products, and that it is better to consider supply chain concerns during product development stage. However, there are few existing studies that provide a quantitative framework for making such decisions early in the architecture selection stage. Even the few researchers who have studied the formal approach for optimization of modular product architecture have focused only on single-objective optimization, such as similarity index or costs of modularization. The key concern is how product architecture configuration can influence the supply chain policies and how to link the two concepts at the concept development phase of the product development. Therefore, it is clearly important from the perspective of product development managers and engineers to have an integrated framework that can help them determine what kind of leverage their firms can gain in its supply chain management by pursuing a specific product architecture strategy. This research work is aimed at providing such an integrated framework for making both product architecture and supply chain decisions concurrently during conceptual stage of product development.

The paper is arranged as follows. In Section 2, we review some of the literature out there on product architecture and supply chain design. We present to proposed solution approach in Section 3. Conclusion and next steps are discussed in Section 4.

2. Literature Review

In the domain of product development, the concept of product architecture is well known and studied: It relates how the functions of a product are allocated to its constituent components (see Ulrich, 1995). Fixson (2005) develops a multi-dimensional framework that enables comprehensive product architecture assessments. He defines product architecture as a comprehensive description of a bundle of product characteristics, including number and type of components, and number and type of interfaces between those components. His framework builds on existing product characteristics concepts such as component commonality, product platforms, and product modularity.

A key dimension of product architecture is the distinction between open (or modular) and closed (or integral) product architectures. Carliss et al. (1997) defines modularity as the process of building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole. Another definition of product modularity is provided by Otto and Wood (2001). Here, modular architecture indicates a one-to-one mapping between functional elements and physical components.

A supply chain network refers to a network nodes of firms engaged in manufacturing and assembly of parts to create a finished product where the nodes represent the functionality that must be performed and the arcs captures the precedence constraints among the nodes. However, for a single company, these nodes can be organization units within the firms that perform functions such as procurement of raw materials, the fabrication of parts, the assembly of components and end-products, and the shipment of finished products to distribution centers/customers. Each node in the supply chain network often has several alternative options for accomplishing its function and is a potential stock point for inventory. For example, two options might be available for procurement of a certain part: a low cost overseas or a high cost local supplier. Deciding what option should be used at each node and deciding where inventory should be placed among these nodes is called Supply Chain Configuration (Graves and Willems, 2001). If there are N nodes and two possible options per node, then there are 2^N possible supply chain configurations.

Garg (1999) described the application of Supply Chain Modeling and Analysis Tool (SCMAT) for designing products and processes for supply chain management at a large electronics products manufacturer. Some of the analyses the tool could perform include: inventory-service level trade-offs, sourcing, location and transportation trade-offs, effects of capacity limitations, impact of lot sizes and designing products/processes for supply chain management. Graves and Willems (2001) studied a supply chain configuration optimization model that minimizes the total supply chain cost using a Dynamic Programming algorithm. The decision variables of their model include option selection and service time for each stage. While the work of Graves and Willems (2001) can be extended to study the impact of product architecture on supply chain network, they failed to provide such analysis.

While it is widely recognized that the type of product architecture dictates the structure of the supply chain network. However, there are very few works to study its impact on the supply chain structure and also integrate supply chain issues with product design during the conceptual

stage of product development. Also most of the studies are either qualitative in nature or use single objective optimization. Fisher (1997) suggested ways to matching the supply chain with the product structure. He defined products as either functional or innovative and proposed corresponding functions (either physical or mediation) for the supply chain. Camuffo (2000) examines some of the implications associated with modularization in design, manufacturing and organization supply chain. He defines modularity in design as defining the design boundaries of a product and of its components such that design features and tasks are interdependent across modules, modularity in manufacturing as designing manufacturing and assembly in order to reduce complexity in the main process by means of sub-assembly, while modularity in organization or supply chain means the organizational processes, governance structures and contracting procedures that are adopted or utilized to accommodate modular production. Also, Salvador et al. (2002) provide empirical studies that explore how manufacturing characteristics affect the appropriate type of modularity to be embedded into the product architecture and how the types of modularity relate to component sourcing using six European companies.

