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Journal of Operations Management 23 (2005) 389–403

JOURNAL OF OPERATIONS MANAGEMENT

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Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach

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Received 23 June 2003; received in revised form 13 April 2004; accepted 23 September 2004
Available online 15 December 2004

Abstract

This paper proposes a goal-programming modeling approach to address three-dimensional concurrent engineering (3D-CE) problems involving product, process and supply chain design. The model enables straightforward representation of the interrelations among multiple objectives and analysis of tradeoffs among those that exhibit conflicts. The model is demonstrated through a discussion of integrality versus modularity in product and supply chain designs that is motivated by events that took place in the automotive industry over the last decade. A numerical example is used to illustrate the model and the paper concludes with possible extensions and guidelines for implementation.

Keywords: Goal-programming; Supply chain design; Concurrent engineering; Integrality; Modularity; Tradeoffs modeling

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1. Introduction

Competition in the marketplace forces manufacturing firms to continuously generate new (and more attractive) product designs while maintaining high quality, low costs and short lead-times. The imperative of smaller batch sizes, coupled with unique advantages of suppliers specializing in particular areas, drive such firms to outsource a growing portion of their product components and sub-assemblies. Traditionally, decisions on these issues were taken in a serial pattern. First, a product design was selected from a set of feasible designs, driven primarily by marketing objectives and engineering constraints. The chosen design was then transferred to the production planning function that developed an appropriate manufacturing plan. Such plans were guided primarily by operational objectives (e.g., cost minimization, capacity utilization, load balancing, etc.). Finally, the product design and the production plan decisions became constraints for the logistics function that determined the supply sources. This serial pattern is known to generate solutions that suffer from two major deficiencies (Gunasekaran, 1998). First, it is slow because parallel processing opportunities are often missed. Second, it leads to sub-optimal

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doi:10.1016/j.jom.2004.09.005

solutions, because each stage can make, at best, sequential locally optimal choices.

Concurrent engineering (CE) is a paradigm aimed at eliminating such flaws. CE 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. The CE concept leads to a fundamental tradeoff. On one hand it reduces the need for re-design and re-work (thus reducing development time) and increases the chances for smoother production (thus helping to minimize cost and improve quality). On the other hand, CE complicates the design problem as it requires joint optimization of a more complex objective with a larger set of constraints (Wu and O'grady, 1999).

Most of the CE research to date has focused on combining production considerations with product design issues (see, e.g., Stahl et al., 1997; Taylor, 1997; Smith and Eppinger, 1998; Chang et al., 1999; Sun et al., 2001). This two-dimensional approach (2D-CE) has led to many useful procedures such as *virtual prototyping* and *rapid prototyping* (see, e.g., Chang et al., 1999). CE applications were reported to achieve a 30–60% reduction in time-to-market, 15–50% reduction in life cycle costs and a 55–95% reduction in engineering change requests (Bopana and Chon-Huat, 1997).

Studies that stress the need to incorporate supply chain issues with product design and production planning (thus creating a three-dimensional concurrent engineering (3D-CE)) have started to emerge only recently. Fisher (1997) suggested 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. Eversheim et al. (1997) proposed a 3D-CE system that incorporates measures such as responsiveness, time-to-market, cost, quality and life cycle considerations. A comprehensive discussion of the 3D-CE approach was first given by Fine (1998). Feng et al. (2001) formulated a model that simultaneously determines the tolerances in the product design and selects the suppliers for the various components. With the exception of the last reference, the 3D-CE studies described above provided *qualitative* insights into the problem. None of these studies offered a unified quantitative methodology that can be used to analyze various 3D-CE tradeoffs.

The purpose of this paper is to close this gap by proposing a *quantitative* model to address various issues of 3D-CE. The common thread of these issues is the potential conflict among objectives. For example, from the logistics point of view, one might like to select the lower cost supplier to provide each component. But, low-cost components can often be associated with low quality and long lead-times thus creating a conflict with the product designer (who might prefer expensive suppliers associated with high quality or suppliers known for their excellent development capabilities) and the process designer (who is typically interested in short and reliable lead-times). Capacity utilization is another potential area of friction. The production department may seek to reach optimal utilization levels of the various production resources, while the logistics department seeks to reduce the risk of production stoppage by qualifying and utilizing a second source.

The model we propose may fit into several managerial process contexts. First, it can be integrated within the stage–gate procedure that was proposed by Cooper (2001) for product development processes. The first two stages in this five-stage procedure determine the scope of the new product and its basic business plan. The gates in each stage filter out proposals for new products that do not meet predetermined criteria. Our model can serve well the third stage where a detailed product and process designs are developed. The multiple objectives in our model can represent the multiple agents that Cooper envisions as taking part in this development stage (customers, technical development personnel, production engineers, etc.). Also, to fit with Cooper's iterative scheme for this stage, rather than running the model once to obtain a single best solution, we can run it iteratively where each time we run it again we change some of the parameter values in response to feedbacks obtained from the participating agents. The second context in which our model may fit is the set-based design methodology (Ward et al., 1995; Liker et al., 1996) for project selection processes. The set-based methodology urges designers to explicitly communicate with others on a set of designs rather than on a specific design. The set is gradually narrowed through eliminating inferior alternatives until the final solution is obtained. Our model can be easily incorporated within the set-based methodology by running it multiple times using a Tabu search concept—each time preventing solutions that were found before to be selected again—thus yielding a set of candidate solutions that can be gradually filtered as the process progresses in time. A third context for our model might be the upgrading of an existing model. Consider the automotive industry where a successful design for specific brands typically stays stable over several years. Still, each year the car manufacturer may change specific components or sub-assemblies (e.g., the exhaust system, the gear box, etc.) while keeping the overall designed unchanged. Unlike the previous two contexts, there is no uncertainty about the fact that the firm will produce the product; the only question is which design will be selected.

We demonstrate our methodology for 3D-CE by focusing on the question of *integrality versus modularity* in product and supply chain designs. While this issue can be found in many industries, it is of particular relevance to the automotive industry as exemplified by Novak and Eppinger (2001) who explored it in this context and found statistically significant relations linking supply chain structure with product architecture in luxury and high-performance vehicles. In Section 2, we discuss at length the role played by such modularity decisions in the remarkable revival of Chrysler from near collapse in the 1980s to an era of great success in the 1990s (Dyer, 1996).

