Int J Flex Manuf Syst
DOI 10.1007/s10696-008-9033-0

Aligning demand and supply flexibility in custom product co-design

Songlin Chen · Mitchell M. Tseng

Abstract Flexibility of supply and demand is essential for successful implementation of a mass customization strategy that delivers sustained competitive advantage. Supply flexibility, i.e., a choice of alternative products designed to perform the same basic function, is made possible by the range of capabilities available in flexible and agile manufacturing systems and in supply chains. Demand flexibility is derived from the degree to which a customer is willing to compromise on product features or performance levels in order to meet budgetary (reflected in price) or schedule (reflected in delivery) constraints. Flexibility of both supply and demand can have significant strategic and financial value if they are properly aligned. However, customers are mostly unaware of mapping of demand flexibility on to supply flexibility and its impact on production cost and time. Recent advances in information technology have made it possible to co-design a product that involves customer on one end and the manufacturer on the other. This creates an aura and an opportunity where a middle ground between the supply and demand flexibility can be explored and a "deal" can be struck where both parties settle for a product that is beneficial to both through a negotiated settlement. In this paper, we develop a framework for such negotiations. The customer requirements are treated as a range of negotiable options instead of a set of fixed inputs. Demand and supply for customization is then matched by aligning the flexibility of manufacturing systems with customers' requirement options. Based on this framework, a negotiation scheme is developed to assist customers and manufacturers in exploring and utilizing demand and supply flexibility information in co-design. The negotiation

S. Chen (✉) · M. M. Tseng
Advanced Manufacturing Institute, Department of Industrial Engineering and Logistics Management, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
e-mail: songlin@ust.hk

M. M. Tseng
e-mail: tseng@ust.hk

scheme is formulated using goal programming. Finally, an interactive problem-solving procedure is developed and implemented with an illustrative example.

Keywords Flexibility · Mass customization · Co-design · Negotiation

1 Introduction

Mass customization aims to deliver customized products at affordable prices consistent with a level of efficiency that is comparable with mass production. Customization allows manufacturers to directly interact with customers and to effectively differentiate from competition. However, customization leads to higher product variety. The consequence of proliferation of product variety can have significant economic impact because of frequent production setups, increase of coordination complexity, and loss of production uniformity and stability. On the receiving end, although customization promises best fulfillment of customers' individual-specific needs, customization is often associated with increased complexity, which may adversely impact customer value or satisfaction (Dellaert and Stremersch 2005) and could result in customer annoyance and confusion (Huffman and Kahn 1998). The move toward mass customization can be generally summarized as an effort to minimize the loss of "economies of scale" incurred by customization on the supply side and to maximize the value to customers on the demand side. Flexibility plays an important role in accomplishing both objectives.

On the supply side, manufacturing system flexibility enables manufacturers to respond to changes in demand, e.g. in product mix or product variants, without incurring high penalty in higher setup cost, lead time, and/or production disruptions. Increasing manufacturing flexibility has been recognized as an effective strategy to mitigate, if not eliminate, the tradeoffs between customization and other competitive priorities, for example cost, quality, and responsiveness (Spring and Dalrymple 2000, Squire and Brown 2006). On the demand side, customers also display flexibility in their purchasing behavior. Customers could be indifferent over some product features and they are often willing to compromise certain attribute values in order to meet budget or delivery constraints. In Simon's terms, customers are "sufficers" rather than "optimizers" (Simon 1996). Flexibility in both demand and supply increases the degree of freedom in locating a satisfactory solution.

In product customization, the process of transferring individual customers' needs into concrete product specifications has been recognized as a collaborative design (co-design) process, in which customers are integrated into value creation by defining, configuring, matching, or modifying an individual solution (Berger and Piller 2003, Piller et al. 2004). Effective co-design enhances customer satisfaction toward customization (Du et al. 2006). Intuitively, flexibility in demand and supply enlarges the range of design alternatives and increases the possibility of finding mutually satisfactory solutions. However, alignment of flexibility in demand and supply requires customers and manufacturers to work interactively through careful analysis and planning. In order for co-design to play the effective role of alignment, at least three technical challenges need to be considered:

1. *Complexity*: On the supply side, a flexible manufacturing system (FMS) is usually composed of resources that have different ranges and levels of flexibility along multiple dimensions (Shewchuk and Moodie 1998). Consequently, supply flexibility often has a complex structure with complicated operational implications. On the demand side, customers are often unable to accurately articulate their needs (Huffman and Kahn 1998, Zipkin 2001). A recent study in marketing research suggests that customers may not have well-defined preferences to be revealed, and they may fail to appreciate customized offers that fit their measured preferences (Simonson 2005).
2. *Preferential conflicts*: As in any buyer-seller relationship, customers and manufacturers have mutually opposing objectives and are not entirely aligned in their preferences where product customization is concerned. The objective of maximizing the value of customization to customers is often at odds with the objective of minimizing the cost associated with customization to manufacturers. Similarly, maximizing the degree of customization may be counterproductive for customers for reasons of higher price and greater product complexity. Finding common ground and balancing different performance indices are often delicate and difficult tasks.
3. *Information asymmetry and "stickiness"*: Customers are often not aware of where the flexibility of manufacturing systems lies or of the economic or scheduling consequences of system flexibility. Conversely, manufacturers have difficulties fully understanding customers' requirements and their possible substitutions. Flexibility in demand and supply is essential constituent of need information and solution information, respectively; these are usually distributed asymmetrically with customers and manufacturers respectively and are "sticky" in the sense that they are costly to acquire, transfer, and use in a different context (Von Hippel 2005).

