Theory and Methodology

Evaluation of supply chain structures through modularization and postponement

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Abstract

This paper introduces a conceptual framework for evaluating different supply chain structures in the context of modularization and postponement. In our analysis, modularization is linked to inbound logistics as the combination of different components (or modules) allow for the assembly of the final product. Postponement, however, corresponds with the outbound logistics since it is through the distribution function that customers’ specific demand is satisfied. Given this perspective, we introduce a taxonomy and develop a corresponding framework for the characterization of four supply chain structures, defined according to the combined levels of modularization and postponement: Rigid, Postponed, Modularized and Flexible.

We also illustrate the applicability of the resulting framework through quantifying the total cost differential for utilizing a particular supply chain structure. By quantifying the total cost for employing a particular supply chain structure we can numerically illustrate structural results that allow for an objective comparison among them. As such, our findings substantiate the empirical evidence that vertical integration along the supply chain is not always desirable. A point of emphasis in this paper is the notion that firms may be better off making combined modularization (outsourcing) and postponement decisions as opposed to separate ones (as they currently do). This also suggests that modularization and postponement decisions need not be independent and that their joint consideration extends operational advantages worthy of contemplation. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Supply chains; Outsourcing; Modularization; Postponement

1. Introduction

The emerging paradigm of globalization and increased competition demands a more efficient utilization of every value-adding operation in most companies and within their functional areas. The functions of product and process design are no exception to this evolution. These technology-specific areas have matured over the years as companies strive to gain a competitive advantage through comprehensive product and process developments that not only cut down response time, but also address their implications down the value
The expanding scope of decision making across temporal, geographical, value chain and functional dimensions provides companies with a sustainable competitive advantage in terms of cost, quality, innovation and delivery performance. Concurrently, through relentless improvements in the manufacturing industry over the past decades, companies have benefitted tremendously through applying different managerial approaches (e.g., JIT, TQM, and FMS). These combined efforts, however, come at the expense of a corresponding increase in the level of logistic activities as needed material, parts and products must be moved from one destination to the next, be it an intra-factory station or an international market. Supply chain management is responsible for maneuvering this flow process through which continued productivity is ensured.

This flow process can be decomposed into two segments: inbound logistics, concerned with providing all the materials and goods required for making the products; and outbound logistics, which deals with the flow of the manufactured products from the factories to the hands of the customer. Companies recognize that efficiencies in logistics have now become as important to strategic planning as are improvements in manufacturing and marketing.

In this paper we discuss two concepts used in product and process design, modularization and postponement, and probe their respective relation to supply chain structures. The two concepts are closely interrelated and by implementing them correctly, companies can obtain sustainable competitive advantages all along the supply chain (procurement, processing and distribution). Although both concepts have been individually discussed in the literature before, the combined potential of these two approaches is presented in an integrated manner in this paper. As such, the primary objective of the paper is to introduce a conceptual framework and a taxonomy for evaluating different supply chain structures in the context of modularization and postponement. Here, modularization is linked to the inbound logistics as the combination of different components (or modules) allows the assembly of the final product. Postponement, on the other hand, is associated with the outbound logistics since it is through the distribution function that market demand is satisfied. By quantifying the total cost for utilizing a particular supply chain structure we also exemplify structural results numerically that allow for an objective comparison among them.

The paper is organized as follows. In the next section the two essential concepts to our work, modularization and postponement, are introduced in some detail with a relevant review of the literature. The associated benefits of the two concepts for the entire supply chain and logistics processes are then explained with a few examples. In Section 3 a conceptual framework is developed through introducing four classes of supply chain structures (Rigid, Flexible, Postponed and Modularized) as a function of the combined levels of modularization and postponement. This essentially helps in classifying the aforementioned taxonomy as well. Section 4 presents a simple analytical model to illustrate the total cost of the different structures and the corresponding structural results, albeit, in an empirical environment. Closing remarks are provided in Section 5.

2. The two concepts

Starr (1965) initially introduced the concept of Modularization in the literature. It implies a product design approach whereby the product is assembled from a set of standardized constituent units. Different assembly combinations from a given set of standardized units give rise to different end-product models and variations. Thus, modular design effectively marries flexibility (of the end product) with standardization (of constituent parts). It provides opportunities for exploiting economies of scope and scale from a product design perspective. The key issue here is to design for efficient linkage mechanisms in the constituent units so that any required combination can be conveniently assembled. This implied flexibility has other related advantages in a manufacturing context. In particular, the higher the level of modularization, the easier it is to outsource manufacturing or its constituent components. In this context, the notion of outsourcing as leveraged
through modularization assumes an important role in the framework we develop.

The Postponement concept was initially discussed by Alderson (1950), where it was observed that products tend to become differentiated as they approach the point of purchase, i.e., as it flows down the supply chain. Although this “differentiation” improves the marketability, the “manufacturability” of the products become more complex. However, by moving the “point of departure” for the differentiated product-models in the manufacturing process closer toward the point of purchase, benefits of consolidation could be exploited which reduces the complexity in manufacturing. This also helps to substantially truncate uncertainty and leads to a reduction in forecast errors by delaying the date at which one must make a production decision associated with a particular demand. In this light, postponement may be defined as a value added process for a set of end products whereby the common processing requirements among them is maximized. The customized or unique processing requirements for each product variety is delayed (or postponed) as much as possible in the value added process. This, in turn, provides scope for exploiting scale advantages without compromising the variety of products (scope advantages) from a process design approach. Chase (1981) and Tarondeau (1993) have also discussed this concept in the context of service systems.