We selected *goal-programming* (GP) as the modeling framework for our needs since it is flexible enough to accommodate a relatively large number of objectives without making the computation intractable; it is rather straightforward to explain to potential users; and it has a large body of reported implementations in various areas to support its credibility (Schniederjans, 1995; Tamiz et al., 1998).

Our main contributions are three-fold. First, we formulate a baseline GP model that is capable of addressing different 3D-CE problems. We believe that this is the first quantitative model to address systematically the three-way concurrency of product, process, and supply chain selection. Second, we illustrate our modeling approach through a *specific*, yet important, 3D-CE problem. Third, we provide a numerical example of the analysis of tradeoffs among the various objectives through the GP vehicle.

The remainder of this paper is organized as follows: In Section 2, we discuss the issue of integrality versus modularity and present the objectives that arise in this context. In Section 3, we formulate a GP model that focuses on the objectives and constraints that are discussed in the previous section. In Section 4, we report on a numerical experiment that implemented the proposed approach and discuss the results of the experiments. In Section 5, we briefly present some of the possible extensions of the GP model and in Section 6 we offer concluding remarks and directions for future research.

2. Integrality versus modularity

In the domain of product development, the concept of product architecture is well known: It relates how the functions of a product are allocated to its constituent components (see Ulrich, 1995). A key dimension of product architecture is the distinction between *integral* and *modular* product architectures. Another key dimension is whether a product's architecture is *open* or *closed*.

Our definition of product modularity follows the notion of *combinatorial modularity* (Salvador et al., 2002), which is a variant of the *slot modularity* in Ulrich's (1995) typology. In combinatorial modularity, each component is a variant within a component family; each component family interacts with a subset of other component families through standardized interfaces; and the interfaces may be different depending on the combination of families they connect but independent of the component variant chosen (see also the discussion in Mikkola, 2003, p. 441). To quantify this definition, we construct in Section 4 a modularity measure that is based on the number of different interfaces among component families and the number of functions performed by each component family.

A product whose architecture exhibits a high degree of modularity will typically have subsystems or components that are loosely coupled together in design as well as in operation. Examples of modular products include stereo systems, bicycles, and desktop personal computers. In modular products, components tend to be fairly standardized, with interchangeable options, such as speakers of different quality in a stereo system or tires in various widths for a bicycle. This enables a product to be upgraded by replacing lesser components with better ones, such as a larger disk drive in a PC. Many modular systems are also open, meaning that the interfaces between components are not protected intellectual property that is closely held by the patent holder. In open systems, any innovator can create a module for the product as long as it connects with the standard interface. In the discussion that follows, we will use the term modular to mean modular *and* open, unless explicitly noted otherwise.

A product whose architecture exhibits a high degree of integrality will typically have subsystems that are tightly coupled together in design as well as in operation. Interfaces between subsystems tend to be complex, non-standard, and designed and built (or at least customized) explicitly for a particular product. Instead of having a clean correspondence between modules and functions in the modular case, integral products tend to have components that perform parts of multiple functions and functions/performance dimensions delivered by multiple subsystems. As an example, the wing of a jet airplane serves both to provide airlift capabilities and to hold jet fuel. In contrast, in an automobile, the fuel tank's sole function is to hold fuel.

Products also exhibit characteristics of an integral architecture if some of their functional requirements must be delivered by various subsystems and cannot be reduced to a single component or subsystem. For example, automobiles and airplanes have stringent requirements for total weight, a functional requirement that spans virtually all of their subsystems (such as chassis, fuel consumption, exhaust, braking, to name a few). Similarly, mainframe computers require that the enormous amount of heat generated by key components be eliminated; otherwise, the system runs the risk of becoming damaged.[1]

Some integral systems are also closed, meaning that the interfaces between components are protected intellectual property that is closely held by the patent holder. In closed systems, only licensees of the relevant technology are permitted to develop subsystems for the product.

Like products, supply chains also have an architectural structure, which can span a spectrum from integral to modular. An integral supply chain is one in which the members of the chain are in close proximity with each other, where proximity can be measured along the four dimensions of geography, organization, culture, or electronic connectivity. A modular supply chain is one where the members of the chain are highly dispersed geographically and culturally, with few close organizational ties and modest electronic connectivity (Fine, 1998, p. 136). Specifically, in the automotive industry, a recent study by Choi and Hong (2002) classified supply chains according to three dimensions: formalization, centralization and complexity. Integral supply chains tend to be characterized by high levels in all three dimensions.

A supply chain with a high degree of integrality, therefore, is one in which a manufacturer and its principal suppliers are concentrated in one city or geographic region, have common or interlocking ownership, share a common business and social culture, and are linked electronically. Excluding the last of these dimensions, the well known 'lean production system' (Womack et al., 1991) was developed within a highly integral supply chain. This highly respected and widely imitated system was conceived and nurtured by Toyota Motor Corporation in the Nagoya/Toyota city industrial region within a highly uniform culture and with significant ownership and managerial participation by Toyota in its suppliers.

Product architecture and supply chain architecture thus tend to be aligned along the integrality–modularity spectrum. We therefore conjecture that integral products would ideally be built by integral supply chains, while modular products would tend to be produced by modular supply chains. A supportive evidence to this conjecture might be found in Doran (2003) who examined the automotive industry. He found that the general shift towards more modular product designs in that industry forces suppliers to re-evaluate their strategies. As a result, many would-be first-tier suppliers must now position themselves as value-added second-tier suppliers to fit with the more flexible characteristics of the emerging modular supply chains. With many products, the choice between integral and modular designs presents a tradeoff. Arguments for integral design are often technical or performance-based, while the rationale

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[1] For a thorough discussion of the theory and application of product architecture, see Cunningham (1998), Cunningham and Whitney (1998) and Baldwin and Clark (1999).

supporting modular design is usually based on economic considerations such as cost and time-to-market.