These challenges, if not properly addressed, could turn flexibility into a source of liability instead of a source of (customer) utility and (manufacturer) profitability. As cautioned by Huffman and Kahn (1998), there is a thin line between mass customization and "mass confusion". Existing approaches to custom product co-design are either manufacturer-centered or customer-centered depending on the relative *stickiness* of need information and solution information (Von Hippel 2005). Both approaches, however, assume full information sharing and information transferability. These approaches become inadequate when there are contextual information and tacit knowledge with preferential conflicts, which is the scenario of co-design this paper is concerned with.

This paper introduces negotiation as new methodology to explore and align demand and supply flexibility in custom product co-design. Customers' requirements are treated as a range of negotiable options instead of a set of fixed inputs. The problem is further mirrored by the flexibility of manufacturing systems. Design decision making is taken as distributed and interactive problem solving with each side alternately making offers and counteroffers and collectively searching for mutually satisfactory solutions. The rest of the paper is organized as the following. First, relevant literature concerning the concept of flexibility, existing co-design approaches, and negotiation as an emerging methodology for engineering collaboration is reviewed. Second, a negotiation framework for custom product co-design is constructed. Based on the framework, a negotiation scheme based on demand and supply flexibility information is proposed for co-design. The negotiation scheme is then formulated using goal programming (GP), and an illustrative example is subsequently presented and discussed.

2 Related work

2.1 Flexibility concept

Flexibility is one of the most widely studied but poorly understood concepts. According to Shewchuk and Moodie (1998), over 70 terms have been reported in literature to characterize and measure flexibility. To avoid confusion with existing definitions, this paper adopts the Merriam–Webster Dictionary definition: *"flexibility represents a property characterized by a ready capability to adapt to new, different, or changing requirements"*. In the context of product customization, we define supply flexibility as a manufacturing system's adaptability to changes in production requirements, and demand flexibility as a customer's willingness to settle with product variants that are different from the ideal specifications. Supply flexibility is similar to the concept of manufacturing flexibility (e.g. Shewchuk and Moodie 1998), while demand flexibility is similar to the concept of demand substitutability in economics and marketing (e.g. Lancaster 1990).

To simplify discussion without loss of generality, product mix is selected as the flexibility type (Sethi and Sethi 1990), and utility and profit are selected as the performance metrics for measuring demand flexibility and supply flexibility respectively. In the context of product customization, product mix represents the range of product variants; demand flexibility and supply flexibility are measured by the impact of design changes on the customer's utility and the manufacturer's profit, respectively. Low impact corresponds to high flexibility.

2.2 Exploiting flexibility in co-design: existing approaches

A key challenge in custom co-design is that customers and manufacturers have asymmetric and *sticky* information, which needs to be reconciled for effective problem solving (Von Hippel 2005). Depending on the locus of problem solving, co-design can be classified into manufacturer-centered or customer-centered. Different modes of co-design correspond to different approaches to share and utilize flexibility information.

In manufacturer-centered co-design, manufacturers actively seek customer-need information, explore demand flexibility, and then customize the product accordingly. Along this line of research, Jiao and Tseng (2004) define flexibility as the cost-effectiveness of a design and the associated production processes to accommodate variations in performance requirements. Based on flexibility, design customizability and process customizability are proposed and applied in design alternative selection and design optimization. One key challenge of manufacturer-centered co-design lies in the difficulty of eliciting customer preferences (Zipkin 2001). Recent research in marketing suggests that customer preferences are often ill defined and susceptible to influences (Bettman et al. 1998). It is often time and resource-consuming to understand customer requirements and their possible substitutions with sufficient accuracy.

In customer-centered co-design, solution information is transferred to customers via systems similar to design toolkits (Von Hippel 2005) and product configurators (Forza and Salvador 2002), and it is the customer that is mainly responsible for making the customization decisions. Under this mode of co-design, supply flexibility is embedded in the supporting systems via structured decision sequences, configuration rules, dynamic pricing schemes, etc. Although manufacturers' sales efforts can be significantly reduced, this approach of co-design often entails a large number of options and exposes customers to the burden of choices, which is particularly severe when customers do not have sufficient knowledge of the product (Piller et al. 2004).

Another approach under customer-centered co-design is to actively assist customers in exploring demand flexibility. Enabled by techniques like data mining, systems like personal advisors and recommendation systems (Stolze and Strobel 2004) are able to suggest product variants based on customers' historical purchasing behavior. This approach, however, requires customers' needs to be relatively stable so that preferences revealed in the past can have predictive power over future needs. Furthermore, customer assistance could be misunderstood as demand shaping, in which customers' demand are maneuvered towards manufacturers' interests. Customers may feel locked in or trapped and consequently resent sharing personal information (Fournier et al. 1998).

In general, there have been a variety of attempts to exploit the value of demand and supply flexibility in custom product co-design. Tools such as sales automation systems, design toolkits, product configurators and recommenders have greatly reduced the complexity of customization decisions for both customers and manufacturers (challenge 1 in the Introduction). However, most of these approaches assume centralized decision making and transferability of flexibility information. The asymmetric and *sticky* nature of need and solution information and the inherent conflicts between customers' and manufacturers' preferences in customization have not been adequately addressed (challenges 2 and 3).