From the above definitions it may be noted that the fundamental principle in the two concepts is essentially the same – marrying the advantages of scale and scope. In our analysis, while modularization does this from a product design point of view, postponement attains it from a process design perspective. Modularization essentially characterizes supplier responsibilities in terms of the outsourcing function. In our view, an integrated product–process approach offers an increased potential for obtaining greater advantages. We will emphasize that most firms may be better off making combined modularization (outsourcing) and postponement decisions, as opposed to separate decisions, which is the current norm. The existing literature in this area has, by way of tradition, highlighted issues and factors that firms need to consider in either their outsourcing or their postponement decisions. By removing this mutual exclusivity, this paper proposes a conceptual framework and taxonomy that helps to emphasize the combined benefits of modularization and postponement as dependent decisions.

Recent literature has cited numerous articles addressing the fact that a product’s manufacturing cost (i.e., inbound logistics) is largely determined by its design. For instance design alone determines 80% of the final production cost of the 2,000 parts in the making of a Rolls Royce, and 70% of the cost of manufacturing truck transmissions at General Motors (Corbett, 1986). Concepts such as design for manufacturability (Whitney, 1988; Dean and Susman, 1989; Taguchi and Clausing, 1990), directly address the importance of considering manufacturing limitations and input. Lee and Billington (1992) contend that the process should go beyond manufacturing and incorporate issues about order fulfilment (i.e., outbound logistics). In particular, they suggest that companies should design for supply chain management more so than design for manufacturability. Concurrently, consumers are forcing companies to increase the diversity of products. This acute condition is further intensified by a reduction in product life cycles for most existing products. The result is an increase in requirements on the flexibility of manufacturing systems that limit the improvements in productivity (Taguchi and Nonaka, 1986; Wheelwright and Sasser, 1989). Such requirements from consumers are increasing both in the number of details and in diversity which make it difficult for companies to anticipate demand. Child et al. (1991) offer a thorough discussion of the operational problems as related to the complexity of product variety.

The general notion of postponement has also been studied from different perspectives. For example, Zinn and Levy (1988) analyze the optimal location problem for a postponed inventory in a marketing channel. They employ the concept of speculative inventory introduced by Buklin (1965) to develop a framework of governance structures. Shapiro and Heskett (1985), Zinn and Bowersox (1988), and Zinn (1990) present other applications of the concept in the logistics and distribution side of business. More recently, however, the problem
has been analyzed as an integrative supply chain model by Lee and Billington (1993), Davis (1993) and Lembke and Bassok (1995). The main objective in these models has been to incorporate the complexities of the complete supply chain management and its relationship to inventory investment. Specific relationships of demands, target service levels, substitutability and lead times have also been considered explicitly within the model’s framework.

However, it should be recognized that the implications of these concepts (modularization/postponement) extend far beyond the immediate value addition processes. The associated benefits include the logistics function in its integrity, inbound and outbound: plant layout, capacity planning, new product development, outsourcing, and reductions in inventory levels and time distribution of products to different market segments.

For instance, the principle of modularization/postponement has been effectively used in designing plant layout. Magneto–Marelli, an international automotive component manufacturing giant, has reorganized its layout at its manufacturing facilities in France into two broad sections, namely, basic products and model-specific lines. The basic product section manufactures component modules (basic products) which are subsequently used in multiple (model-specific) end product lines. This layout pattern simplifies material flow and control as it further amplifies the benefits of low inventory in a just-in-time environment.

The capacity planning approach of Texas Instruments (TI) also illustrates another potential benefit. The two broad semiconductor categories of TI are low-cost DRAM memory chips and expensive customized microprocessors and other integrated circuits. Quick delivery and service are very important in this business. TI has developed an “ingenious” capability to “stretch” its capacity to accommodate manufacturing of high-end customized microprocessors. This is effected through a specialized product and process design whereby 90% of the production process (placing transistors and chips) is identical for the two product categories; i.e., customization through expensive refinement is “postponed” to the end of the process.

With this set-up, TI always operates its plant at full capacity by using production of memory chips as buffer: adjusting its volumes in correspondence to the demand for the customized chips. Thus in 1992, it increased its output of customized chips from 10% to 60% of the capacity. This gives TI a strategic and competitive edge in all customer segments. It effectively and efficiently caters to its customers of specialized products without affecting the DRAM market segment, which is a commodity item “sold by 13 other hungry manufacturers” (Tully, 1993).

Modularization in product design can help speed up the new product development process. Orienting the basic design of new products so as to maximize the use of existing standardized component units would mean economy in resource usage (financial and human) as well as reduced time requirements. It would also imply savings (time and money) in development of corresponding processes.

Companies that have successfully exploited the benefits of modular design and its consequent standardization of parts include the Japanese car maker Suzuki (Friedland, 1994). It has led the industry in standardizing auto parts and reducing variations. Two of its latest product models, the Wagon R minivan and the Alto, share 70% of their parts with other Suzuki models. This “frugal” design strategy is ideally suited for periods of economic downturns when companies are strapped for resources but are still unable to scale down their innovative efforts. Additional case examples include Dell Computers, Nike, IBM and General Motors and are given by Tully (1993).