The Chrysler corporation's extraordinary leap, from near bankruptcy in the late 1980s to explosive growth in the early 1990s, offers additional insights on the importance of aligning product and supply chain architecture (see Fine, 1998, chapter 4). In the mid 1980s, Chrysler was the smallest and financially weakest of the three large US automakers. As such, it was typically third in line with its suppliers who typically gave higher priority to the larger firms (GM and Ford). In this vertically structured era, US automakers tended to keep their development work on components and subsystems in-house, outsourcing only the low-end production of individual parts according to rigidly detailed specifications. As it was reaching the brink of financial collapse, Chrysler initiated a radical change in the way they would do business with suppliers. Instead of dictating detailed design specifications to its suppliers and pitting them constantly against each other, Chrysler would commit to long-term relationships with its suppliers–partners who would develop and build entire subsystems. At the same time, Chrysler dramatically reduced its internal technology and component development activities, shifting its focus to design, assembly and marketing. The supplier–partners were soon gracing Chrysler's vehicles with the latest technical advances, while Chrysler entered a renaissance in design and styling (for example, see the detailed case of Chrysler's relations with its windshield wipers providers during that era in Mikkola, 2003). Chrysler's strategic shift towards more modular product design and more modular supply chain architecture turned out to be a huge success. The company surpassed its competitors in launching timely, appealing and profitable minivans, pick-up trucks, SUVs and 'image' vehicles such as the Prowler and the Viper (Dyer, 1996; Fine, 1998).

Towards the end of the 1990s Chrysler was so successful, it became a target for takeover by other firms, eventually ending up in 1998 in the hands of Daimler-Benz. Mercedes was another great automotive success story of the 1990s. It has dramatically improved its expensive craft-based manufacturing practices by introducing lean-production methods. Mercedes also expanded the scale and scope of its market and successfully repulsed aggressive assaults on its luxury market by Toyota and other automakers.

While both Mercedes and Chrysler were 1990s success stories, their product and supply chain architectures were dramatically different. In contrast with Chrysler's modular product and supply chain design, Mercedes designed highly integral vehicles in which the subsystems meshed flawlessly to deliver superior performance in ride and durability. Mercedes also controlled carefully its supply base (clustered mainly near its Stuttgart core).

The result of the 'forced marriage' between two very different firms with incompatible product and supply chain architectures, did not take long to emerge—it was a colossal failure. Less then two years after the merger, the market value of the new automaker had fallen by about 50%.

The Daimler–Chrysler case clearly indicates the importance of coordinating decisions on product design and supply chain architecture. Integral products require support from supply chains that are themselves fairly integrated while modular products benefit from the speed, flexibility and cost-reduction opportunities offered by modular supply chains. Force-fitting incompatible designs is a recipe for disaster.

3. The proposed methodology

The Daimler–Chrysler case suggests that the need to align product and supply chain architectures is not fully understood in industry. Further, we are not aware of any quantitative models that integrate product, process, and supply chain design decisions in a way that highlights the issues faced when making this simultaneous set of design decisions. Thus, there is a need for models that are able to account for the kinds of tradeoffs we described earlier in quantitative manner.

Our proposed approach employs a weighted GP (WGP) technique that simultaneously solves for the best combination, per each product version, of product design, assembly plan, and supply chain design. We call a triplet of product version, design, and assembly sequence a *configuration*. We wish to select a single configuration (j) out of a set of candidate configurations (J). We model this decision through a binary variable (z_j) whose value is 1 if configuration j is selected and 0 otherwise. The make/buy decision is modeled by the binary variable x_{is}, whose value equals 1 if element i is supplied by supplier s, and 0 otherwise (in-house production is designated by $s = 0$). For each configuration j, the set I_j includes all elements participating in that configuration. In addition, the set S includes all potential suppliers. The binary variable y_s, whose value is 1 if supplier s is selected to supply any of the elements and 0 otherwise, will be used to signal the inclusion of supplier s in the supply chain. Following the discussion in the previous section, we focus our attention on five conflicting, yet crucial, objectives: fidelity, cost, lead-time, partnership, and dependency. The aspiration level of objective τ is denoted as $\gamma_\tau(\tau = 1, \ldots, 5$ for the five objectives, respectively). The variables η_τ^-, η_τ^+ denote under and over deviations in objective τ, respectively. We let $\tilde{w}_\tau^-, \tilde{w}_\tau^+$ denote the weights associated with these deviations in the objective function. Thus, the objective function of our model is:

$$\min \sum_{\tau=1}^{5} \tilde{w}_\tau^+ \eta_\tau^+ + \tilde{w}_\tau^- \eta_\tau^- \tag{3.1}$$

Our first goal is to achieve a certain value for the overall product fidelity. We define the fidelity of an element as the degree to which the element's design conforms to the tasks it is intended to perform[2] and assume that each element $i \in I_j$, supplied by supplier s, is characterized by a fidelity value β_{is}. We further assume that the contribution of such a component to the overall product fidelity is weighted through w_i^j. Then, the fidelity goal constraint is given by a weighted average as shown below:

$$\sum_{j=1}^{J} z_j \sum_{i=1}^{I_j} w_i^j \sum_{s \in S} \beta_{is} x_{is} + \eta_1^- - \eta_1^+ = \gamma_1 \tag{3.2}$$

We note that a weighted average is not the only modeling option as other alternatives (e.g., the MIN operator) are possible. But, for the sake of simplicity, we prefer to retain the weighted average option. In any case, choosing an alternative option will not have a fundamental effect on the model.