2.3 Design collaboration via negotiation

Negotiation has been widely practiced as a general mechanism for resolving conflicts and building consensus in situations that are characterized by ill defined problem structure, information asymmetry, and conflicting preferences. It has been extensively studied in various disciplines that include social science (e.g. Fisher et al. 1991, Raiffa et al. 2003), economics (e.g. Myerson and Satterthwaite 1983), and computer science (e.g. Bichler et al. 2003) etc. In economics/marketing literature, the term negotiation is interchangeably used for bargaining. It is usually modeled as a zero-sum game in which each participant tries to claim a larger share from a fixed pie. Myerson and Satterthwaite (1983) have proved "*the general impossibility of ex post efficiency of bargaining without outside subsidies*". In other words, negotiation as a bi-lateral trade mechanism is inherently inefficient. There is always a chance that negotiators may fail to reach agreement, even though win–win solutions are possible.

Raiffa et al. (2003) differentiates *integrative negotiation* (integrating participants' capabilities and resources to generate more value) from *distributive negotiation* (dividing a fixed good among negotiating parties). Integrative negotiation assumes there are multiple issues at stake and different parties have different preferences over these issues. Through take-and-give over issues that are relatively more and less important, negotiators can move the joint solution towards an *efficient frontier*, a set of solutions that cannot be improved unilaterally, or, put differently, *agreements with no money left on the table*.

In recent years, negotiation has been recognized as an important activity in engineering design as engineering becomes increasingly integrated with other functions like marketing, manufacturing, and purchasing, etc. Lu (2003) proposes engineering collaboration via negotiation (ECN) as a new methodology for distributed engineering decision making. Ge and Lu (2005) develop a direct synthesis method to support negotiation in engineering design and apply the method in large-scale mechanical system design. Chen and Tseng (2005) develop a negotiation support system based on a product configurator for defining specifications of custom products. The issue of flexibility, however, has not been explicitly addressed in this stream of research.

3 Flexibility in co-design

Design in general can be viewed as a series of *what-to-how* mappings from customer needs $\{CN\}$ to functional requirements $\{FR\}$, to design parameters $\{DP\}$, and finally to process variables $\{PV\}$ (Suh 1990). $\{CN\}$ represents a customer's real, but often hidden, needs; $\{FR\}$ is the articulated customer needs in terms of desired product functionality or features; $\{DP\}$ represents a technical solution that satisfies $\{FR\}$; and $\{PV\}$ describes how the designed product can be produced. Collectively, $\{FR,DP,PV\}$ represents a complete set of product specifications. The mapping relationships between $\{FR\}$ and $\{DP\}$ and between $\{DP\}$ and $\{PV\}$ are characterized by design matrixes $[A]$ and $[B]$, respectively.

$$\{FR\} = [A]\{DP\}, \{DP\} = [B]\{PV\} \tag{1}$$

Design matrixes may or may not be in numeric form but generally indicate the inter-relationships between different design domains. According to the axiomatic design theory, the actual process of (innovative) design is an iterative zigzag process across different design domains following a hierarchical structure (Suh 1990). Design in product customization is usually not functionally innovative but application oriented, i.e. tailoring existing solutions to individual customer's specific needs based on pre-established product family architecture (PFA) (Tseng and Jiao 1996). As a result, design matrices $[A]$ and $[B]$ can be assumed as fixed and given.

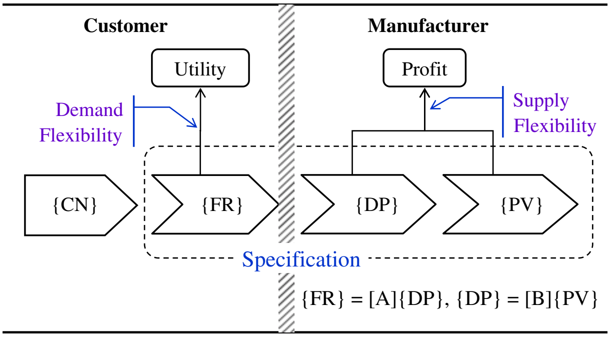

Fig. 1 Flexibility in custom product co-design

In custom product co-design, it can be generally assumed that a customer's need information is reflected in $\{FR\}$ whereas a manufacturer's solution information is reflected in $\{DP\}$ and $\{PV\}$. The customer's utility and manufacturer's profit can be henceforth assumed as functions of $\{FR\}$ and $\{DP,PV\}$ respectively. The customer's objective in co-design is to find a product represented by $\{FR\}$ that maximizes a utility U, while the manufacturer's objective is to find a technical solution $\{DP,PV\}$ with highest profit π while satisfying customer requirements. Since $\{PV\}$ and $[B]$ are functionally equivalent to $\{DP\}$ and $[A]$, respectively, they are omitted in subsequent discussions without loss of generality.