Many companies have also strategically used the benefits of modularization and outsourcing. One such example is the US automobile manufacturer Chrysler which designs its cars to be built in modules (Tully, 1993). Its highly successful LH series involves a modular design approach: the interior is composed of four easy-to-install units that are delivered ready as built by separate suppliers. This facilitates “consolidated” outsourcing activities like system purchase and black box design which, in turn, are oriented towards exploiting advantages of low production costs and advanced technology.
The combined concepts of modularization and postponement taken together have strategic and tactical implications and advantages. A classical case in the logistics advantages of using modularization and postponement is Benetton which uses a very convenient combination of contract manufacturing in their operations strategy (Benetton, 1985). For Benetton, 90% of its sales are of standardized items with a seven month advance committed order which are conveniently contracted out based on known stable plans; the remaining demand pattern of 10% is unpredictable and hence postponed under in-house manufacturing until just five weeks before delivery. This offers the company strategic and operational flexibility. Application of the postponement principle to innovative packaging design and process could result in increased efficiency in materials handling, storage and transportation, while providing the customer with a better looking package and continued service by maintaining the high fill rate targets (Howard, 1991). This has been applied to the case of HP DeskJet 500 printers, whereby the packaging of market specific (which resulted in 26 versions of 2 basic models) manuals, software and other accessories were “localized” by using the basic principle of “substitutability” between generic models (i.e., modularization). The benefits included a 187% rise in material handling productivity and a 47% reduction of storage space requirements. Lee et al. (1993) presents a case example of the benefits of postponement through an application to the distribution of HP printers. Minimal changes in the location of value addition (delocalization) has led to substantial proficiencies through inventory savings for the company. Standardized products may be rolled out from a centralized facility and then routed to destination markets where a minimal market specific value addition is undertaken.

In light of the aforementioned examples the link between these two concepts becomes quite evident. Simply, this link implies a close relationship between product and process design. As products have to be designed to maximize the number of common standardized constituent units among a set of end-products, processes must allow for a flow of discrete steps in the supply chain in order for the postponement to take place. The implication is then clear that outsourcing and postponement should not be viewed as independent decisions. The ideal situation is to have the best of both worlds, economies of scale and scope. Of course, it is not possible to obtain the maximum level of modularization and postponement in every case. There are either technological restrictions that impede modularization (e.g., steel manufacturing), or organizational structures that constrain coordination (e.g., decentralized organizational structures that constrain integration). The framework presented in this paper aims at evaluating the different trade-offs that exist in each case.

In the following section we present a taxonomy and a conceptual framework for evaluating supply chain structures. The framework captures the trade-offs faced by different supply chains through categorization into the two levels of inbound and outbound logistics.

3. Framework for analysis

Toward characterizing the different supply chain structures, we consider the inbound and outbound logistics to capture the degree of modularization and postponement. Thus, inbound modularization is the dimension that captures the degree of outsourcing and the usage of subcontractors for making the components. A low inbound modularization represents a supply chain with a high degree of vertical integration. It may be constrained by either product design specifications or by industry structure. A high inbound modularization, however, is a supply chain highly decentralized which outsources many of the components from multiple suppliers.

Outbound postponement captures the extent of customization the supply chain is offering. Therefore, a high outbound postponement is a supply chain basically organized around a make-to-order environment where customer demand triggers the completion of the final product. A low outbound postponement is characteristic of a make-to-stock environment where an inventory of finished products is maintained to satisfy customer demand.
Outbound logistics involves a form transformation since it moves products from the plant to the customer. Zinn and Bowersox (1988) and Lee and Billington (1992) define different levels of postponement according to where in the supply chain the product is differentiated or customized. They summarize the options into time and form postponement. In time postponement, one refers to delays in product movement, while form postponement refers to the delay in the product’s final configuration. Note that the concepts (of modularization and postponement) are applicable to products involving a flow of discrete steps in the supply chain. In our model we simplify the logistics flow pattern by dividing it into three distinct steps: manufacturing, assembling and packing. Manufacturing involves the production of the component parts. Assembly requires putting together the different components for creating the product. Packaging involves the actual packaging and labeling of the final product to satisfy customer demands. In this simple context, the assembly step is viewed as a separating buffer that, essentially, links inbound (manufacturing) with outbound (packaging) logistics. The distinction among these steps is not trivial: postponing manufacturing is quite different from assembly and packaging. That is why we associate manufacturing with modularization and packaging with postponement. However, given the approach taken in the analytical section of this paper, the refinement of the steps in the supply chain will be deferred to future research.

On the basis of our previous depiction of the two dimensions of inbound and outbound logistics we now define four supply chain structures: Rigid, Flexible, Postponed and Modularized (see Fig. 1). The Rigid structure represents the classical vertically integrated supply chain where the objective is to exploit economies of scale in production of large runs by maintaining large inventories of finished products. The other extreme is the Flexible structure where many subcontractors are used to make the different components and the assembly of the final product is in response to a specific demand. Economies due to the commonality effect are expected with respect to inventory.