Obtaining the desired level of fidelity tends to be costly. To get a balanced design, one must also consider a cost goal. We let p_{is}^{p} be the cost of purchasing/producing element i from/by supplier s (in-house product is implied when $s = 0$) and p_{ikj}^{a} be the cost of assembling element i to element k in configuration j. To differentiate in-house elements from purchased elements, we use the parameter a_{ikj}. If element i is assembled with element k, in configuration j, then a_{ikj} equals 1, otherwise it is 0. To compute the cost of an element, based on its fidelity, we use the linear relationship $p_{is}^{\mathrm{p}} = k_{01}^{\mathrm{s}} + k_{11}^{\mathrm{s}} \beta_{is}$. The positive parameters $k_{01}^{\mathrm{s}}, k_{11}^{\mathrm{s}}$ indicate that purchasing/production costs are positively correlated with higher fidelities. In addition, these parameters are supplier-specific in order to differentiate among suppliers. As mentioned earlier, the inclusion of each supplier s in the chain incurs a fixed cost, denoted by p_s. Thus, the cost goal constraint, comprised of purchasing/production, assembly, and supplier's fixed contact costs is given by:

$$\sum_{j=1}^{J} z_j \left[\sum_{i=1}^{I_j} \sum_{s \in S} p_{is}^{\mathrm{p}} x_{is} + \sum_{i=1}^{I_j} \sum_{\substack{k=1 \\ k \neq i}}^{I_j} a_{ikj} p_{ikj}^{\mathrm{a}} \right] + \sum_{s \in S} p_s y_s + \eta_2^- - \eta_2^+ = \gamma_2 \tag{3.3}$$

We note that in this formulation we integrate three aspects of the problem: the selection of the product's configuration (represented by z_j) that determines its design, the assembly plan (embedded in the assembly cost term), and the suppliers' network (embedded in the purchasing cost and the supplier-contact terms).

Next, we define λ_{is} as the lead-time of component i purchased from supplier s and formulate the lead-time goal constraint as:

$$\sum_{j=1}^{J} z_j \sum_{i=1}^{I_j} \sum_{s \in S} \lambda_{is} x_{is} + \eta_3^- - \eta_3^+ = \gamma_3 \tag{3.4}$$

In constructing the lead-time goal constraint we were faced with two alternatives. First, to follow the work of Clark (1989) who found implicit relations between lead-time and the product network (which dictates the assembly sequence). In particular, he found that in the automotive industry, with fewer unique parts the firm

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[2] Alternatively, we could use the term 'product quality' but we prefer the term 'fidelity', which is quite common in the design literature (see, e.g., Hamza et al., 2004).

could outsource more of its components to external suppliers and thus shorten the resultant lead-time. Second, to consider the lead-time as a simple summation over the lead-times of the individual elements. To maintain a conservative approach, we chose the second option. Naturally, one can chose other options here (e.g., use the MAX operator). Finally, we note that Eq. (3.4) does not account for the assembly time as it is assumed to be marginal.

Partnership is another important topic captured in our formulation. We assume that a certain supplier, designated as s^*, was determined (through a decision that is exogenous to our model) and formulate the following partnership goal constraint:

$$\sum_{j=1}^{J} z_j \sum_{i=1}^{I_j} x_{is^*} + \eta_4^- - \eta_4^+ = \gamma_4 \tag{3.5}$$

We note that later, in Section 5, we will elaborate on alternative ways to address the issue of partnership.

Another supply chain-related aspect is dependency. This expression measures the level of risk incurred by the firm under consideration as a result of its reliance on external suppliers. Dependency could be defined by several supplier-related measures (e.g., see, the ones proposed by Fine, 1998). Here, we chose to define dependency as the ratio between the number of selected suppliers and the number of elements in the selected configuration. Again, in Section 5, we propose alternative ways to model this aspect. The goal constraint in this case is:

$$\sum_{j=1}^{J} z_j \frac{\mathrm{BE}^j - \sum_{\substack{s\in S\\ s\neq 0}} \sum_{i=1}^{I_j} x_{is}}{\mathrm{BE}^j} + \eta_5^- - \eta_5^+ = \gamma_5 \tag{3.6}$$

where BE^j is the number of basic elements in configuration j.

Finally, we define the structural constraints on the binary variables. The first equation in Eq. (3.7) ensures that each element is purchased from at most one supplier. The second equation relates the 'buy' decision with the supplier's inclusion indicator, where M is a large number. The third equation ensures that only one configuration is selected. The last two relations define the class of variables in the model.

$$\begin{aligned}
&\sum_{\substack{s\in S\\ s\neq 0}} x_{is} && \leq 1, \quad \forall i\\
&\sum_{i=1}^{I_j} x_{is} && \leq M y_s, \quad \forall s, j\\
&\sum_{j=1}^{J} z_j && = 1\\
&z_j, x_{is}, y_s \in \{0,1\}, \quad \forall j, i, s\\
&\eta_\tau^+, \eta_\tau^- \geq 0, \quad \forall \tau
\end{aligned} \tag{3.7}$$

4. Numerical example

This section presents a numerical example that demonstrates the usefulness of the proposed WGP approach to 3D-CE problems. Rather than developing an extensive numerical example for a general case, we focus on a simple example that explicitly quantifies the tradeoffs among the five goal constraints that were modeled in the previous section. We start with a description of the database structure and the way in which we constructed the various parameters. Then, we present the results of the model and analyze them.

4.1. Structure of the database

We consider a product that is produced in three versions where each version is aimed towards a different market. Each version is required to perform the same functional tasks like all other versions, albeit, not necessarily at the same fidelity level. Each of the versions has three possible designs and five possible assembly sequences. Thus, we have a total of 45 (3 × 3 × 5) different configurations, containing a total of 45 basic elements. A basic element is an element that resides in the lowest level of the assembly graph (typically described as the leaves in an And/or graph, see De Mello and Sanderson, 1990). Each element in any configuration can be manufactured in-house or by four external suppliers. The set of external suppliers contains a catalogue (termed CATL)—generally, associated with relatively short lead-times, low fidelities, and low costs; a local supplier–partner (termed LocS1); an international supplier—associated with high performance; a secondary local supplier (LocS2). We note that this example fits best the 'upgrading' context in which our model might be implemented (see Section 1). Hence, the example tacitly implies that all purchased element and subassemblies are 'off-the-shelf' type rather than customized items. However, the example can be easily adopted to incorporate a full range of items from off-the-shelf to tight buyer-supplier design integration and a full range of suppliers featuring various levels of supplier–OEM relationship, to fit with the other two contexts presented earlier (stage–gate product development process or set-based project selection).