The increasing trend of competition among firms due to globalization has led to increase in product variety, in turn leading to increase supply chain complexity. Thonemann and Bradley (2002) investigates the impact of product variety on supply chain performance and their analyses show that product variety has considerable impact on supply chain lead-time especially when setup times are significant.

Doran (2003) explores the development of modular supply within the automotive sector with particular emphasis on the impact that modularization is likely to have on the value-adding process of the key component suppliers. Sako and Murray (1999) suggest two different ways of dealing with modularity in supply chain, the integrator role and the modularizer role. In the integrator role, the OEM retains module control, while in the modularizer role, the OEM transfer module control to first-tier suppliers that possess the capabilities required to provide modular solutions. Fixson (2005) develops a multi-dimensional framework using product architecture to help coordinate many decisions across the domain of product, process and supply chain.

Only a handful of researchers have attempted to use optimization model to study the effect of product design and development on production and supply chains. Kin and Chhajer (2000) used an optimization model to study the effect of commonality and modular design on the market acceptance of a product. In another study, Feng et al. (2001) developed an optimization model for concurrent selection of design tolerance and suppliers. Fujita (2002) also used an optimization model to optimize the product variety in the market. Also, Kim et al. (2002) develop a mathematical model and solution algorithm for assisting manufacturer to configure its supply chain for a mix of multiple products sharing some common raw materials and/or components. The model evaluates how much of each raw material and/or component to order from which supplier under such constraints as the supplier's capacity limit. However, they do not consider the impact of sharing components across multiple products. More recently, Fine et al. (2005) argues that all three domains (product, process, and supply chain) possess architecture, and matching these architectures is key to the success of three dimensional concurrent engineering (3D-CE). He then proposes a goal-programming model approach to address the 3D-CE during product development period.

While all the above studies provide early attempts to link product design decisions with both process and supply chain design decisions, they are all single focused. For example, Feng et al. (2001) are more focused on product design, while Fine et al. (2005) concentrate on the supply chain and do not consider the functional aspects of a product. The proposed research is different

from the above studies in two ways: firstly, it will integrate the supply chain decisions into the product architecture selection (or product modularization) using multi-objectives functions in the decision making. These objectives will span the domains of customer related attributes (e.g. quality), manufacturing (manufacturability) and supply chain.

Secondly, since the product and supply chain architectures will both be established during the conceptual stage of the product development (PD) cycle where the information available on the product is generally vague and ambiguous and decisions are made based subjective evaluation criteria. By extending the work of Nepal et al. (2005), a fuzzy logic based method is used to model the performance indices of both product architecture and supply chain based on subjective information available through expert interview. An optimization method is then used to determine optimal product architecture (product modularization) and supply chain network (suppliers' selection) by considering multiple objectives and constraints related to product, manufacturing process, and supply chain design.

In conclusion, the research gaps found in the literature above falls into three categories:

The first category includes studies related to product architecture only. The second category includes studies related to supply chain configuration only while the third category includes studies relating product architecture to supply chain configuration either through empirical studies or single objective mathematical models. These are the research gaps this work will fill.

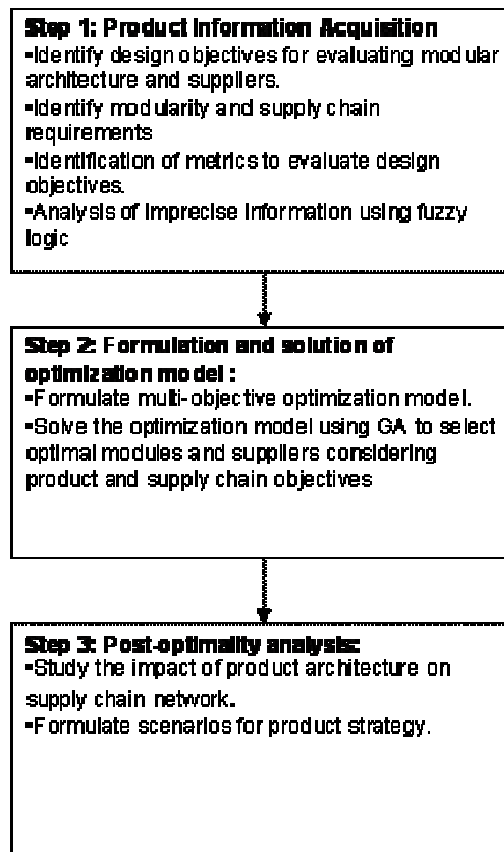


Figure 1. Integrated framework matching product architecture to supply chain network