There are also two intermediate structures. The Modularized structure, which has multiple sources

![Fig. 1. Framework for supply chain structures](image-url)

The figure illustrates the three distinct steps: manufacturing (M), assembly (A), and packaging (P). The options for each step are represented as high or low, indicating different levels of modularization or postponement. The diagram shows how these steps come together in different supply chain structures: Rigid, Flexible, Postponed, and Modularized.
for the components but the output of the assembly process is the finished product. This is probably the most typical supply chain structure for most industries (Tully, 1995). Finally, the Postponed structure that exploits economies of scale in the making of components but customizes the finished product to satisfy specific customer or market demand.

On this basis, it is not intuitively clear what supply chain structure best suits the needs of a company. We see very rigid structures, companies like Kamaz (a truck manufacturer), which is vertically integrated and basically purchases all the raw materials used in the production of its trucks. Others are more flexible, like BMW which buys 80% of its car’s components. Rolls Royce customizes production and does not assemble or distribute a car until a customer’s order is received (Bowersox and Morash, 1989). Arguments in favor or against these concepts can go in either direction: from functional specialization and operational flexibility to losing control and information leaks. In the computer industry, for example, Apple, IBM and Dell contract their needed components from companies such as SCI Systems, Solectron or Jabil Circuit. Compaq, on the other hand, manufactures all of its computers in-house. In the car industry, GM is the most vertically integrated of the three car companies by producing 70% of its components in-house. Chrysler, however, buys 70% of the materials used in each car from suppliers (Tully, 1994).

So, what supply chain structure is the most appropriate choice for a company. In answering this question appropriately, we note that there is an explicit trade-off in cost and service levels that has to be accounted for. When companies increase the level of inbound modularization (e.g., by using more modularized contracting), it becomes possible to significantly reduce the fixed costs involved. Dell, for example, has $2.9 billion in annual revenues with $60 million in fixed assets. It takes $35 of sales for every dollar of fixed assets while for Compaq the figure is $3 (Tully, 1993, 1995). The trade-off has to be in the variable cost (i.e., the per unit variable cost is higher) since some level of margin to the subcontractors has to be accounted for. For the postponement case the situation is reversed. By allowing for a higher outbound postponement, companies may incur the extra fixed cost of maintaining multiple equipment for packaging and labeling (e.g., warehouse facilities with machines to label). However, the variable cost is reduced because of centralized inventories, less risk associated with lower finished goods inventories, and/or bulk shipping from the plants. Zinn and Bowersox (1988) and Lee and Billington (1992) present an excellent discussion on similar trade-offs. The combination of fixed and variable costs for the different supply chain structures will be elaborated upon in more detail in the next section. Table 1 illustrates our conceptual framework using the companies introduced earlier (see Table 1).

4. Analytical formulation of the framework

In this section we quantify the economic impact of adopting any of the different supply chain structures introduced earlier. The objective is to derive structural findings that will allow us to illustrate comparative results for selecting one structure over another. In what follows we provide a simple analytical framework for evaluating various supply chains on a differential cost basis. The advantage of this approach, in addition to providing comparative results, is that it allows for incorporation of a host of factors influencing operating costs. Of course, this comes at the expense of increased computational complexity. However, in this paper we are only concerned with the development of a general framework upon which other future work can be based.

To focus discussion, consider a company that sells a product (e.g., ice cream) to two different markets (e.g., England and France) with no demand correlation between them. The only difference between the two market requirements is in the packaging since the labels come in different languages (labels are stickers put on the package). Following our introductory framework, manufacturing will be associated with the inbound
logistics where the ice cream could be either made in house, or could be modularized in standardized containers. Assembly consists of preparing and/or filling the packages. Finally, packaging consists on labeling the ice cream for its final destination (i.e., the two different markets that require different labels).

Under the Rigid structure the company makes two (packaging) runs of ice cream for each of the markets based on the expected demand for each market (i.e., incur a fixed cost and a variable cost for labeling in one location). Under the Postponed structure, the company postpones packaging by having a separate labeling process in each of the countries (i.e., incur a fixed and variable cost in each country). Under the Modularized structure the company subcontracts ice cream production to different dairy companies though, packaging and labeling for the final markets is performed in-house. Finally, under the Flexible structure the company subcontracts making the ice cream, packages it in-house and has a labeling machine in each of the countries where the postponed shipments are labeled according to the market specifications.

The bulk of savings from postponement will arise from a reduction in the variability of demand (assumed Normal) when the company decides to package “later”. However, a higher fixed cost will be incurred by having two labeling processes as opposed to one. When subcontracting with other (dairy) companies, the fixed cost of production is lower but the variable cost will be higher. Please note that in our setting, the term flexibility is associated with flexibility of options. Then, for example, at the inbound logistics, Rigid and Postponed structures will mainly use their existing equipment for making (i.e., manufacturing) the products, while the Modularized and Flexible could use different suppliers and even change them from time to time (i.e., they have more options).

At the outbound logistics, the Rigid and Modularized structures will finish the final product earlier than the Postponed and the Flexible structures. The Postponed and Flexible structures delay the actual finishing of the products until more information about final demand is known and therefore have more options for changing the mix of finished products. When flexibility is thought in terms of control or contractual alternatives, our definition may not apply.