In-house production is done by another department which we treat here as another supplier (i.e., with given contact cost, lead-time, etc.). Later, in Section 5, we discuss how the model could be extended to include other aspects that are relevant to in-house production (such as capacity utilization). The performance of the suppliers in our example varies across the triplet: price, fidelity, and lead-time, as presented in Table 1.

The lead-time of element i supplied by supplier s, λ_{is}, is comprised of a fixed and a variable parts. In our example, the fixed part ranges uniformly in [15,30], regardless of the supplier. The variable part is supplier-specific and relies on the supplier's performance, as elaborated in Table 1. The lead-time of the supplier–partner (LocS1) is an average of the lead-times of all other suppliers.

We assume that the fidelity of an element is negatively correlated with its modularity since more modularity implies more interfaces among components and consequently, higher risks of performance degradation. The modularity of element i, denoted by m_i, is a function of the number of functional tasks the element performs, denoted by F_i, and the number of coupling interfaces it has with other elements, denoted by In_i. We calculate modularity as

$$m_i = \frac{\zeta_1}{F_i + \zeta_2 \,\text{In}_i}$$

where $\zeta_1, \zeta_2 > 0$ are two normalization scalars (ζ_1 is selected to bring the modularity values to a range of [0, 1] and ζ_2 weighs the In_i with respect to the F_i). Notice that the denominator is always positive since $F_i > 0$ and $\text{In}_i \geq 0$ by definition.

The more functional tasks and coupling interfaces the element has, the less modular it is. For example, we consider the transmission subsystem in the elevators example given in Mikkola and Gassmann (2003). The authors developed a modularity index that takes into account the number of components in the subsystem, the number of new-to-the-firm components, the degree of coupling and the degree of substitution. The authors' definition of the number of components (Mikkola and Gassmann, 2003 p. 206) is similar to our definition of the number of functions and their definition of the degree of coupling is nothing but the number of interfaces per component (function). Using the authors' example (Table 4, p. 214), with $\zeta_1 = 1100$ and $\zeta_2 = 20$ we compute the modularity index for two alternative subsystems (hydraulic versus traction) and get:

I	Number of functions	Number of interfaces	Our modularity index (m_i)	Modularity by Mikkola and Gassmann (2003)
Traction elevator	38	4.83 × 38 = 183.54	0.297	0.07
Hydraulic elevator	37	4.02 × 37 = 148.74	0.365	0.36

Table 1
Cost and lead-time data generation

Supplier	Title	Cost	Lead-time
Catalogue	CATL	$\text{P01} = U(50,70)$ $\text{P11} = U(8,12)$ $\text{P1} = \text{P01} + \text{P11}$	$\text{L1} = U(15, 30) + N(6, 1.2)$
In-house	SELF	$\text{P2} = (0.8 \times \text{P01}) + (1.3 \times \text{P11})$	$\text{L2} = U(15, 30) + N(10, 1.2)$
Supplier–partner	LocS1	$\text{P3} = (0.5 \times \text{P01}) + (1.9 \times \text{P11})$	$\text{L3} = (\text{L1} + \text{L2} + \text{L4} + \text{L5})/4$
Local supplier	LocS2	$\text{P4} = (0.7 \times \text{P01}) + (1.5 \times \text{P11})$	$\text{L4} = U(15, 30) + N(15, 1.5)$
International supplier	INTER	$\text{P5} = (0.68 \times \text{P01}) + (1.7 \times \text{P11})$	$\text{L5} = U(15, 30) + N(20, 1.2)$

U and *N* symbolize uniform and normal distribution, respectively.

While the values we obtain are different than those obtained by Mikkola and Gassmann, the basic outcome (that the hydraulic subsystem is more modular than the traction one) is maintained.

The fidelity of element i supplied by supplier s, β_{is}, is reciprocal to the modularity and is expressed by

$$\beta_{is} = \frac{\varepsilon_s}{(m_i)^{\alpha}}$$

where ε_s is a supplier-specific factor whose purpose is to differentiate among suppliers and α is a positive number. For each element i in the example, F_i is calculated as $U(1, 2) + \mathrm{BE}^j$, where $U(a, b)$ is a discrete uniform distribution in the range $[a, b]$ and BE^j is as defined earlier. In_i is also calculated as $U(1, 2) + \mathrm{BE}^j$. The random terms in the last two expressions allow the number of functional tasks/interfaces to be greater than the number of basic elements. Finally, the fidelity of a complete configuration is the weighted sum of the fidelities of the elements it is comprised of. The weights assigned to each element rely on the importance of the element in the relevant configuration. We assume that a sub-assembly is more important than the basic elements that comprise it, since some work has already been invested in assembling it. The factors affecting the weight of an element in a specific configuration include: the number of functional tasks the element performs (F_i), the number of coupling interfaces that the element has with all other elements and sub-assemblies in the configuration (In_i), and the position of the element in the And/or graph. The values of these factors are scaled so as to enable the use of a linear relation to quantify the importance of the element. These quantities are then normalized to get weight values in the [0, 1] range.

The cost of a manufactured element is linearly dependent on its fidelity. To generate the fixed part of the equation (k_{01}^{s}) we select a value from a uniform distribution in the range [50, 70], and multiply it by (1.0, 0.8, 0.7, 0.68, 0.5) for the catalogue, in-house, local supplier, supplier–partner, and international supplier, respectively. The slope of the linear equation (k_{11}^{s}) is also supplier-specific. The value of this slope is taken from a uniform distribution in [8, 12], which is then multiplied by a factor (1.0, 1.3, 1.5, 1.7, 1.9) for catalogue, in-house, local supplier, supplier–partner, and international supplier, respectively. This relation allows situations in which low fidelities are much cheaper to obtain from the catalogue relative to a supplier or in-house production. We note that in a more realistic case, we should not expect to have a continuous function for the fidelity; rather, it is more likely to be given through a set of discrete points that represent the possible pairs of fidelity and cost. However, for demonstration purposes, we relax this requirement. The schematic figure (Fig. 1) depicts a specific instance of the cost graphs, as described above.