Demand flexibility indicates customers' sensitivity of utility relative to changes in $\{FR\}$, while supply flexibility indicates manufacturers' sensitivity of profit relative to changes in $\{DP\}$. Mathematically, the derivative of a function represents the function's sensitivity with respect to changes of a certain argument. Since $\{FR\}$ and $\{DP\}$ are usually multi-dimensional, demand and supply flexibilities are consequently reflected along multiple dimensions. In this paper, the inverse of the first-order derivatives of utility and profit functions f_i^d and f_j^s are used to measure demand flexibility and supply flexibility with respect to FR_i and DP_j, respectively. The inverse operation converts the flexibility measurement to be aligned with the practical usage of flexibility: i.e. high rate of change corresponds to low flexibility.

$$f_i^d = \left(\frac{\partial U}{\partial\{FR_i\}}\right)^{-1}, \{FR\} = \{FR_i | i = 1, 2, \ldots, M\} \tag{2}$$

$$f_j^s = \left(\frac{\partial \pi}{\partial\{DP_j\}}\right)^{-1}, \{DP\} = \{DP_j | j = 1, 2, \ldots, N\} \tag{3}$$

Figure 1 displays the role of demand and supply flexibility in a general decision framework for custom product co-design.

4 A negotiation framework for custom product co-design

Raiffa et al. (2003) define negotiation as "*a process of joint decision making, which entails joint consequences, or payoffs, for each individual*". Custom product co-design can be taken as a negotiation process in which a customer and a manufacturer collectively search for a joint solution $\{FR,DP\}$ that is mutually satisfactory according to the payoff functions U and π, respectively. The mapping relationship represented by design matrix $[A]$ indicates the inter-dependence between two distributed decisions and establishes a channel for communication. Demand and supply flexibility reflect the customer's and manufacturer's preferences, respectively, over different design alternatives.

4.1 Aspiration levels

Without knowing what the counterpart is willing to accept, negotiators usually start with offers that they *aspire* to achieve (Raiffa et al. 2003). This strategy is reflected both in customers' purchasing behavior and manufacturers' sales practices. Customers often ask for high quality, low price, and fast delivery, which could be beyond the manufacturer's capabilities. On the manufacturer's side, different products or product variants usually have different profit margins. Manufacturers have incentives to promote the most profitable alternatives, which may not be what the customer really wants. In this perspective, customers' articulated needs and manufacturers' default offerings can be taken as their respective aspiration levels, which may not be feasible or acceptable to the other side. In this paper, the customer's and manufacturer's target solutions are represented as $\{FR_c^t\}$ and $\{DP_m^t\}$, respectively. Their corresponding utility and profit are denoted as the customer's aspired utility and manufacturer's aspired profit, respectively. It is worth noting that both sides can update their aspiration levels during the negotiation process as more information becomes available.

$$U^t = U(FR_c^t), \quad \pi^t = \pi(DP_m^t) \tag{4}$$

4.2 Reservation values

There is usually a limit to what a negotiator is willing to compromise in negotiation, beyond which he/she prefers no agreement. The minimum value that a party commits to achieving is defined as his/her reservation value (RV) (Raiffa et al. 2003). Fisher et al. (1991) introduce the concept of best alternative to a negotiated agreement (BATNA) as the threshold condition to stay in negotiation. Based on BATNA, Raiffa et al. (2003) apply decision-analysis techniques to evaluate RVs. In the context of custom product co-design, a standard product with specifications close to the customized requirements can be taken as the customer's BATNA. Similarly, the product variant with the least profit margin can be taken as the manufacturer's BATNA. The customer's and manufacturer's BATNAs are represented as $\{FR_c^r\}$ and $\{DP_m^r\}$, respectively, and their corresponding utility and profit are denoted as the customer's and manufacturer's RVs, respectively:

$$U^r = U(FR_c^r), \quad \pi^r = \pi(DP_m^r) \tag{5}$$

4.3 Zone of possible agreement (ZOPA)

The range of agreements that are both feasible and acceptable to all participants is defined as the zone of possible agreement (ZOPA) in negotiation (Raiffa et al. 2003). However, ZOPA is usually unknown because each party's reservation value is private information. As a result, negotiation is fundamentally different from optimization. Instead of searching for optimal solutions from a given solution space, negotiators need to constantly update their understanding of the solution space based on partial information revealed during the negotiation process. In the context of custom product co-design, the customer may have certain constraints over functional requirements ($h_c\ (FR) \leq 0$); while the manufacturer may be subject to constraints over the design parameters ($h_m\ (DP) \leq 0$). ZOPA represents all feasible design solutions that simultaneously satisfy these constraints and fulfill the RV requirements:

$$\begin{aligned} ZOPA = \{ & (FR, DP) | h_c(FR) \leq 0, h_m(DP) \leq 0, U^r \leq U(FR), \pi^r \leq \pi(DP), \\ & FR = [A]DP \} \end{aligned} \tag{6}$$

4.4 Agreement and surplus

A negotiation concludes when an agreement is reached or any party decides to walk away. Both parties derive zero gains/losses from non-agreement (the cost of negotiation is neglected in this study, but could be significant in some situations). When there is an agreement, the extra value above the reservation value is called the *surplus* (Raiffa et al. 2003). In custom product co-design, the customer's and manufacturer's objectives can be taken to find an agreement $(FR^*, DP^*) \in ZOPA$ that maximizes utility surplus ϕ_c and profit surplus ϕ_m respectively.