We are now in a position to set forth an analytic framework for comparison purposes where the following notation is introduced:

- $i$ index for the different supply chain structures $R, F, O$ and $P$
- $j$ index for the two markets $A$ and $B$
- $F_i$ fixed cost under structure $i$
- $V_i$ variable cost under structure $i$
- $H$ holding cost per unit for the inventory of finished goods
- $B$ backorder cost per unit for demand not satisfied, where in most realistic applications $B \geq V_i$
- $f(\cdot)$ probability distribution of demand
- $(\mu_j, F_j)$ mean and standard deviation parameters for the demand in market $j$

Let $S$ define the production quantity under each structure considered. In light of the above notation, the total cost under structure $i$ is given by

Table 1
Illustration of the framework

<table>
<thead>
<tr>
<th>Inbound modularization</th>
<th>Outbound postponement</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Postponed</td>
<td>Rigid</td>
<td>Modularized</td>
</tr>
<tr>
<td>Texas Instruments, Magneto-Marelli, Rolls Royce</td>
<td>Compaq, Kamaz General Motors</td>
<td>Dell Computers, Benetton, Suzuki, Hewlett-Packard</td>
<td>IBM, Nike, BMW, Chrysler</td>
</tr>
</tbody>
</table>
\[ TC(S) = F_i + V(S) + H \int_0^S (S - x)f(x) \, dx + B \int_S^\infty (x - S)f(x) \, dx. \tag{1} \]

The first two terms in Eq. (1) capture the fixed and variable cost of production and packaging. Assembly is not explicitly captured in the formulation because all structures include it in a similar fashion. Each supply chain structure will have a different combination of parameters to be discussed later. We assume, as in Zinn and Bowersox (1988), that variable costs reflect those that would drop to zero as a consequence of eliminating the product. Fixed costs are defined as those that do not change with the quantity produced. The third and fourth terms capture the total holding and backorder costs, respectively. For simplicity we assume an order-up-to level inventory policy. Note that \( H \) and \( B \) are assumed the same under the four supply chain structures and for the two markets. The total holding and backorder cost are a function of the finished goods inventory (outbound logistics) and not a function of the manufacturing method selected.

The quantity to be produced, \( S \) may be expressed in two distinct ways depending on the level of outbound postponement considered. If the outbound postponement is low (i.e., the structure is rigid or modularized), the company treats each market independently since we have assumed no demand correlation, and the quantity to be produced is a function of the expected demand. This quantity is expressed by

\[ S_L = \mu_A + k_A \sigma_A + \mu_B + k_B \sigma_B \tag{2} \]

where the constants \( k_A \) and \( k_B \) depict the service level parameters (measured as deviations of \( F \)) for markets \( A \) and \( B \) and defined according to the strategic priorities of the company.

If the outbound postponement is high (i.e., the structure is postponed or flexible), the company benefits from the commonality effect for the safety stock (as in Baker et al., 1986) and the resulting production quantity is expressed as

\[ S_H = \mu_A + \mu_B + \sqrt{k_A^2 \sigma_A^2 + k_B^2 \sigma_B^2}. \tag{3} \]

To simplify matters somewhat, suppose that \( k_B = \alpha k_A \) and \( \sigma_B = \beta \sigma_A \) for \( \alpha, \beta \geq 1 \). It then follows that

\[ S_H = \mu_A + \mu_B + k_A \sqrt{1 + \alpha^2 \beta^2}. \tag{4} \]

These expressions allow for derivation of the total cost function for the different supply chain structures. Toward this objective, denote the standard normal distribution as \( g(z) \) and let

\[ G_z(k) = \int_k^\infty (z - k)g(z) \, dz. \tag{5} \]

Upon substituting Eq. (5) into Eq. (1), while maintaining our assumptions we obtain the following expression:

\[
\begin{align*}
TC_R(S_L) &= F_R + V_R(\mu_A + \mu_B + k_A \sigma_A + k_B \sigma_B) \\
& \quad + H(\sigma_A(k_A + G_z(k_A)) + \sigma_B(k_B + G_z(k_B))) \\
& \quad + B(\sigma_A G_z(k_A) + \sigma_B G_z(k_B)) \tag{6}
\end{align*}
\]

where by rearranging the terms in the total cost function for the rigid supply chain structure yields

\[
\begin{align*}
TC_R(S_L) &= F_R + V_R(\mu_A + \mu_B + k_A(1 + \alpha \beta) \sigma_A) \\
& \quad + H\sigma_A(k_A(1 + \alpha \beta) + G_z(k_A) + \beta G_z(z k_A)) \\
& \quad + B\sigma_A(G_z(k_A) + \beta G_z(z k_A)). \tag{7}
\end{align*}
\]

**Proposition 1.** Under the Rigid Supply Chain Structure the service level parameter, \( k_A \) that minimizes the total cost satisfies the following critical ratio condition:

\[
(1 + \alpha \beta) \frac{(B - V_R)}{(H + B)} = F(k_A) + \alpha \beta F(z k_A) \tag{8}
\]

where \( F(\cdot) \) is the cumulative function of \( f(\cdot) \).

