Customer Flexibility Integration for Order Commitment Process in High Mix Low Volume Production

By

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This is to certify that I have examined the above PhD thesis and have found that it is complete and satisfactory in all respects, and that any and all revisions required by the thesis examination committee have been made.

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Customer Flexibility Integration for Order Commitment Process in High Mix Low Volume Production

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Abstract

With increasing product variety and escalating demand volatility, manufacturing industry is moving towards high product mix and low order volume production. Consequently, achieving high service level and low manufacturing cost simultaneously in such dynamic environment becomes ever challenging. Typically, most order fulfillment approaches take manufacturing flexibility as an effective mean to buffer the market uncertainty and resolve demand-supply mismatching problems in the high mix low volume production environment. However, to tackle the challenge purely by using manufacturing flexibility sometimes can reach a limit, and it can be very expensive. On the other hand, it has been observed that customers are often indifferent to certain product specs and delivery schedules. This customer behavior brings additional degree of freedom in promising customer orders and arranging production resources. In this research, this customer behavior is named “customer flexibility”.

It has been recognized that the customer flexibility does appear in the interface between the customer and the manufacturing firm during a process of making order commitments. The order commitment process, which commits product specifications and delivery schedules to customer order requests, plays the most
critical role in tackling the challenge through matching the customer requirements with manufacturing capabilities and available resources.

To this end, this research takes a new perspective to tackle the challenge of matching customer needs with manufacturing resources by integrating customer flexibility into the order commitment process. In order to do that, a systematic approach to characterize and measure customer flexibility is developed. Models and algorithms are then developed for order commitment decision making, which integrate both customer flexibility and manufacturing flexibility to facilitate demand-supply matching in high mix low volume production environments. An industrial case study in a garment manufacturing company is conducted to verify the proposed approaches and to study the interactions between customer flexibility and manufacturing flexibility with regards to the impacts on system performances. It has been demonstrated that a better positioning of manufacturing flexibility together with a proactive management of customer flexibility can help the manufacturer better shape the manufacturing capability and customer demand, and achieve improved demand-supply matching in this dynamic production environment.
CHAPTER 1
INTRODUCTION

1.1. Background

Manufacturing companies can no longer follow Henry Ford’s famous strategy of “any color as long as it’s black”: capturing market share and high profit by producing large volumes of standardized products. Today, more and more companies are providing large variety of products to meet diversified customer needs. As a result, the market is getting more fragmented and customer demands become more fluctuating in terms of both product mix and volume (Pine 1993, Tseng 1996).

With increasing product variety and dynamic demand fluctuation, it can be observed that manufacturing is moving towards a configure-to-order and make-to-order environment with high product mix and low order volumes (Hopp 2000). Consequently, manufacturing companies are facing increasing challenges which include:

(1) Complication of order management processes

With increasing product variety and demand uncertainty, manufacturing is shifting from the conventional forecast-driven Make-to-Stock production to the order-driven Make-to-Order or Assemble-to-Order production. More sophisticated order management processes and systems are demanded to process
customer order and manage order oriented manufacturing activities efficiently and effectively.

(2) Increasing uncertainty in both demand and supply side

With the diversity of customer requirements, customers are more tightly connected with manufacturer and upstream suppliers. The supply chain is becoming more complicated comprising closely integrated collaboration parties distributed globally. More dynamics and uncertainties are coming from both the supplier side and the customer side.

(3) Increasing focus on specific customer service dimensions

In addition to product quality and cost, companies are competing in a number of service quality dimensions including delivery reliability, order commitment speed and quality, flexibility and responsiveness (Zhao et al. 2005).

The most commonly used solution to the above mentioned challenges faced by today’s manufacturing industry is the use of manufacturing flexibility. Manufacturing flexibility has become one of the most sought after properties in modern manufacturing systems (Upton 1994, 1997; Toni and Tonchia, 1998; Shewchuk, 1999; Iravani et al. 2005). For example, in car manufacturing industry, many production lines can process various types of product models with quick changeovers. Production capacity can also be adjusted quickly through worker reallocation and flexible working hours to cope with dynamic volume changes. Therefore, many order management systems integrate manufacturing flexibility as
an effective mean to enable better adaptability and enhance demand-supply matching in this dynamic environment.

However, tackling the market challenges from manufacturing flexibility solely sometimes could reach a limit (Iravani et al. 2005). Even for companies like General Motors, which is well-known for its flexible assembly lines, could only meet the exact specification 60% of the time (Holweg, 2004). Moreover, manufacturing flexibility can be very expensive (for frequent changeovers or buying overtime capacity, for example). In this research, a brand-new perspective to tackle the challenges in the high mix low volume production environment has been explored.

1.2. Customer flexibility

It has been observed that customers are often indifferent to some product features or certain ranges of attribute values, and they are willing to compromise certain product attributes in exchange of other ones such as price and delivery date (Lancaster 1990; Moodie and Bobrowski 1999; Wang et al. 1999). For example, a survey of 1,033 new car buyers in UK in 2000 and 2001 reports that 22% customers have accepted changes from their original specifications. As shown in Figure 1, colour and paint type was the most accepted change, followed by interior options. For the order-to-delivery lead time, the survey also reveals a wide range of customer perceived ideal lead time (Figure 2). This inherent property in customer requirements shares similar characteristics with manufacturing flexibility as they
both exhibit the adaptability and tolerance to changes. In this research, this customer behaviour is categorized as **customer flexibility**.

Figure 1  Percentage of customers accepting alternative specifications for each feature.