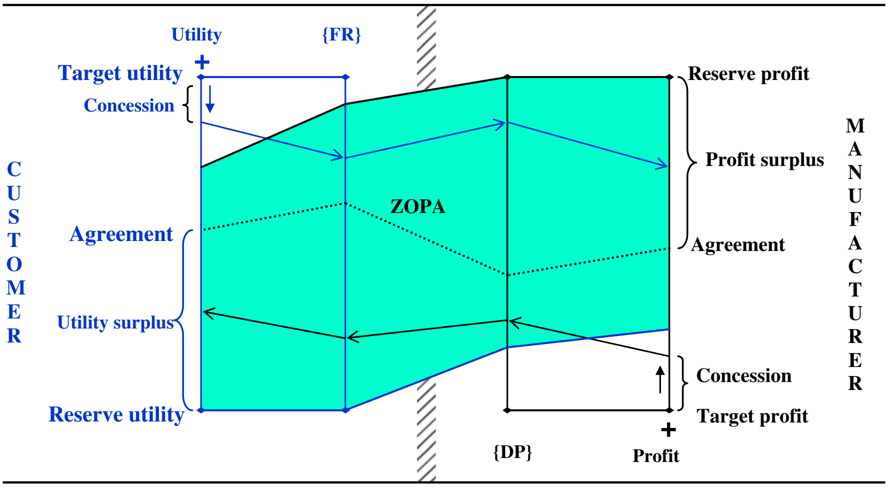

Fig. 2 A negotiation framework for custom product co-design

$$\phi_c = U(FR^*, DP^*) - U^r \tag{7}$$

$$\phi_m = \pi(FR^*, DP^*) - \pi^r \tag{8}$$

Figure 2 presents a negotiation framework for custom product co-design.

5 A negotiation scheme based on goal programming

5.1 Aspiration levels as goals

The aspiration levels U^t and π^t can be taken as *goals* for the customer and manufacturer, respectively. The advantage of representing aspiration levels as goals instead of constraints is that goals do not have to be satisfied, thus giving more flexibility in terms of modeling. Because of preferential conflicts, these goals cannot be aggregated into a single objective in the best interests of both sides. In other words, U^t and π^t cannot be achieved simultaneously and compromises are necessary to reach agreements. As a result, the customer's and manufacturer's design decisions can be taken as two interrelated goal programming (GP) problems aiming to find a joint solution (FR^*,DP^*) that minimizes the deviations from $U^t$and π^t, which is equivalent to maximizing ϕ_c and ϕ_m, respectively.

5.2 Making concessions based on flexibility information

Without knowing each other's RV (i.e. the boundary of ZOPA), neither party is in a position to command a *take-it-or-leave* offer without the risk of either sacrificing potential gains or failing to reach an agreement. Consequently, both parties need to start from their aspired levels and gradually make concessions in seek of an agreement. In the context of co-design, this means the customer and the manufacturer need to iteratively adjust $\{FR_c^t\}$ and $\{DP_m^t\}$ respectively, and suggest design alternatives accordingly.

As the size of concession is concerned, there is a tradeoff between being competitive (concede slowly to reduce the risk of over compromising) and being cooperative (concede aggressively to enhance the chance of striking a deal). The sensitivity of concessions in terms of utility and profit with respect to changes in $\{FR\}$ and $\{DP\}$ is the demand and supply flexibility, respectively. Based on the flexibility information, concessions should be made preferably over design attributes with high flexibility, thus maximally contributing to resolving the outstanding disagreement without significant compromise on the payoff. Based on this intuition, two GP algorithms are developed to calculate the "optimal" counteroffers for the customer and manufacturer, respectively, assuming a fixed amount of concession in utility and profit (Fig. 3). It is worth noting that flexibility information is not explicitly expressed in the algorithms, but calculated and utilized in the searching process of optimization. In gradient-based optimization methods, the local gradients of utility and profit functions correspond to the inverse of demand flexibility and supply flexibility as defined in Eqs. 2 and 3, respectively.

GP-1: Customer's Counteroffer

Given:

$\{FR_c^t\}, \{FR_m^t, DP_m^t\}$

$U = U(FR)$, ΔU

Find:

$\{FR\}$

Satisfy:

$U(FR_c^t) - U(FR) \le \Delta U$;

$FR_i + d_i^- - d_i^+ = FR_m^t$;

$d_i^- * d_i^+ = 0, d_i^- \ge 0, d_i^+ \ge 0$;

$h_c(FR) \le 0$;

$i = 1,2,\ldots,M$.

Minimize:

$$Z_c = \sum_{i=1}^{M} (d_i^+ + d_i^-)$$

GP-2: Manufacturer's Counteroffer

Given:

$\{FR_c^t\}, \{FR_m^t, DP_m^t\}$

$\pi = \pi(DP), \Delta\pi$

Find:

$\{DP\}$

Satisfy:

$\pi(DP_m^t) - \pi(DP) \le \Delta\pi$;

$DP_j + d_j^- - d_j^+ = DP_c^t$;

$d_j^- * d_j^+ = 0, d_j^- \ge 0, d_j^+ \ge 0$;

$h_m(DP) \le 0$;

$j = 1,2,\ldots,N$.