**Proof.** It is straightforward to verify that the total cost function given by Eq. (7) is convex in \( S_L \). The proof follows thereafter.
In a similar fashion we may obtain an expression for the total cost function in the case of Flexible Supply Chain Structure:

\[ TC_F(S_H) = F_R + V_R \left( \mu_A + \mu_B + k_A \sqrt{1 + x^2 \beta^2} \sigma_A \right) \]

\[ + H \sigma_A \left( k_A \sqrt{1 + x^2 \beta^2} + G_z \left( k_A \sqrt{1 + x^2 \beta^2} \right) \right) \]

\[ + B \sigma_A G_z \left( k_A \sqrt{1 + x^2 \beta^2} \right). \]

**Proposition 2.** Under the Flexible Supply Chain Structure the service level parameter, \( k_A \) that minimizes the total cost satisfies the following critical ratio condition:

\[ \frac{B - V_F}{H + B} = F \left( k_A \sqrt{1 + x^2 \beta^2} \right) \]

where, without loss of generality we have assumed in all cases \( B \geq V_i \), for all \( i \), to ensure the critical ratio is non-negative.

The proof follows in a straightforward manner, as in Proposition 1.

The total cost functions for the modularized and postponed supply chain structures are similar to the ones derived in Eq. (7) and Eq. (9) by adjusting for the appropriate fixed and variable costs. The total cost function for these structures is different in that the modularized uses the low outbound postponement (like the Rigid) while the postponed uses a high outbound postponement (like the Flexible). In addition, the structural results as provided by Propositions 1 and 2 also remain valid and may be extended to account for the current cases considered by appropriately adjusting the corresponding variable costs. In comparing the four supply chain structures the relationship between fixed and variable costs for each of them must be analyzed. The holding and backorder costs are assumed fixed in all cases and therefore have no direct impact on the analysis. As we have already remarked, the rigid structure exploits economies of scale in production and packaging when making \( S_L \) units. The flexible structure, on the other hand, results in a lower fixed cost for producing the components (since it subcontracts) while a higher fixed cost for packaging is incurred (two different labeling machines are required), in order to make \( S_H \) units. For comparison purposes, we assume that the resulting fixed cost for the flexible supply chain structure is equal to the fixed cost of the rigid supply chain structure, so that an increase in postponement cost is equally offset by a corresponding decrease in subcontracting expense. Similar assumptions can also be made regarding the variable costs. The other two supply chain structures (Modularization and Postponed) are reflective of intermediary situations as presented in the following table; where \( \Delta F \) and \( \Delta V \) define any two positive numbers and where their magnitude will be specific to each case. We are aware of the restriction of these assumptions and use them only as a means of simplifying the comparison (for illustrative purposes) among the different supply chain structures. Further research should explore in more detail the range and variability for these parameters.

<table>
<thead>
<tr>
<th>Supply chain structure</th>
<th>Fixed cost</th>
<th>Variable cost</th>
<th>Units produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid ( S_L )</td>
<td>( F )</td>
<td>( V )</td>
<td>( S_L )</td>
</tr>
<tr>
<td>Postponed ( S_H )</td>
<td>( F + \Delta F )</td>
<td>( V - \Delta V )</td>
<td>( S_H )</td>
</tr>
<tr>
<td>Modularized ( S_L )</td>
<td>( F - \Delta F )</td>
<td>( V + \Delta V )</td>
<td>( S_L )</td>
</tr>
<tr>
<td>Flexible ( S_H )</td>
<td>( F )</td>
<td>( V )</td>
<td>( S_H )</td>
</tr>
</tbody>
</table>

These relationships allow us to derive the following propositions where their corresponding proofs are deferred to Appendix A.

**Proposition 3.** Given a service level parameter \( k_A \), the total cost for the Flexible Supply Chain Structure can never exceed the total cost for Rigid Supply Chain Structure, i.e.

\[ TC_F(S_H) \leq TC_R(S_L). \]

**Proof.** See Appendix A.
ported by recent empirical evidence that a majority of companies are seeking and entering contractual agreements with suppliers in moving towards a make-to-order type arrangement (Zarley, 1995).

Proposition 4. For a given service level parameter $k_A$, the total cost for the Modularized Supply Chain Structure is lower than the total cost for the Rigid Supply Chain Structure if the following condition holds:

$$TC_0(S_L) \leq TC_R(S_L) \iff F/AV \geq S_L.$$  

(12)

It follows, without loss of generality, that the same concept applies to the other case by replacing Modularized by Postponed, Rigid by Flexible and $S_L$ by $S_H$. That is,

$$TC_P(S_H) \leq TC_F(S_H) \iff F/AV \geq S_H.$$  

(13)

Result from Proposition 4 are similar to the classical results in the make versus buy decisions where the driver is the ratio of fixed to variable costs relative to the quantity to be produced.

Proposition 5. Let $(X,Y)$ represent any of the following pairwise combinations: (Postponed, Modularized), (Flexible, Modularized), or (Postponed, Rigid). Then, for a given service level parameter $k_A$, the total cost for the $X$ supply chain structure is lower than the total cost for the $Y$ supply chain structure if the following condition holds:

$$TC_X(S_H) \leq TC_Y(S_L)$$

$$\iff F_X - F_Y \geq V_Y(S_L) - V_X(S_H) - K,$$  

(14)

where

$$K = Hk_A\sigma_A\left(\sqrt{1 + \alpha^2\beta^2} - (1 + \alpha\beta)\right) + (H + B)\sigma_A\left(G_Z(k_A)\sqrt{1 + \alpha^2\beta^2} - G_Z(k_A)\right) - \beta G_Z(\alpha k_A).$$  

(15)

Proof. See Appendix A.