Figure 2  Different customers’ expectation on order-to-delivery lead time

Customer flexibility brings additional degree of freedom in fulfilling customer requirements. Intuitively, incorporating the customer flexibility in the order fulfilment process could help the company better matching the customer’s true needs with existing manufacturing resources. Consequently better customer service levels will be achieved together with a better utilization of manufacturing and/or supply chain resources. To this end, this research takes a new perspective to the high mix low volume production challenges by systematic incorporation of \textit{customer flexibility}. To do this, however, we must identify and encounter the customer flexibility at the right moment when the order specifications are being confirmed, which is during the order commitment process.

\textbf{1.3. The order commitment process}

The order commitment process is carried out during the order enquiry stage. It helps the manufacturer to decide whether or not to accept a customer order, and if accepted, what due date and product specifications should be committed to the corresponding customer (Chen \textit{et al.} 2001, 2002). The ultimate goal of this process is to achieve high customer service level and low supply chain cost simultaneously through effective planning and allocation of available production/delivery resources to match customer requirements.

In traditional production systems with low product variety and high production volume, forecast-driven make-to-stock production strategy is often adopted. Consequently the conventional order commitment process makes the commitments
based on the so-called available-to-promise (ATP) quantity, where the ATP quantity is calculated based on the unallocated portion of finished products or planned production quantities maintained in master production schedules (APICS Dictionary 10th edition, 2002). However, in make-to-order/assemble-to-order production systems, the order commitment process takes a much more critical role in order fulfillment and production planning. From the resource management point of view, the process manages increased types of production resources including not only the finish-goods inventory, but also the raw materials, subassemblies, production capacity and even other type of supply chain resources (such as the logistic capacity and supplier’s capacity, etc.). From the system’s planning hierarchy point of view, the order commitment process is a customer demand management process and a short term production planning/scheduling process at the same time, because in a make-to-order/assemble-to-order production system it would be impossible to provide promising commitments (regarding the order due date, quantity and product specifications) if without a careful planning and allocation of various production resources. As shown in Figure 3, the order commitment process in many make-to-order/assemble-to-order (MTO/ATO) manufacturing firms serves as an interface between the firm and its customers. When receiving customer order requests, the order commitment process looks into the resource available-to-promise in both finish-goods, materials and production capacities, based on which it confirms order specifications with customers and updates production plans and master production schedules at the same time. The characteristics and functionality
of the order commitment process makes it extremely critical in make-to-order production, and most appropriate for the identification and incorporation of customer flexibility.

![Figure 3 Order commitment process in MTO/ATO systems](image)

**1.4. Research objective**

To this end, the objective of this research is to integrate customer flexibility in the order commitment process that will best match customers’ needs with manufacturing resources and capabilities in high mix low volume production. Specifically, the results of this research include a systematic approach to characterize and measure customer flexibility, and an effective order commitment model that integrates customer flexibility to commit order specifications that best match customer’s requirements with available manufacturing resources.

**1.5. Relevance and Significance of Research**
The ultimate goal of this research is to help manufacturing enterprises find effective solution to improve service level and reduce cost in the dynamic high mix low volume production environment. Towards this goal, we set our focus on customer flexibility and its integration in the order commitment process, which we believe is an important but often neglected aspect in order management practices and literatures. In conventional order commitment approaches, customer order specifications are often assumed to be completely given and fixed. The scope of order commitment is then limited to the planning and allocation of supply chain resources to meet fixed specifications. With the concept of customer flexibility however, a brand-new perspective can be explored to address this problem, which enables a holistic consideration of flexibility from both demand and supply. Potentially, customer flexibility can complement manufacturing flexibility for achieving high level of customer satisfaction without compromising manufacturing efficiency and costs. Alternative solutions can be found to fully utilize various types of manufacturing resources (including finish-goods, WIP, raw material and production capacity) throughout the production pipeline. These are the potential benefits that will never be possible if the focus is restricted to the supply side only.

1.6. Research challenges and methodology

In order to fully integrate customer flexibility in order commitment process, there are important research issues to be addressed:

- How to characterize and quantitatively represent customer flexibility?
How to integrate customer flexibility in order commitment process?

To address the above research issues, the order commitment system has to confront several technical challenges, namely:

(1) Ambiguity and complexity in customer flexibility characterization

In order to integrate customer flexibility in order commitment process, customer flexibility needs to be characterized and formally represented. Characterizing flexibility has always been a challenging research issue due to its conceptual ambiguities and multi-dimensional character (Sethi and Sethi 1990). The customer flexibility is a relatively new concept which, compared with manufacturing flexibility, is even more difficult to characterize and measure since it is inherent in the customer requirements and often hidden from the manufacturer. In order to accurately characterize and represent customer flexibility, it is important to consider individual order attributes, but also the customer preference and tradeoffs among multiple attributes. With higher product variety and complicated production configurations, the complexity increases rapidly.

(2) Complexity in connecting customer flexibility with manufacturing flexibility

Customer flexibility reflects customer requirements in terms of preferences and constraints defined in customer domain. On the other hand, manufacturing flexibility, particularly mix and volume flexibility are often characterized by different ranges and levels of process capability and capacity among various production resources (Shewchuk and Moodie 1998). Consequently, the interrelationship and alignment
between customer flexibility and manufacturing flexibility is inherent in the mapping relations across customer requirements, product design, manufacturing process and resource capability, which involves many intertwining factors and constraints in different domains. Synchronizing the flexibility from both sides to achieve high level of matching between customer requirements and manufacturing capabilities is a very challenging and complex planning task.