Minimize:

$$Z_m = \sum_{j=1}^{N} (d_j^+ + d_j^-)$$

Fig. 3 Algorithms for calculating counteroffers

5.3 Stopping criteria

There are no optimality conditions to terminate a negotiation process due to negotiators' conflicting objectives and indeterminacy of negotiation results. Empirically, negotiations conclude either with agreements when the joint solution converges to a point that is mutually acceptable or with no agreements when a deadlock is reached while at least one party is not satisfied but does not want to continue. In many situations, negotiations are terminated according to predetermined deadlines or agendas. This paper assumes a fixed number of iterations that the customer and manufacturer are willing to negotiate, which can be interpreted as the maximum amount of efforts that they are willing to invest in co-design.

5.4 A negotiation procedure for custom product co-design

Generally speaking, negotiation is an iterative process of distributed decision making with partial information exchange. Figure 4 illustrates a negotiation procedure for custom product co-design. The customer's announced needs $\{FR_c^t\}$ and manufacturer's most profitable product variant $\{DP_m^t\}$ are taken as their respective opening offers, or initial *goals*. Both parties have a limit on the number of rounds (K_c and K_m for the customer and manufacturer respectively) that they are willing to negotiate. The negotiation process starts with the customer deciding an amount of concession ΔU and making a counteroffer $\{FR_c^t\}$ toward minimizing the distance to the manufacturer's offer $\{FR_m^t\}$ (GP-1). Responding to the customer's offer, the manufacturer finds a solution $\{DP\}$ that satisfies $\{FR_c^t\}$ with highest profit. If no feasible $\{DP\}$ can be found, the manufacturer insists on the current offer $\{FR_m^t, DP_m^t\}$; otherwise, the manufacturer makes a concession $\Delta\pi$ and proposes a counteroffer $\{FR_m^t, DP_m^t\}$ (GP-2). With each concession, the customer and manufacturer update their goals. The process iterates until an agreement is reached if any party's current goal (adjusted by concessions) is fulfilled by the counterpart's current offer or ends with no agreement when any party's limit of rounds is reached.

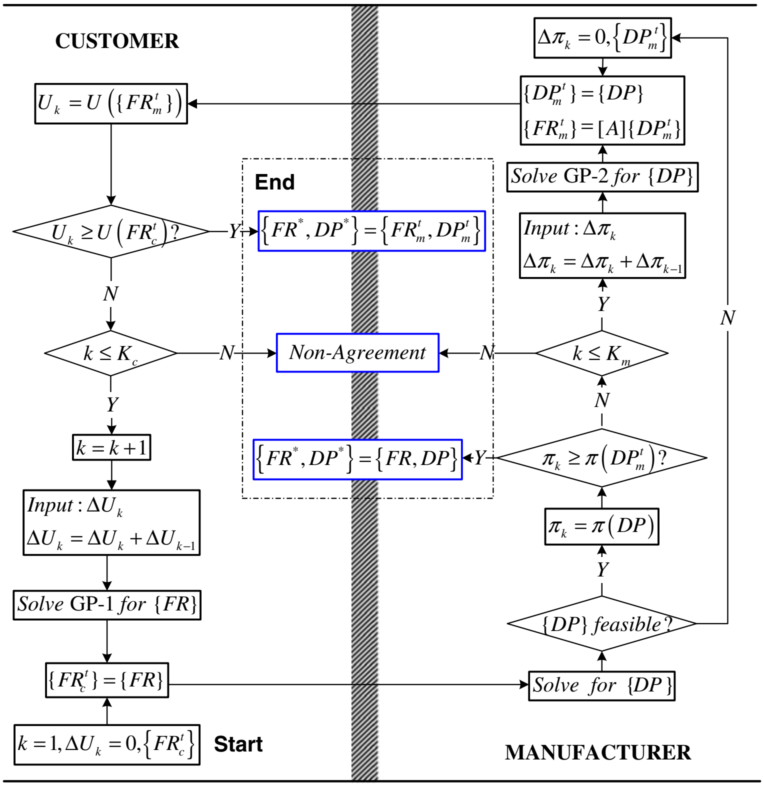

Fig. 4 A negotiation procedure for custom product co-design

6 An illustrative example

An example is constructed to illustrate the process and result of custom product co-design via negotiation. Suppose a customer needs to customize a product's dimensions, e.g. length (FR_1) and width (FR_2), which are also the manufacturer's design parameters DP_1 and DP_2 respectively. The design matrix $[A]$ is a 2×2 identity matrix.

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}$$

Both the customer's utility and manufacturer's profit are assumed to be functions of length, width, and area. Both sides have desired values for the dimensions and certain constraints over the dimensions and the overall payoffs. Such information is private and asymmetrically distributed with the customer and the manufacturer. Table 1 captures the information structure.