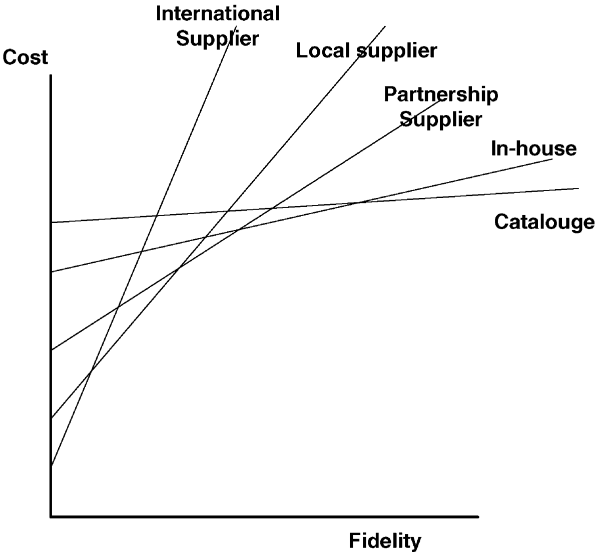

Fig. 1. A schematic depiction of the suppliers' cost functions.

The cost of assembly is given for each pair of elements and the total assembly cost is the sum of the relevant pair-wise costs. The factors affecting this cost are the number of basic elements and the number of coupling interfaces in each of the assembled elements. We use the relation $\sqrt{F_k} + \sqrt{F_l} + \sqrt{(\mathrm{In}_k)^2 + (\mathrm{In}_l)^2}$ to generate the cost of assembling element k to element l. The square root function was chosen to reflect the existence of some returns-to-scale in the assembly operations.

In addition to the assembly cost and the production cost, we have supplier-contact cost. This cost reflects the fact that establishing a business relations with a supplier entails costs, regardless the volume of business done with that supplier.

The experiment consisted of three stages. First, we constructed about 60 instances of the data set where the values of the parameters in each instance were generated randomly as explained above. Second, we ran the WGP model for each instance to gain insights on the tradeoffs among the various goals. Finally, in the third stage, we analyzed the results and attempted to draw general conclusions. Our primary interest in the results of these runs was in the relations among the product's fidelity, its configuration and its associated suppliers' network.

4.2. *Results*

4.2.1. *Fidelity versus purchasing cost*

The data generation procedure of our example forces these two factors to be positively correlated. If cost were the only objective, we would have seen a reflection of the assumed linear relationship in the results. But, since the WGP combines several objectives, the solutions that the model generated do not follow a strict linear relation. That is, occasionally we buy from a more expensive supplier that does not necessarily improves the product's fidelity but contributes to other goals such as lead-time or dependency. These results are reflected in Fig. 2.

4.2.2. *Assembly cost versus modularity*

As expected, with higher modularity one needs to assemble more components in the selected configurations. This relationship is shown in the results given in Fig. 3.

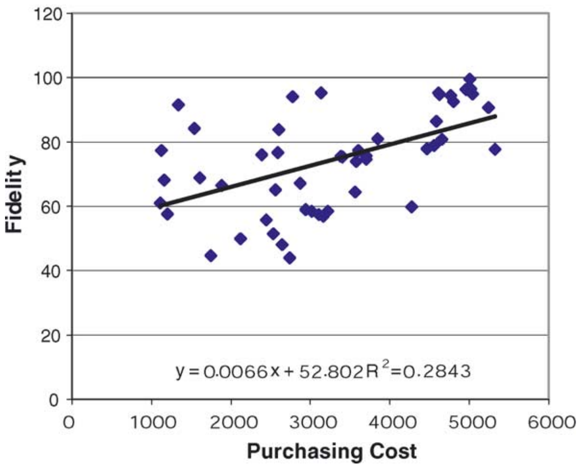

Fig. 2. Purchasing cost vs. product fidelity.

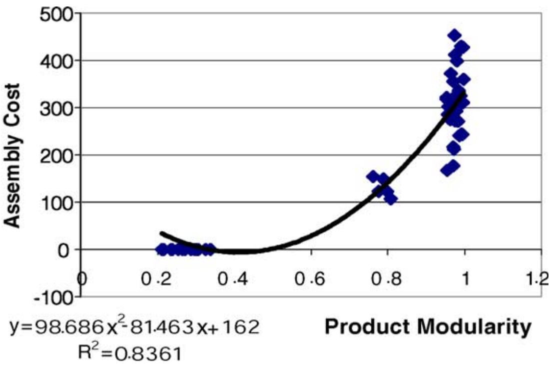

Fig. 3. Assembly cost vs. product modularity.

4.2.3. *Fidelity versus modularity*

The data generation procedure assumed reciprocal relationship for these two factors. Indeed, the results shown in the figure below generally reflect this relationship. But, as before, there are deviations. First, we note that although the data generated various modularity values, the results of the WGP model seems to fall into two to three well-defined clusters. That is, the model selects solutions either with large or small modularity, but refrains from medium levels of modularity. We shall return to this point in our subsequent discussion of modularity versus integrality. Second, the fidelity–modularity relation was defined at the element level through the reciprocal relation: $\beta_{is} = \varepsilon_s/(m_i)^{\alpha}$. When the elements' fidelities are aggregated into an overall product fidelity, we no longer observe strict reciprocal relations (notice the deviations above and below the regression line in Fig. 4).

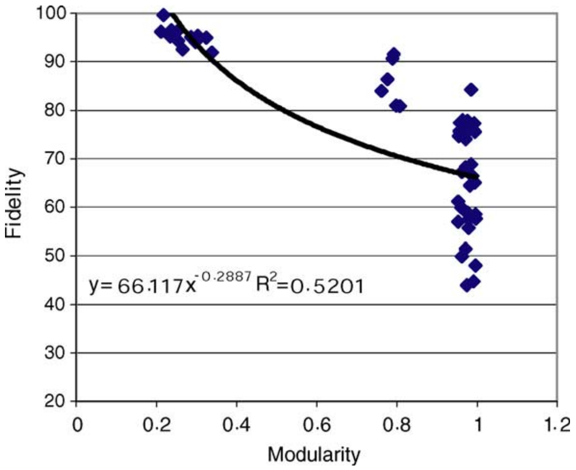

Fig. 4. Fidelity vs. modularity.