To address the research challenges, the following research methodology is proposed as illustrated in Figure 4. The research starts with literature reviews of existing approaches on customer preference modeling, flexibility characterization and order commitment, which lead to the fundamental approaches applied in this research. In the second stage, the concept and representation model for customer flexibility is developed. Order commitment models with integration of customer flexibility and manufacturing flexibility are then developed. The research is then verified through industrial case studies. The interrelationship between customer flexibility and manufacturing flexibility is also analyzed through the case study and simulation analysis, from which managerial insights are derived.
1.7. Research scope

The research is mainly focused on single manufacturing system with build-to-order (particularly assemble-to-order) production mode, since in high mix low volume production this is the most cost-effective production strategy. Due to the short planning horizon often incorporated in the order commitment process, it is assumed that existing product family designs are used instead creating new designs for specific customer requirements. In this research, our discussion of manufacturing flexibility will mainly be focused on operational types, namely, volume and mix flexibility. Flexibility types such as new product flexibility and expansion flexibility are important for strategic level planning and system designs, but not relevant to the short term resource planning and order management as focused in this research.

1.8. Organization of the thesis
The thesis is organized based on the above mentioned research framework. In the current chapter we presented the background and identified the relevance and significance of this research. Based on that, we set our research objective and scope and further identified the challenges in accomplishing the research objective. The research framework and tasks were then outlined in the later part of this chapter.

In Chapter 2, relevant literature review has been conducted which emphasized in three related areas. First of all, the literature review is focused on the research area in customer behavior study and customer preference modeling, which is mainly in the marketing research areas. The approaches for quantitative measuring of customer preference and satisfaction are summarized, which is served as a foundation for approach developed to model customer flexibility in this research. Secondly, the existing methodologies to characterize and measure manufacturing flexibility are reviewed. The review helps to understand the nature of flexibility in general, and identifies common characteristics of flexibility in both manufacturing domain and customer domain, which helps us to derive appropriate measures for customer flexibility characterization. In the third part of the review, the state of the art of currently available order commitment approaches is reviewed.

In Chapter 3, the approach to customer flexibility characterization and representation is presented. Two flexibility dimensions, namely Range and Response, are identified for effective characterization of customer flexibility. Based on the two dimensions, quantitative measurements and representation models are
developed for customer flexibility. Particularly, the utility-based customer preference functions are used for the measurement of customer’s satisfaction towards different order configurations, from which the flexibility response can be derived. Methods to obtain critical parameters for accurate customer flexibility formulation are presented in the latter part of the chapter, which is based on customer grouping (based on empirical or historical data) and the establishment of customer flexibility profiles.

In Chapter 4, the approach to integrate customer flexibility in the order commitment process is outlined. Customer requirements and the inherent flexibility are first mapped into manufacturing resource requirements based on product and process variety structures. A generic representation model (a flat Generic Bill-of-Material and Operations structure) is employed to organize the mapping information in a compact form, and to facilitate linear integer modeling of all resource requirements and product configuration constraints. A Mixed-Integer-Programming model for single order commitment is then developed, in which both the customer flexibility and manufacturing flexibility are incorporated as constraints. The model takes a rather generic form so that it can be extended to suit for different production system settings. An extension of the model, which makes order commitments over multiple customer requests are presented.

In Chapter 5, the overall approach is validated with a case study in the Garment industry. The customer flexibility is first characterized based on the approach
proposed in this research. Simulation studies are carried out to analyze the sensitivity of system performances in relation to different system inputs, such as demand rate, product mix, and different levels of customer/manufacturing flexibility. The interactions between customer flexibility and manufacturing flexibility with regards to the impacts on system performances are analyzed based on simulation results. It has been demonstrated that a better positioning of manufacturing flexibility together with a proactive management of customer flexibility can help the manufacturer better shape the manufacturing capability and customer demand, so that to achieve improved demand-supply matching in the high mix low volume production environment.

Finally Chapter 6 summarizes the conclusions and research contributions. It also suggests directions for further research.
CHAPTER 2
LITERATURE REVIEW

The purpose of literature review in this research has two folds. One is to understand the current state-of-art of research in related areas and identify gaps which this research is positioned to fill. Second, the review also identifies potential problem solving approaches and modeling techniques which can be applied to this research.

2.1. Research on customer preference

In marketing research, customer preference is characterized as customer’s valuation to different attributes or alternative products/services. Customer preference models are widely used for understanding customer satisfaction structures to facilitate product/service design, to predict customer’s purchasing and browsing behavior in e-commerce, or to deliver product customizations (Murthi and Sarkar 2003).

For example, Bulter, et al. (2007) presents the potential applications of multi-attribute preference models (MAPM) in e-commerce. MAPM are methodologies for modeling complex preferences that depend on multiple attributes, which include multi-attribute utility theory, conjoint analysis, and the Analytic Hierarchy Process. In their study, they present different MAPM approaches to show how individual’s preferences may be assessed in existing websites. Some guidelines for MAPM implementation are then followed. Keen, et al. (2004) presents a conjoint analysis approach to investigate the structure of consumer preferences on product purchasing through different retail formats. Du, et al. (2006) proposes a
customer value analysis approach to understand customer preferences for various product features and facilitate the company’s justification of different product customization solutions. Adaptive conjoint analysis is employed to capture the utility function of product quality with respect to many product features.

In other papers, customer preferences are analyzed and used to give recommendations for products and services. Recommendation systems are expert systems which allow companies to offer customized solutions. For example, Shih and Liu (2007) propose a product recommendation system that uses customer demand information derived from past purchasing preference of similar customers. Ansari, et al. (2000) describes a Bayesian preference model that allows statistical integration of five types of information useful for making recommendations: a person's expressed preferences, preferences of other consumers, expert evaluations, item characteristics, and individual characteristics. Weng and Liu (2004) propose a recommendation system in which clustering techniques are used based on transaction records and product feature databases. The system finds customers that have similar interests as target customers and recommend products to fit customers’ potential requirements.