As in Proposition 4, in Proposition 5 the decision is also determined by the relationship between fixed and variable costs. The difference between this case and the previous is that the quantity to be made is different, i.e., the Postponed structure makes $S_H$ units and the Modularized structure makes $S_L$ units.

5. Numerical illustration

To illustrate the framework developed herein the following set of case parameters are employed where

- $\mu_j$: 100 units for markets $A$ and $B$
- $\sigma_j$: 20 units
- $F$: 500\$\n- $V$: 3\$/unit
- $H$: 1\$/unit
- $B$: 8\$/unit
- $DF$: 250 (fixed cost is reduced or increased by 50% in the Modularized or Postponed structures)
- $DV$: 1 (variable cost is reduced or increased by 33%)
- $\alpha$: 1 (safety factor for market $B$ is equal to the safety factor for market $A$)
- $\beta$: 3 (variability of demand for market $B$ is three times the variability for market $A$)

By applying Propositions (1) and (2) to the above case parameters the following table of summarized results is obtained:

<table>
<thead>
<tr>
<th>Supply chain structure</th>
<th>Optimal service level parameter $k_A$</th>
<th>Optimal units produced</th>
<th>Total cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid</td>
<td>0.139</td>
<td>211.17</td>
<td>1384.45</td>
</tr>
<tr>
<td>Postponed</td>
<td>0.136</td>
<td>208.62</td>
<td>1215.45</td>
</tr>
<tr>
<td>Modularized</td>
<td>−0.139</td>
<td>188.82</td>
<td>1334.45</td>
</tr>
<tr>
<td>Flexible</td>
<td>0.044</td>
<td>202.79</td>
<td>1171.11</td>
</tr>
</tbody>
</table>

No direct comparison can be made among the four supply chain structures since we have computed the optimal $k_A$ in each case. However, it is interesting to observe that the rigid structure resulted in the highest cost but with the highest
service level. The flexible structure has the lowest cost and a lower service level than the rigid. This might be explained by the commonality effect (i.e., less safety stock is required to obtain a similar service level).

The Modularized structure is not an attractive option for the choice of case parameters used here since it provides a low level of service with a high total cost. The postponed structure offers a higher level of service with a total cost still under the rigid structure.

In order to compare the different supply chain structures we fix the service level parameter \( k \) at 0.1 and calculate the resulting total cost. For this \( k \) the resulting values of \( S_H, S_L \) and \( K \) are 206.33, 208.00 and \(-207.44\) respectively.

Through changing the values for \( D_F \) and \( D_V \) we can observe how the optimal supply structure changes.

<table>
<thead>
<tr>
<th>Supply chain structure</th>
<th>Base case</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta F = 250 )</td>
<td>$1384.67</td>
<td>$1384.67</td>
<td>$1384.67</td>
</tr>
<tr>
<td>( \Delta V = 1 )</td>
<td>$1215.88</td>
<td>$1422.21</td>
<td>$965.88</td>
</tr>
<tr>
<td>Rigid</td>
<td>$1342.67</td>
<td>$1134.67</td>
<td>$1592.67</td>
</tr>
<tr>
<td>Postponed</td>
<td>$1172.21</td>
<td>$1172.21</td>
<td>$1172.21</td>
</tr>
</tbody>
</table>

As expected from Proposition 3, the rigid supply chain structure implies an inferior chain structure in all cases. Scenario 1, assumes a no increase in the variable cost case because of using subcontractors (e.g., competition among the potential suppliers is high). Even though we end up producing \( S_L \) units, the Modularized structure is preferred over any other because of the savings result in the overall fixed costs.

In scenario 2, we assume no increases in the fixed cost for postponing (e.g., no fixed cost required for packaging), but a certain reduction in the variable cost because of economies of scale in transportation of the common product. In this case the postponed supply chain is preferred.

Of further interest is the resulting comparative statics when considering sensitivity analysis with respect to the model parameters \( \alpha \) or \( \beta \). In particular, given a specific supply chain structure we consider parametric conditions under which a switch to an alternative structure may be more economical from a differential cost perspective. Recalling that by definition (i) \( k_B = \alpha k_A \) and (ii) \( \sigma_B = \beta F_A \), for each of the following comparisons (as shown in Table 2) we first fix \( \alpha = 1 \) and consider the impact of changing \( k_A \) and \( \beta \) on total cost differentials and later by fixing \( \beta = 1 \) we consider cost ramification as \( k_A \) and \( \alpha \) are changed. In this analysis, total cost differentials reflect the total cost of a particular structure (e.g. rigid), less the total cost of an alternative structure considered (e.g. modularized). Total cost figures are calculated by Eq. (1).

An interesting and further consideration with respect to the above sensitivity analysis and the structures defined in Fig. 1 is a comparison between the rigid and flexible structures. As before, we probe parametric conditions under which a given structure may be a more suitable option over an alternative structure from a total cost differential perspective. For this analysis, \( \alpha \) and \( \beta \) are set equal to one as in Table 2 and sensitivity analysis with respect to the parameters of interest are conducted in the customary fashion. Unlike the previous cases summarized in Table 2, here the total cost differential function behaves differently across the range of parameters considered. As a result, and depending on the parameter values, the choice of a particular structure evolves as described below:

(i) \( \alpha = 1 \). As \( k_A \) increases from zero and \( \beta \) also increases
   (a) Initially the rigid structure is a more cost effective choice.
   (b) Later, as \( k_A \) and \( \beta \) continue to increase the flexible structure is a more economical alternative.