According to the payoff functions, the customer prefers both dimensions to be large while the manufacturer prefers the opposite. Because of information asymmetry and preferential conflicts, the customer and manufacturer could haggle over the design

Table 1 Information structure in the custom product co-design example

	Customer	Manufacturer
Payoff	$U = 0.3FR_1 + 0.1FR_2 + 0.6FR_1\ FR_2 + 50$	$\pi = 100 - 0.2DP_1^{\ 2} - 0.6DP_2^{\ 2} - 0.2DP_1DP_2$
Goals	$\{FR\} = [12;10]$	$\{DP\} = [2;1]$
RV	$U \geq 60$	$\pi \geq 60$
Bounds	$3 \leq FR_1 \leq 12$	$2 \leq DP_1 \leq 10$
	$2 \leq FR_2 \leq 10$	$1 \leq DP_2 \leq 8$
Flexibility	$f_1^d = (0.6FR_2 + 0.3)^{-1}$	$f_1^s = -(0.4DP_1 + 0.2DP_2)^{-1}$
	$f_2^d = (0.6FR_1 + 0.1)^{-1}$	$f_2^s = -(1.2DP_2 + 0.2DP_1)^{-1}$

solution attribute by attribute and end up with disagreement, even though mutually satisfactory solutions are available. The flexibility structure indicates that the customer is relatively more flexible (or less sensitive) with FR_2, while the manufacturer is relatively more flexible with DP_1. As a result, concessions should be made preferably over FR_2 by the customer and DP_1 by the manufacturer. A simulated negotiation process programmed in MATLAB is displayed in Fig. 5 (data are normalized to be within [0,1]). The concession patterns are aligned with the calculated flexibility structure. The customer gains over FR_1 while the manufacturer gains over DP_2, and a mutually satisfactory solution is found during the negotiation process.

It is worth noting that in the simulated example the customer and the manufacturer are assumed to have a fixed amount of utility and profit to concede in each round. In real practice, concession-making will depend on dynamic evaluation of the counterpart's negotiation behavior and estimation of his/her reservation value with updated information.

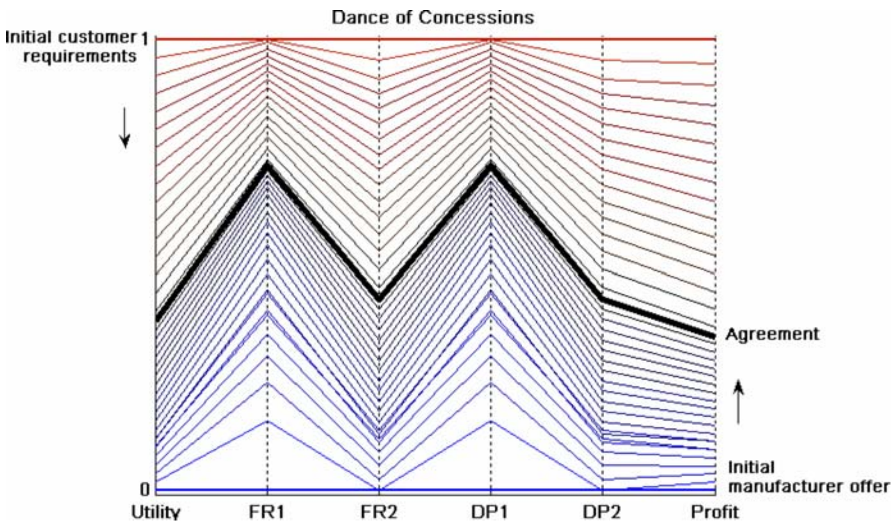

Fig. 5 Graphical display of a co-design process via negotiation

A further point to note is that the two dimensions represented here are essentially generic to a general argument for negotiations. These two dimensions, for instance, could well be the performance levels of a product (e.g., RAM and speed of a PC) and may have a discrete utility function for just a few options offered by manufacturer instead of a continuous utility function presented here. Thus, this analysis could easily be applied to a product with multiple configurations, each offering a different level of performance for a selected set of functions.

The algorithms developed in this paper can be extended to cope with the situation by providing an interface for designers to manually input the amount of concessions in each round. Another practical consideration is that negotiators may strategically withhold their private information and try to outwait each other with minimal concessions. The setup of a fixed and hidden limit on the rounds of negotiation in our proposed negotiation procedure can counterbalance such strategic behavior by exposing the strategically patient negotiators to the risk of no agreement. In general, although highly simplified, the example demonstrates the feasibility of aligning demand and supply flexibility in custom product co-design via structured negotiations. The negotiation framework for custom product co-design and the concept of utilizing flexibility information to explore the design solution space can be generalized to more complicated customization situations.

7 Summary

Manufacturing flexibility has been recognized as a critical enabler for mass customization. A recent study in marketing research suggests that customers also possess flexibility in their demand for customization, as evidenced by their indifference in certain product features and willingness to tradeoff certain attributes in order to meet budget or schedule constraints. Both demand flexibility and supply flexibility increase the degree of freedom in locating a mutually satisfactory solution. However, aligning demand and supply flexibility is often a challenging task because flexibility information is usually ill defined, asymmetrically distributed, and not freely shared because of preference conflicts.

This paper proposes negotiation as a new methodology to systematically explore and align demand and supply flexibility in custom product co-design. Product mix is selected as the dimension to characterize flexibility. Demand flexibility and supply flexibility are subsequently defined as the sensitivity of customers' utility and manufacturers' profit upon design changes in functional requirements and design parameters, respectively. Conversely, demand and supply flexibility information influences co-design decisions. A negotiation framework is constructed to capture the essential decisions in custom product co-design, and algorithms utilizing demand and supply flexibility are developed to suggest design alternatives during the negotiation process. The negotiation scheme is implemented with an illustrative example, which demonstrates the feasibility of custom product co-design via negotiation.

Flexibilities play a critical role in both fulfilling customer's individual-specific needs and mitigating the economic impact of customization on manufacturers.