In view of the literature related to customer preferences, the primary focus is on maximization of overall customer satisfaction in relation to different features or attributes through the suggestion of appropriate products or services. In terms of modeling, most of the related works use multi-attribute utility-based measurements
to represent customer preference as a function of different product characteristics/features.

2.2. Research on manufacturing flexibility characterization

Manufacturing flexibility is widely recognized in both academia and industry as being of crucial importance in manufacturing (Shewchung 1999). It is being considered as the ability to continue functioning effectively regardless of changes or as the ability to change and adjust the production to new circumstances (Kara, 2004). Over years, many researches have been undertaken to conceptualize and characterize manufacturing flexibility.

In analysing flexibility, most of the authors view flexibility as a multi-dimensional concept. Slack (1983) identified range and response as the two main dimensions of manufacturing flexibility based on a survey of ten manufacturing organizations. Range refers to the number of different positions, or alternative options; response corresponds to the “ease of movement” and can be measured in terms of cost or time. Upton (1994) defines range, mobility and uniformity as the three distinct dimensions of flexibility. The idea behind the range and mobility is similar to that of proposed by Slack (1983), while uniformity refers to the consistency of a performance measure (such as yield or quality). Cheng, et al. (1997) presents a “capability and capacity” approach to interpret and integrate various types of flexibility throughout the manufacturing system. Three flexibility indices are used to characterize the flexibility of a manufacturing system, namely: diversity, response and volume. The
concept of diversity and volume can be viewed as the range dimension represented in capability and capacity respectively. Gupta (2004) also employs range and response as two major dimensions of flexibility, and proposes four flexibility descriptors, namely capability range, capability response, capacity range, and capacity response, for manufacturing flexibility characterization in various system levels. In view of all the authors, range and response seems to be the common dimensions to characterize the flexibility in the system.

2.3. Research on order commitment approaches

In recent years, with the trend of product proliferation and the corresponding shift from make-to-stock (MTS) to make-to-order (MTO) production, it is gaining increasing attention on customer order management processes. Especially on the order quotation and commitment during the customer enquiry stage, a growing number of research works are emerging.

(1) Lead time (due date) estimation for order commitment

Some early work considers order due date assignment together with production scheduling using some highly simplified lead time estimation equations. For example, CON assigns a constant for the due dates of all jobs; SLK are defined as processing times (or processing times and release dates) plus a common slack time for all jobs; the TWK due dates are defined as a multiple of processing times. There are many others such as JIQ and WIQ. Recently Gordon (2002) put up a survey which summarizes most of the due date assignment and scheduling approaches for
single-machine job shops. For more realistic multi-machine manufacturing systems, statistical models are used to estimate lead times and set order due dates. For example, Hendry et al. (1992, 1993) apply work load control concept to predict order due dates and generate order acceptance and job release decisions accordingly. Lawrence (1995) assigns due dates by estimating order flow times using six lead time estimators. Hopp and Sturgis (2000) combine factory physics, statistical estimation and control charting to create a lead time estimator that is generally applicable in different manufacturing companies regardless the details in production process and resource information.

However, most of the due date assignment and lead time estimation approaches assume that order due dates can be endogenously assigned by the manufacturer without considering customers’ preferences. This does not reflect the true characteristics of customer flexibility in practice. Further more, there are hidden assumptions in those due date estimation approaches such as stable production throughput and product mix, and unlimited capacities in the system. These assumptions are generally acceptable for job scheduling problems under high volume production, but are less applicable for high mix low volume make-to-order environments.

(2) Available-to-promise for MTO

Recently, developments on order commitment approaches propose various models and algorithms to generate reliable order commitments by matching customer
requirements with available manufacturing resources. These models are often referred as Available-to-Promise (ATP) models (Pibernik, 2005). ATP in traditional mass production environment simply means the uncommitted portion of end product inventory or scheduled productions maintained in master schedules (APICS Dictionary 10th edition, 2002). However, under make-to-order environment, more sophisticated models are required for ATP to manage various types of resources for reliable order commitment.

Xiong et al. (2003) develop a dynamic BOM (bill-of-materials) generation technique to calculate the available quantity of a particular product variant for reliable order promising. Taylor et al. (1999) propose effective mechanism to calculate available production capacities (called “capacity-to-promise”, CTP) based on existing production schedules. Jeong et al. (2002) further apply the CTP calculation technique to an order promising system developed for an LCD manufacturing supply chain.

Others develop optimization models for order commitment that not only decide a list of orders to be promised, but also specify the resource allocations and determine the master production schedules. Chen et al. (2001, 2002) and Zhao et al. (2005) develop mixed-integer-programming models for order commitment systems operating in a batch mode. Their discrete-time models consider material and aggregate production capacity constraints to compute promises in terms of quantity and due date for a batch of customer orders that arrive within a predetermined time
interval (batch-interval). Özdamar and Yazgac (1997) focus on firm’s capacity constraints and develop linear capacity planning model for order due date settings. Jung et al. (2003) propose an order promising system in global supply chain environment based on a linear programming model, in which aggregated capacity in various departments (such as warehouse, transportation and factory) are used for order commitment. Pibernik (2005) summaries many of the ATP systems classified by three problem characteristics: “resource availability” (regarding the scope and type of manufacturing resources), “operating mode” (regarding the commitment response time to customer), and the “interaction with production execution”. Based on the classification, the author also presents order commitment mechanisms for two generic ATP system types.

2.4. Literature summary

Based on the above review of published literatures, the following conclusions can be drawn:

Customer preference models are widely adopted in marketing research in measurement of customers’ overall satisfaction in relation to multiple product features/attributes. Despite the systematic modelling of customer’s valuation in multi-attribute decision making, the adaptability and tolerances in customer requirements are not reflected in customer preference models.