While continuing to increase \( \beta \) with \( k_A \) decreasing from zero
   (a) Initially rigid is a better choice, and
   (b) Later, the flexible structure becomes more cost effective.

In this particular case, \( (\alpha = 1) \), for \( k_A = 0 \) and for changing \( \beta \) values, the flexible structure is the choice alternative.
As $A$ increases from zero and for increasing $a$ values

(a) The rigid is initially a more cost effective choice.

(b) The flexible structure becomes a better alternative later on.

In decreasing $A$ with $a$ increasing

(a) Rigid is more attractive initially, and

(b) Flexible improves later on.

Here too, for $A=0$ and for different choices of $a$, the flexible structure always results in a better choice given our parametric analysis. For this analysis, Fig. 2 provides a schematic presentation of the cost function in light of the model’s parameters.

Of course, these results are only illustrative in nature. Yet, they do provide the basic theoretical means for comparing the four supply chain structures introduced earlier. In this sense and as a basic theoretical foundation, other assumptions or needed modifications regarding flow patterns in the supply chain or costs may be incorporated for the purposes of future research.

### 6. Conclusion and future directions

Competition in the global business environment has forced companies to view the entire supply chain in an integrative manner. It is no longer adequate to optimize the manufacturing function without linking it to the distribution function or vice-versa. Consumers are more informed, more demanding and less loyal (Fortune, Autumn/Winter 1993). The concepts of outsourcing and postponement allow companies to combine economies of scale and scope through the integration of product and process design.

In this paper we have introduced a conceptual framework to answer what supply chain structure is the most appropriate choice. Based on the degree of outsourcing and postponement we can compare and contrast clearly differentiated supply chain structures. An interesting result of our analysis has confirmed the empirical evidence that vertical integration along the supply chain is not desirable. More and more companies are replacing vertical integration with vertical coordination and developing long term arrangements with outside suppliers.

The decision among the remaining three alternatives is by no means trivial. The answer to the question: When a Modularized structure is a better choice than a Postponed or a Flexible structure depends on many factors that are not captured in the model. Our framework, though simple in its structure, provides a way to initiate the decision process. The framework could also be used to evaluate the structural options available for a company regarding the appropriate choice of an alternative that best satisfies different products. Then for example, in pharmaceuticals, contract manufacturing and make-to-stock are used for the generic brands while the risky, capital intensive biotech business follows a make-to-order (Tully, 1993).

An interesting direction for future research would be to consider a more elaborate analysis of the cost elements and the resulting service level

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4 The Economist, 14 May 1994.
implications. Given the shortening in product life cycles, some analysis of different demand patterns for different products and different markets could also be useful.

Acknowledgements

The authors thankfully acknowledge helpful comments from the referees.

Appendix A

Proof of Proposition 3. Taking the difference between Eq. (3) and Eq. (4) and rearranging terms we obtain

$$TC_F(S_H) - TC_R(S_L) = (V + H)k_a\sigma_A \left( \sqrt{1 + \alpha^2\beta^2} - (1 + \alpha\beta) \right)$$
\[ + (H + B)\sigma_{A} \left( G_{z} \left( k_{A} \sqrt{1 + x^{2} \beta^{2}} \right) - G_{z}(k_{A}) \right) \]
\[ - \beta G_{z}(\alpha k_{A}) \]. \tag{A.1}

We have to prove that this difference is always negative. Given that \( x, \beta > 1 \) and the following relationship:

\[
\sqrt{1 + x^{2} \beta^{2}} = \sqrt{(1 + x\beta)^{2} - 2x\beta} \leq \sqrt{(1 + x\beta)^{2}} = (1 + x\beta), \tag{A.2}
\]
guarantees that the first term is negative when \( k_{A} > 0 \).

For the second term we know that \( G_{z}(x) \) is always positive and a decreasing function of \( x \). (Silver and Peterson, 1985). Therefore,

\[
G_{z}(k_{A}) + \beta G_{z}(\alpha k_{A}) > G_{z} \left( k_{A} \sqrt{1 + x^{2} \beta^{2}} \right) \tag{A.3}
\]

since both \( k_{A} \) and \( \alpha k_{A} \) are smaller than \( k_{A} \sqrt{1 + x^{2} \beta^{2}} \). Thus, the second term is always negative.

If \( k_{A} < 0 \) the first term in Eq. (A.1) is positive. However, the second term is greater than the first term since by definition \( G_{z}(-x) = G_{z}(x) + x \) (Silver and Peterson, 1985) and \( B > V \). Therefore,

\[
G_{z}(k_{A}) \geq k_{A} \sqrt{1 + x^{2} \beta^{2}}, \tag{A.4}
\]

\[
G_{z}(\alpha k_{A}) \geq \alpha k_{A}.
\]

Proof of Propositions 4 and 5. The result is obtained by simply taking the difference in cost between the relevant supply chain structures and rearranging terms. Note that \( K \) is always \(< 0 \) following the previous proof.

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