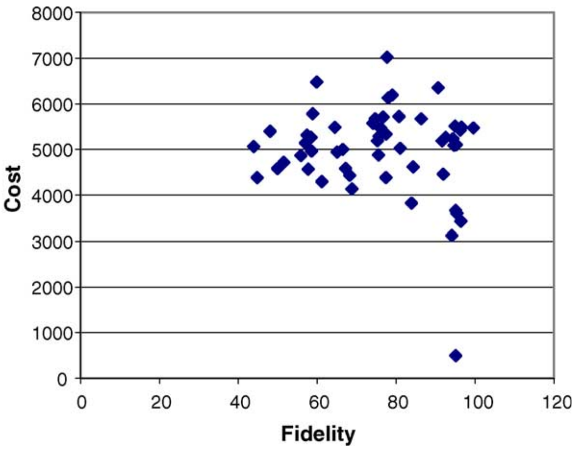

Fig. 5. Cost vs. fidelity.

4.2.4. *Total cost versus fidelity*

The cost function (3.3) includes several terms that work in opposite directions. First, the purchase cost of elements increase with the fidelity due to the positive values of k_{11}^{s}. In the other direction, overall product fidelity decreases with its modularity, thus creating an incentive for more integral product designs. But, with more integral product design, we pay less for assembly and we need to pay fewer supplier contact costs. Hence, there is no clear trend in the relations among total cost and overall product's fidelity in our example as seen in Fig. 5.

4.2.5. *Lead-time versus fidelity*

Recall that the lead-time for each supplier consisted of two parts: a fixed part that was randomly drawn from the same distribution and a variable part that was drawn from supplier-specific distributions. As seen in Table 1, while the mean values of the normal distributions increase with the fidelity associated with the relevant suppliers, the variance that was built into this data generation formulae allows for cases in which a certain supplier will be better than another one in both fidelity and lead-time. The results, shown in Fig. 6, reflect such cases. Indeed, the lead-time seems to increase with fidelity till the latter reaches the range of 80–90. Then, at the top fidelity level (100), a large variety of lead-times were realized causing a slight decrease in the trend line.

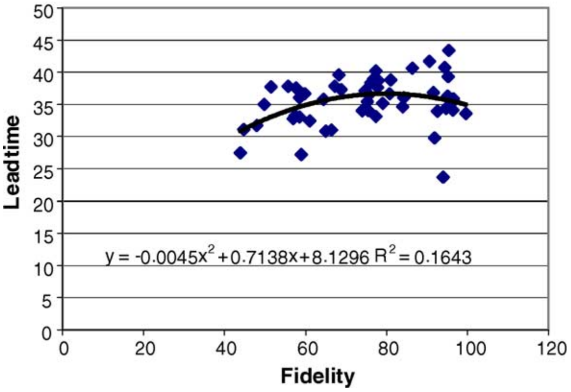

Fig. 6. Product lead-time vs. fidelity.

4.2.6. *Modularity versus integrality*

We finally arrive at the issue that motivated our example—modularity versus integrality in both the product design and the supplier's network. The outcomes of the experiment indicate quite clearly that the WGP model yields solutions that are either modular–modular or integral–integral for the product and supply chain designs, respectively. We have already observed this 'clustering' effect with respect to the fidelity modularity relations (above), but here the effect is even more visible. Splitting the positive quadrant in Fig. 7 according to the median value in each dimension into four sub-quadrants, we observe that all the solutions are found either in the top-right

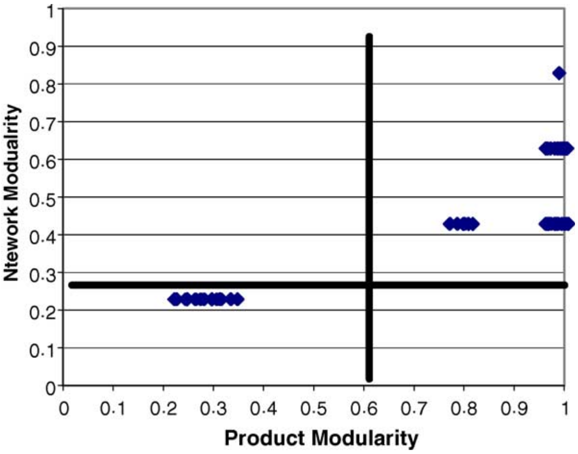

Fig. 7. Modularity vs. integrality in product and supply chain design.

sub-quadrant (modular–modular) or in the bottom-left sub-quadrant (integral–integral).

5. Extensions

In this section, we propose several extensions to the GP model presented earlier. In general, the GP model is quite flexible and can be constructed with many different combinations of goal constraints that correspond to various 3D-CE issues. Some of the additional goal constraints are presented below.

5.1. Size

An important product design feature that can be incorporated is size. Typically, smaller sizes are associated with greater fidelity and hence, larger costs. Size can be treated in the same way as fidelity. We let the size of element *i* from supplier *s* be denoted by σ_{is}. The overall product size is approximated as a weighted average of the component sizes, i.e., the contribution of a component to the overall product size is weighted through ρ_i^j. Other alternatives (such as using the MAX operator) are possible. Thus, the size goal constraint is given by:

$$\sum_{j=1}^{J} z_j \sum_{i=1}^{I_j} \rho_i^j \sum_{s \in S} \sigma_{is} x_{is} + \eta_6^- - \eta_6^+ = \gamma_6 \tag{5.1}$$

5.2. Dependency

One way to capture this consideration was already given in Section 3. Alternatively, we may define ψ_i^jas the degree of customization of element *i* in configuration *j* (a fraction between 0 and 1). Letting the number of potential external suppliers for element *i* be θ_i^j, we can state the following goal constraint:

$$\sum_{j=1}^{J} z_j \frac{\sum_{i=1}^{I_j} \frac{\psi_i^j}{\theta_i^j} \sum_{s \in S} x_{is}}{\sum_{i=1}^{I_j} x_{is}} + \eta_7^- - \eta_7^+ = \gamma_7 \tag{5.2}$$

Dependency is here viewed as a function of two factors: the number of available external suppliers for an element and the degree of customization in the outsourced elements. As the number of available suppliers for each outsourced component decreases, the firm becomes more dependent. In the other direction, dependency increases with a higher degree of customization. Consequently, the aspiration level in this goal constraint should be specified as a fraction between 0 and 1. Values close to 0 reflect little dependency while values close to 1 reflect large dependency. At one extreme, a 0 value means the part is done in-house or that it is a totally standard part that can be purchased from catalogues and hence there is no dependency at all. At the other extreme, a value 1 means complete dependency, e.g., when there is just one available supplier—the ‘Intel Inside’ phenomenon (Fine, 1998).