Manufacturing flexibility effectively enhances the system’s adaptability to demand uncertainties. Lots of efforts have been made in order to characterize and measure
flexibility. As a multi-dimensional concept, Range and Response are the commonly agreed dimensions in characterizing manufacturing flexibility. However, the primal discussion of flexibility still limits itself on the supply side.

Most existing order commitment approaches put emphasis on supply side resource allocation and production scheduling in meeting predetermined order specifications. From the demand side, it is generally assumed that all order specs, particularly product specifications, are specifically defined. Very few have incorporated the adaptability or tolerances in customer demand to alternative product specifications and delivery schedules.

Overall, there is a lack of systematic approach to extend the flexibility concept into customer domain, and to address the order commitment problem from both supply side and demand side.
CHAPTER 3
CUSTOMER FLEXIBILITY CHARACTERIZATION AND REPRESENTATION

3.1. Customer flexibility characterization

In chapter 2, different approaches to characterize and measure manufacturing flexibility are reviewed. Customer flexibility as the term suggests, share a lot of common properties with manufacturing flexibility. First of all, similar to manufacturing flexibility, customer flexibility is an inherent property in customer requirements which contains potentials. The potential that customer would like to accept alternative order configurations. Secondly, customer flexibility also exhibits a multi-dimensional character, as customers not only may appreciate a set of alternative options, but also have their valuation on different order configurations which exhibit their tolerance or adaptability in their requirements. As Simon (1996) points out: customers are often “sufficers” instead of “optimizers”, this new concept avoids narrowed decision making purely on customer preference maximization, but take the opportunity from customer’s willingness of making tradeoffs to maximize or balance both the manufacturer’s and customer’s interest.

From this perspective, we define customer flexibility as the customer’s indifferences or tolerances to certain order attributes such that any order configuration (combination of different attribute levels) within the customer acceptable range would not affect or have little impacts on customer satisfaction. Following this

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definition, customer flexibility can be characterized through two dimensions, namely: Range and Response.

**Customer Flexibility Range (CFRG)** refers to the total scope of different order configurations that a customer would accept as an order commitment solution. This could include a range of product variety and delivery time windows as well as an acceptable range of order quantity and price. Taking the computer product as an example: suppose the company offers three types of CPUs, 1.2GHz, 1.5GHz and 2GHz. If one customer wants a new PC with CPU speed no slower than 1.5GHz, then the CFRG on CPU is 1.5GHz and 2GHz for this particular customer request. The CFRG describes a “hard constraint” on order configuration, that is, any commitment solutions that fall outside the CFRG would not be accepted by the customer.

On the other hand, **Customer Flexibility Response (CFRP)** reflects the sensitivity of customer satisfaction in response to changes in order configuration. As industrial practice suggests that customer preference is often beyond the accept/reject answers, and it is common that customer would perceive different degree of satisfaction towards different order commitment solutions within the acceptable range. For example, it is possible that a customer would accept the order due date to be within a certain time window, but earlier the better (better satisfaction level). Having the Response dimension of customer flexibility would help the manufacturer to capture the sensitivity in customer flexibility. In addition, with the Response dimension
defined, it would be much easier to explain and model the trade-offs that customers are often encountered with, for example: “what will be a satisfactory price discount if I accept to receive my order one week later?”

Based on the two customer flexibility dimensions, quantitative models are developed in the next section to represent customer flexibility.

3.2. Customer flexibility representation

In general, a customer order request contains four aspects of requirement information, namely: order quantity, delivery schedule (i.e. due date), product specification and pricing requirements (e.g. the budget constraint, discount or premium that customer is willing to take on the product price). It can be generally assumed that customer flexibility could be inherent in any of these aspects. The representation of customer flexibility is based on the four basic elements.

3.2.1 Representation of Customer Flexibility Range (CFRG)

Based on customer’s order request, a set of customer preferred options can be identified for different order attributes. Let $D$, $Q$, $P$ and $A$ denote the set of options in due date, order quantity, price and product specification, respectively. Then the CFRG can be represented as:

$$D = \{d \mid d \in [de, dl]\}$$

$$Q = \{q \mid q \in [ql, qu]\}$$

$$P = \{p \mid p \in [pl, pu]\}$$
\[ A = (a_1, a_2, ..., a_n)^T, \text{ where } a_k = \{v_k \mid v_k \in V_k\} \]

In the above representation, \(de\) and \(dl\) denote the earliest and latest due date required by customer. \(ql\) and \(qu\) are the lower and upper limit of order quantity. \(pl\) and \(pu\) are the lower and upper bound for the price discount levels. Note here, besides due date, quantity and price are single-attribute sets, the product specification \(A\) is a multi-attribute supper set which is constituted from a set of product attributes, denoted by \(a_1, a_2, ..., a_n\); each attribute contains a set of different options specified by the set \(V_k\) (for some product attributes, customer may specify a specific attribute level, and in such case, \(V_k\) contains only a single value). In many business environments, it is usually the case that manufacturer would provide a standard set of product attributes for customers to specify their desired product specification by defining/selecting attribute levels. Therefore in this study it is assumed that there is a fixed number of predetermined attributes for customers to specify their range of levels for each attribute. In many industrial scenarios, product attributes contain limited number of levels (options), and therefore it is practical to represent product attributes in discrete format, such as: \(a_k = \{a_{k1}, a_{k2}, ..., a_{km}\}\).