Aligning demand and supply flexibility is becoming an increasingly important research problem as markets move towards mass customization and manufacturers continue to deploy flexible manufacturing systems. Negotiation has shown promise in determining product specifications in engineering collaboration. This research contributes to the general area of developing interactive design methodologies, supporting systems, and tools to effectively engage customers into the value-creation process of product customization.

Acknowledgements This research is supported by National Natural Science Foundation of China (NSFC: No.70418013) and Hong Kong Research Grants Council (RGC: N_HKUST625/04). The authors would also like to express our gratitude to the anonymous reviewers for their thorough and insightful comments on previous manuscripts.

References

Berger C, Piller F (2003) Customers as co-designers. IEE Manuf Eng 82(4):42–45

Bichler M, Kersten G et al. (2003) Towards a structured design of electronic negotiations. Group Decis Negot 12(4):311–335

Bettman J, Luce M, Payne J (1998) Constructive consumer choice processes. J Consum Res 25(December):187–217

Chen S, Tseng MM (2005) Defining specifications for custom products: a multi-attribute negotiation approach. CIRP Ann 54:159–162

Dellaert BGC, Stremersch S (2005) Marketing mass-customized products: striking a balance between utility and complexity. J Mark Res 42(2):219–227

Du X, Jiao J, Tseng M (2006) Understanding customer satisfaction in product customization. Int J Adv Manuf Technol 31:396–406

Fisher R, Ury W et al. (1991) Getting to yes: negotiating agreement without giving in. Houghton Mifflin, Boston

Forza C, Salvador F (2002) Managing for variety in the order acquisition and fulfillment process: the contribution of product configuration systems. Int J Prod Econ 76:87–98

Fournier S, Dobscha S et al. (1998). Preventing the premature death of relationship marketing. Harv Bus Rev 76(1):42–44

Ge P, Lu SC-Y et al (2005) Supporting negotiations in the early stage of large-scale mechanical system design. J Mech Des 127(6):1056–1067

Huffman C, Kahn BE (1998) Variety for sale: mass customization or mass confusion? J Retail 74(4):491–513

Jiao JX, Tseng MM (2004) Customizability analysis in design for mass customization. Comput Aided Des 36:745–757

Lancaster K (1990) The economics of product variety: a survey. Mark Sci 9(3):189–206

Lu S (2003) Engineering as collaborative negotiation: a new paradigm for collaborative engineering. http://wisdom.usc.edu/ecn/index.htm

Myerson R, Satterthwaite M (1983) Efficient mechanisms for bilateral trade. J Econ Theory 29:265–281

Piller FT, Moeslein K et al (2004). Does mass customization pay? An economic approach to evaluate customer integration. Prod Plan Control 15(4):435–444

Raiffa H, Richardson J et al (2003) Negotiation analysis: the science and art of collaborative decision making. Belknap Press, Cambridge, Mass

Sethi AK, Sethi SP (1990) Flexibility in manufacturing: a survey. Int J Flex Manuf Syst 2(4):289–328

Shewchuk JP, Moodie CL (1998) Definition and classification of manufacturing flexibility types and measures. Int J Flex Manuf Syst 10(4):325–349

Simon HA (1996) The sciences of the artificial. MIT Press, Cambridge, Mass

Simonson I (2005) Determinants of customers' responses to customized offers: conceptual framework and research propositions. J Mark 69(1):32–45

Spring M, Dalrymple JF (2000) Product customisation and manufacturing strategy. Int J Oper Prod Manag 20(4):441

Squire B, Brown S et al (2006) The impact of mass customisation on manufacturing trade-offs. Prod Oper Manag 15(1):10–21

Stolze M, Strobel M (2004) Recommending as personalized teaching: designing personalized user experiences in eCommerce. Kluwer Academic Publishers, Norwell, MA, USA

Suh NP (1990) The principles of design. Oxford University Press, New York

Tseng MM, Jiao J (1996) Design for mass customization. Ann CIRP 45/1:53–156

Von Hippel E (2005) Democratizing innovation. MIT Press, Cambridge, Mass

Zipkin P (2001) The limits of mass customization. MIT Sloan Manage Rev 42(3):81

Songlin Chen is a Ph.D. candidate in the Department of Industrial Engineering and Logistics Management at the Hong Kong University of Science & Technology. His research interest is focused on negotiation and auction theory and its application in mass customization, engineering design, and supply chain collaboration. Mr. Chen holds a Bachelor degree (2001) in Aerospace Engineering from the National University of Defence Technology in China and a Master degree (2003) in Aeronautics and Astronautics from Stanford University in U.S.

Mitchell M. Tseng Chair Professor and Director, Advanced Manufacturing Institute and Zhejiang Advanced Manufacturing Institute of Hong Kong University of Science & Technology (HKUST). Prof. Tseng joined HKUST as the founding Department Head of Industrial Engineering in 1993 after holding executive positions at Xerox and Digital Equipment Corporation. He previously held faculty positions at University of Illinois at Champaign Urbana and Massachusetts Institute of Technology. Prof. Tseng is an elected fellow of the International Academy of Production Engineers (CIRP). He is widely recognized for his work in Mass Customization and has been serving as a co-chair of the World Congress of Mass Customization and Personalization. He received his M.S. and Ph.D. degrees in Industrial Engineering from Purdue University, and B.S. degree in Nuclear Engineering from National Tsing Hua University.