5.3. Partnership

We have already incorporated partnership in Section 3 by representing it through the proportion of the number of elements supplied by the designated supplier–partner. Other variants of this goal include representation of the above proportion in financial terms rather than quantities, forcing a subset of all possible elements to be purchased only from the supplier–partner, etc.

5.4. Commonality

The commonality level of a configuration is derived from the commonality level of its elements. Letting χ_i^jdenote the commonality level of element *i* in configuration *j*, the commonality goal can be given by:

$$\sum_{j=1}^{J} z_j \sum_{i=1}^{I_j} \chi_i^j \sum_{s \in S} x_{is} + \eta_8^- - \eta_8^+ = \gamma_8 \tag{5.3}$$

5.5. Capacity utilization

This goal constraint is particularly important to the production planners who wish to make the best usage of the available resources. We let μ_i^j represent the capacity needed to manufacture element *i* in configuration *j* and write the capacity constraint as:

$$\sum_{j=1}^{J} z_j \sum_{i=1}^{I_j} \mu_i^j \frac{x_{i'self'}}{\sum_{s \in S} x_{is}} + \eta_9^- - \eta_9^+ = \gamma_9 \tag{5.4}$$

In addition to the 'soft' constraints shown above, the GP model can accommodate various 'hard' constraints for which no deviation from the aspiration levels is allowed. For example, budget constraints and technological constraints that limit the set of feasible ways to assemble certain configurations. Finally, the objective function of the model needs to be customized according to the combination of goal constraints selected to participate in it.

6. Conclusions

Our aspirations for 3D-CE are high. We would like a decision model that aids product designers, manufacturing decision makers, and supply chain professionals in addressing the multiple, interdependent challenges they face in designing and preparing a product for the marketplace. We are concerned not only with the immediate challenges in doing this, but also in the strategic supply chain considerations of the firm, such as avoiding excessive dependency on a small set of suppliers.

To achieve this, our paper proposes a quantitative approach to implement the concepts of the 3D-CE paradigm. These concepts, which appeared in the literature only towards the late 1990s, have so far been discussed mostly in a qualitative manner and, to the best of our knowledge, ours is the first attempt to back them up with a comprehensive quantitative model. To demonstrate the usefulness of our modeling approach, the paper focuses on the tradeoffs between integrality and modularity in product and supply chain designs. We construct a WGP model that addresses this issue and follow it up with a detailed numerical example. The main outcome of this experiment is a clear indication that under the assumptions of our example the WGP model prefers modular–modular and integral–integral solutions (for the product design and supply chain design, respectively) to integral–modular or modular–integral solutions. This outcome concurs with the qualitative observations made by Fisher (1997), Fine (1998) and others on the proper linkage between these two design issues. The experiment also exhibits the various tradeoffs that we discussed in the paper (e.g., assembly cost versus modularity) and demonstrates the relative ease in the actual computation of the WGP model.

Our modeling scope has focused on the strategic and tactical levels of decision-making. We deliberately avoided the operational level that must be addressed after the tactical decisions are done. Thus, we do not investigate specific technical questions such as what tools to keep in the tool magazine of each machine or how to react in case we experience a machine breakdown. We recommend that this approach will be kept in future extensions of our approach. Attempting to provide 'catch-all' solutions that mix operational and strategic considerations are bound to cause more confusion than benefit. From a practical point of view, it should be noted that the model suggests 'optimal' compromise solutions, which result in a compatible supply chain, process and product designs. Hence, these solutions should not be considered as the ultimate solutions. Rather, they should be treated as 'first round' solutions that might require some fine-tuning at later stages.

The managerial context in which the proposed methodology can be utilized is quite flexible. In Section 1, we discussed three possible contexts (stage–gate product development processes, set-based project selection processes, and upgrading processes). In all of these settings, our model can serve as a decision analysis tool to support decisions that would have otherwise been taken subjectively.

Our modeling tool is goal programming. This is a well-known methodology that has already proven itself in many application areas. Nevertheless, one should be aware of the potential weaknesses of this technique (see, Romero, 1991). In particular, its sensitivity to changes in the goal values (which are usually determined subjectively prior to the implementation of the model itself) and their respective weights (see, e.g., Min and Storbeck, 1991; Schenkerman, 1991). The implication is, therefore, that this is not a model that can be taken 'off-the-shelf' and used as-is. Potential users of the model should be informed of the meaning of the values they determine for the aspiration levels, weights, etc. The literature on GP offers some useful procedures for weights' elicitation (see, e.g., Gass, 1986 who proposed a procedure based on the analytical hierarchy process to determine weights' values and the related review in Tamiz et al., 1998, Section 2.3). Still, it is expected that some customization will be required before a model can be fitted to a specific environment.

Another potential difficulty in our approach is its complexity. It requires the collection and processing of a substantial body of data as well as the application of appropriate optimization software. However, this difficulty is mitigated by the recent advances in information technology (that offer easy means to handle the data issues) and by the availability of powerful optimization software packages that can easily handle problems of the scale we present here.

Future research may include the exploration of specific 3D-CE issues (such as the modularity-integrality issue we considered here) and the customization of appropriate GP models to address them. That is, determining the objective functions that will enter the model, determining aspiration levels for these objectives and suggesting appropriate weights for them. Another direction for future research might be to develop a full-scale case study in which the method will be implemented with real data. We hope that the present paper will pave the road to such future implementations.

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