3.2.2. Representation of Customer Flexibility Response (CFRP)

In order to measure customer flexibility response, it is required to quantify the customer satisfaction in relation to different order configurations. This research applies a utility-theory-based preference measure to describe customer satisfaction and derive customer flexibility response in relation to different order attributes. The
utility-based customer preference modeling is commonly used in marketing research (Thurston 1991, Chen and Yuan 1999). A preference function of a particular order attribute is a function defining the degree of satisfaction in terms of utility upon different options of an order attribute. Let \( U_s(\Lambda_s) \) denotes the general expression of a preference function for any order attribute. In general, the preference function may possess various types of forms depending on the customer’s utility on certain attributes, and it is convenient to scale each of the preference functions from zero to one, where higher values represent more preferable choices. Examples of different preference functions are shown in Figure 5. In practice, it is more often that discrete forms of preference functions are used as customers are often provided with discrete options in different order attributes.

![Preference functions for different order attributes](image)

Figure 5 Preference functions for different order attributes

(a. due date preference function;   b. order quantity preference function

c. price preference function;   d. product attribute preference function)

Based on the preference functions defined for each order attribute, we can measure the customer’s overall satisfaction upon a combination of different attribute values. As additive preference functions are commonly accepted in literatures (Bichler and Kalagnanam 2005), the overall customer preference can be modeled by aggregating
the preference functions of all order attributes into a single, overall utility measure, which can be formulated as:

\[ U = w_d U_d(d) + w_q U_q(q) + w_p U_p(p) + \sum_{k} w_k U_k(a_k) \]

where \( w_d + w_q + w_p + \sum_{k} w_k = 1 \)

In the above representation, we denote the preference functions for different categories of order attributes by separate notations, namely, \( U_d(d) \), \( U_q(q) \), \( U_p(p) \), and \( U_k(a_k) \) (\( k = 1, 2, ..., n \)) for due date, quantity, price and product attributes, respectively, and \( w_d, w_q, w_p, w_k \) are the weights assigned to different attributes.

The CFRP can be derived based on the overall utility measure. As CFRP is defined as the sensitivity of customer satisfaction in response to changes in different order attributes, it can be represented by the partial derivatives of the overall utility on particular order attribute, such as:

\[ CFRP_{\Lambda} = \frac{\partial U}{\partial \Lambda} \] (1)

Where \( \Lambda \) is a particular order attribute, which can be either \( d, q, p \) or \( a_k (k = 1, 2, ..., n) \).

Note here the assignment of appropriate weights is critical to the representation of customer flexibility response. There are many well established approaches for assigning reasonable weights for additive multi-attribute preference model, but they
all should be consistent with the results obtained from tradeoff judgments (Keeney and Raiffa 1993). One approach is to list out several trade-off statements to form a set of indifferent equations. The solution of these linear equations gives the weights. For example, we may consider the trade-off between price and due date and found two indifferent configurations: (one-day delivery, 100% price) and (two-day delivery, 95% price). Let us use \((d_1, p_1)\) and \((d_2, p_2)\) to represent the two configurations respectively, therefore we have:

\[
wpU_p(p_2) + wdU_d(d_2) = wpU_p(p_1) + wdU_d(d_1)
\]  

We may find other trade-offs for other attributes so that several equations like the above can be obtained. Given the preference functions of all single attributes, we can solve the linear equation set to obtain the weights. There are other ways to determine weights, such as conjoint analysis (Luce and Tukey 1964) and Analytic Hierarchy Process (AHP) (Dyer 1990), which applies statistical techniques for weight determination under more complicated situations. In the case of AHP, the key principle is based on the mathematical structure of consistent matrices and their associated right-eigenvector’s ability to generate true or approximate weights.

The above discussion assumes the independency among order attributes as it preserves the linearity and additive form of the constraints. Interaction effects among attributes although relevant in many scenarios are often neglected in real-world implementations (Keeney and Raiffa 1993; Bichler and Kalagnanam 2005), since the notion of interaction among attributes is one of the most difficult
concerns in utility theory and multi-criteria decision making. One potential approach is to construct artificial attributes whose levels represent the cross product of the interacting attributes. For example, suppose we have two interacting attributes, namely, “interior color” and “exterior color”, each with 2 levels: red and blue. If the customer prefers a consistent color theme, the two attributes are dependent, as the utility of interior color depends on the selection of exterior color, and vice versa. In this case we could remove the interaction by combining the two interacting attributes into a new attribute named “color” with 4 levels (red-red, red-blue, blue-red, blue-blue). As long as the number of levels and the number of dependent attributes is small this is a fairly effective approach.

**Customer tradeoffs constraints**

In many cases, the customer’s indifference often involves multiple order attributes, and the insufficiency of one order attribute could be compensated by the gain in other order attribute(s). This relationship is commonly expressed as the trade-offs. For example, customer would consider a one-day delivery at full price and a two-day delivery at 5% price discount as indifferent offers (same level of satisfaction). In this case, trade-off relations can be established between the two order attributes. Figure 6 shows a typical trade-off curve between two order attributes for a particular customer. Any point (each point represent a particular order configuration) on the same curve is considered indifferent by the customer. In fact, customers usually have minimum requirements on their trade-offs. For example,
a customer would require at least 5% price discount for a one-day-delay in due date. With the customer preference functions and the formulation of customer flexibility response, the trade-off constraints can be represented as:

$$\sum_g w_g U_g (\Lambda_g) \geq \mu_r$$  \hspace{1cm} (3)

In the above inequality, $U_g (\Lambda_g)$ represents the customer preference function of a particular order attribute $g$ which is involved in this trade-off constraint. Here in order to simplify the notation, we use $\Lambda_g$ to denote all types of order attribute, which can be the due date $d$, price $p$, order quantity $q$ or product attribute $v_k$, and use a generic index $g$ for indexing. $w_g$ is a weight assigned to order attribute $g$ involved in the particular trade-off consideration, which is normalized so that $\sum_g w_g = 1$. $\mu_r$ is a constant which specifies the minimum preference level in this tradeoff constraint $r$. If all order attributes take discrete levels, then the inequality can be written as:

$$\sum_g w_g \sum_j u_{gj} \tilde{x}_{gj} \geq \mu_r$$  \hspace{1cm} (4)