3. Proposed Framework

An integrated framework is proposed for creating optimal modular design and supplier selection by considering multiple objectives that are related to product performance, manufacturing process, and supply chain design. The framework will consist of the following three phases:

- (i) product information acquisition,
- (ii) formulation and solution of optimization model to select optimal modules and suppliers,
- (iii) scenario or post-optimality analysis.

3.1 The Optimization Model

The decision variables and parameters that will be used in the formulation of the optimization model are given as follows:

$x_{ijkl} = 1$ if component i supplied by supplier j is combined with component k supplied by supplier l into one module, 0 otherwise.

$y_{ij} = 1$ if component i is supplied by supplier j , 0 otherwise.

$\beta_{ijkl} =$ Performance index for a candidate module consisting of component i supplied by supplier j and component k supplied by supplier l with respect to “larger is better” objective p .

$\alpha_{ijkl} =$ Performance index for a candidate module consisting of component i supplied by supplier j and component k supplied by supplier l with respect to “smaller is better” objective q .

The objective functions are given as:

$$\text{Maximize } \sum_i \sum_j \sum_k \sum_l (y_{ij} \times \beta_{ijkl} \times x_{ijkl}) \quad \forall p \quad (\text{larger is better objective})$$

$$\text{Minimize } \sum_i \sum_j \sum_k \sum_l (y_{ij} \times \alpha_{ijkl} \times x_{ijkl}) \quad \forall q \quad (\text{smaller is better objective})$$

and the constraints are:

1. $\sum_j \sum_k \sum_l x_{ijkl} = 1 \quad \forall i$ (each component is assigned to one module)
2. $x_{ijkl} \leq x_{ijij} \quad \forall i, \forall j, \forall k, \forall l$ (components are assigned to modules that have a median component)
3. $x_{ijkl} \leq y_{ij} \quad \forall i, \forall j$, (a component is only selected if and only if one of its suppliers is selected)
4. $\sum_j y_{ij} = 1 \quad \forall i$ (only one supplier is selected for each component – for single sourcing problem)
5. Non-negativity constraints.

Because of the multiple objective functions in the model, a goal programming method is then used to formulate the final optimization model. In goal programming model, all the multiple objectives are converted into goals. These goals are then treated as “soft” constraints while the original constraints are treated as “hard” constraints in the new model.

Let δ represents the deviation of any of the soft goal from the targets (or aspiration levels) μ_p for goal type p and λ_q for goal type q , then the soft constraints can be written as:

1. $\sum_i \sum_j \sum_k \sum_l (y_{ij} \times \beta_{ijkl} \times x_{ijkl}) + \delta \geq \mu_p \quad \forall p$ (larger is better goal constraints)
2. $\sum_i \sum_j \sum_k \sum_l (y_{ij} \times \beta_{ijkl} \times x_{ijkl}) + \delta \geq \lambda_q \quad \forall q$ (smaller is better goal constraints)

The objective of the new model is to minimize the deviation δ , subject to the five original hard constraints and the new soft constraints. The resulting model is then solved as single-objective optimization model.

4 Conclusion

While it is a generally accepted fact that the decisions made during the product development stage have huge impact on the downstream decisions. However, there are very few qualitative models on how to study the effect of such downstream decisions and help integrate them into product development decisions. Most of the previous methods were heuristic based or single objective optimization problem. This research work hopes to fill this gap by providing an integrated framework for linking product architecture decisions with supply chain policies during the conceptual stage of product development. To achieve this, we propose a multiple objective optimization model by considering objectives related to both product architecture and supply chain. It is hoped that such model will provide resolution to conflicts inherent in such integrated decision making.

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