Where $\tilde{x}_{gj}$ is a binary variable indicating the selection of attribute levels ($\tilde{x}_{gj} = 1$ if option $j$ of attribute $g$ is selected and 0 otherwise).
CFRG and CFRP are two important dimensions of customer flexibility, which represents the complete profile of customer preferences, tradeoffs and tolerances. In this research, both dimensions are represented based on customer utility models. The representation of Customer Flexibility (in both range and response) can be visualized graphically as a hyper-dimensional surface. Figure 7 shows an example with two order attributes in which a three-dimensional surface can be plotted. In the graph, customer flexibility range is shown as colored regions located at different heights in three-dimensional space. Different heights actually represent different customer satisfaction, which reflect the response of customer flexibility.
Comparison between customer flexibility and manufacturing flexibility

Table 1 shows a comparison of the characterization between manufacturing flexibility and customer flexibility. As discussed in the literature review, range and response are two widely accepted dimensions for manufacturing flexibility. Similarly, range and response are also used in the characterization of customer flexibility with identical meanings. This helps establishing the consistency for flexibility characterization across different domains, which eases the interconnection between customer flexibility and manufacturing flexibility to facilitate matching between customer requirements and available production resources.

Table 1 Comparison of manufacturing flexibility and customer flexibility

<table>
<thead>
<tr>
<th>Elements</th>
<th>Manufacturing flexibility</th>
<th>Customer flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capability</td>
<td></td>
<td>Due date</td>
</tr>
<tr>
<td>Capacity</td>
<td></td>
<td>Quantity</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Range</td>
<td>Price</td>
</tr>
<tr>
<td></td>
<td>e.g.</td>
<td>Product specification</td>
</tr>
<tr>
<td>Process cap</td>
<td>Ø40, Ø60, Ø80</td>
<td></td>
</tr>
<tr>
<td>body color</td>
<td>{red, yellow}</td>
<td></td>
</tr>
</tbody>
</table>
3.3. Practical remarks for customer flexibility modeling

The above sections illustrate how to establish customer flexibility representation model based on the customer preference function and overall utility measurements. The accuracy of the customer flexibility model directly affects the quality of order commitment decisions, and therefore impact on the company’s service quality and profit. In practice, in order to ensure the accuracy of customer flexibility modeling, appropriate working procedures need to be designed. In this section, some practical remarks are proposed and discussed.

3.3.1 Choosing the right order attributes

In high mix low volume production, products normally contain many attributes. For example, a desktop computer can have many attributes including CPU, memory, hard disk, operating system (OS), display card, etc. If every product attribute is incorporated in the modeling of customer flexibility, the model would be extremely complex and it is difficult to obtain accurate estimation of customer utility measures. Simplification and selection of appropriate attributes is important. In general, not every order attribute is necessary to be incorporated in the customer flexibility modeling. During the modeling process, we need to select the most critical order attributes. The criteria to select critical order attributes are based on the mapping
relationship between customer flexibility and manufacturing resource flexibility. Figure 8 categorize different order attributes into four types, based on their relationship with customer requirements and manufacturing resources. The Type I and Type III attributes are located in the high sensitivity zone in customer requirements. This means customers are very inflexible on these order attributes (i.e. they are very sensitive to any changes in the attribute values). In this case, it is not necessary to incorporate Type I and Type III attributes in the customer flexibility model. On the other hand, some order attributes have minor impacts on the requirements of manufacturing resources. In the below figure these attributes are categorized as Type I and Type II attributes. This means no matter how flexible the customer is regarding these order attributes, the required resource is more or less the same and therefore it does not affect the resource allocation and order commitment decisions. In the customer flexibility model these attributes can be ignored too. Therefore, only the Type IV attributes are critical to the customer flexibility modeling. These are the order attributes which has significant impacts on manufacturing resource requirements (resource-sensitive attributes), and at the same time, customer is insensitive to the attribute value changes.
3.3.2 Customer flexibility profile

The characterization of customer flexibility requires thorough understanding of customer preferences and behavior. In order to ensure the accuracy of customer flexibility modeling, a method is proposed based on the grouping of customer with similar preferences and the establishment of customer flexibility profile.

In practice, customers often share similar requirements and preferences. For example, some customers are very cost sensitive; others are averse to waiting and/or are picky on specific product configurations. Based on the similarities in their requirements and preferences, customers can be categorized into different groups. For each group of customers, a master customer flexibility model can be established to represent the group behavior. By applying the same technique for customer flexibility characterization introduced in previous section, the master customer
flexibility model can be characterized by range and response dimensions. In this thesis, we call such master model the **Customer Flexibility Profile (CFP)**.

Generally speaking, the CFP is an aggregated model of customer flexibility for a group of customers with similar preferences. In order to accurately define a CFP, the following process flow (see Figure 9) can be used in an order commitment system to gradually improve the modeling accuracy of customer flexibility through historical order data and customer’s feedback regarding alternative commitment solutions.

![Figure 9: The learning and refinement of customer flexibility profile](image-url)

Figure 9: The learning and refinement of customer flexibility profile
CHAPTER 4
CUSTOMER FLEXIBILITY INTEGRATED ORDER COMMITMENT PROCESS

Order commitment in general can be viewed as a searching process that finds the best match between customer requirements and available production resources. In order to fully integrate customer flexibility and manufacturing flexibility in the order commitment decision making process, firstly it is required to transform customer requirements and its flexibility, characterized by range and response, into the requirements of manufacturing resources in terms of materials and production processes. Optimization model can be developed to match resource requirements with flexible production resources by conducting order configuration, resource allocation and production scheduling at the same time.

4.1. Mapping customer requirement with manufacturing resources

In today’s high variety business, fulfilling diverse customer needs through assemble-to-order or configure-to-order production based on existing product family structure and modular designs is a widely adopted manufacturing strategy. To this end, we mainly focus on the assemble-to-order production and assume the product family design is given and remained stable within the planning time horizon of order commitment (in practice, this planning horizon is relatively very short, depending on the industry nature, it is normally about two weeks to 2~3 months).
In order to make a feasible and reliable commitment, customer order specifications need to be transformed into the requirements in production materials and processes for matching with the manufacturing resources and capabilities. This is often called a Mapping process. Given the product family structure, detailed mapping relationships between product attributes and bill-of-materials (BOM) and processing requirements can be obtained from the company’s Product Data Management System (PDM). When incorporating customer flexibility, the mapping is not dedicated to one particular product variant and its corresponding bill-of-materials and production processes. Instead, there could be a number of alternative mapping solutions for a single customer order. With the increasing product/process variety, the formulation of the order-resource mapping could be very complicated.

For this reason, a compact data model is required to represent the material and process requirements for mapping customer flexibility. In this research, by implementing the “generic” concept (Jiao, 2000), a tree structure product model is used to accent commonality and reduce modeling complexity. As shown in Figure 10, there are two types of generic items in the tree structure, namely generic components/modules (denoted by $X_i$) and generic process (denoted by $Y$). One or several instances are attached to each generic item (indicated by $x_{kj}$ and $y_r$ for component instances and process instances, respectively. $x_{kj}$, $y_r$ = 1 if the particular instance is selected, and 0 otherwise), which represent different alternatives of components, modules or processes. Note that this generic structure is a simplified version of the GBOMO (Generic bill-of-materials and operations)
structure, which is proposed by Jiao et al. (2000). In an assemble-to-order manufacturing system however, this flat tree structure is sufficient for representing all the material and process requirements for accurate order commitment decisions.

![Diagram showing the generic BOM and process structure for flexible customer order configuration]

**Configuration constraint handling**

There are a number of important constraints that have to be modeled explicitly in an order commitment model. Typically they can be categorized as product configuration constraints and process configuration constraints.

Product configuration constraints basically specify the selection rules for different component alternatives. For example, a compatibility constraint (which is one of the
most common type of configuration constraints) can be written as “if \( \tilde{x}_{11} \) is chosen, then \( \tilde{x}_{23} \) cannot be selected”.

Process configuration constraints on the other hand specify the mapping relationship between product configuration (selection of components) and process requirements. For example, one could find a constraint written as “process \( \tilde{y}_1 \) should be used if and only if component \( \tilde{x}_{11} \) is chosen”.

In general, all configuration constraints can be represented by logical expressions. Formally, let us use “\( \Rightarrow \)” to represent the Logical Implication, i.e. “IF-THEN” relation, and use “\( \Leftrightarrow \)” to represent the Logical Equivalent, i.e. “IF-AND-ONLY-IF” relation. Further more, some other logical operators such as “\( \neg \)” (NOT), “\( \land \)” (AND) and “\( \lor \)” (OR) can also be used when necessary. With these expressions, the above two examples can be written as:

\[
\tilde{x}_{11} \Rightarrow \neg \tilde{x}_{23} \quad (5)
\]

\[
\tilde{x}_{11} \Leftrightarrow \tilde{y}_1 \quad (6)
\]

In order to obtain an equivalent mathematical representation for all the logical expressions, one must first consider these basic logical operators to determine how each can be transformed into an equivalent representation in the form of a linear equation or inequality. Raman and Grossman (1991) specify transformations, which can then be used to convert general logical expressions into an equivalent
mathematical representation. Some of these transformations are described in Table 2 (all variables are binary indicators, which equals 1 if the particular item is chosen).

Table 2 Representation of logical relations with linear inequalities

<table>
<thead>
<tr>
<th>Logical relation</th>
<th>Pure logical expression</th>
<th>Representation as linear inequalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logical “OR”</td>
<td>$\tilde{x}<em>{11} \lor \tilde{x}</em>{21} \lor \tilde{x}_{31}$</td>
<td>$\tilde{x}<em>{11} + \tilde{x}</em>{21} + \tilde{x}_{31} \geq 1$</td>
</tr>
<tr>
<td>Logical “AND”</td>
<td>$\tilde{x}<em>{11} \land \tilde{x}</em>{21}$</td>
<td>$\tilde{x}<em>{11} \geq 1 ; \tilde{x}</em>{21} \geq 1$</td>
</tr>
<tr>
<td>Implication ($\Rightarrow$)</td>
<td>$\neg\tilde{x}<em>{11} \lor \tilde{x}</em>{21}$</td>
<td>$1 - \tilde{x}<em>{11} + \tilde{x}</em>{21} \geq 1$</td>
</tr>
<tr>
<td>Equivalence ($\Leftrightarrow$)</td>
<td>$(\neg\tilde{x}<em>{11} \lor \tilde{x}</em>{21}) \land (\tilde{x}<em>{11} \lor \neg\tilde{x}</em>{21})$</td>
<td>$\tilde{x}<em>{11} = \tilde{x}</em>{21}$</td>
</tr>
</tbody>
</table>

Following this procedure, the first constraint in the above example can be converted into pure logical expression as “$\neg\tilde{x}_{11} \lor \neg\tilde{x}_{23}$”, which can then be represented as the following linear inequality:

$$\tilde{x}_{11} + \tilde{x}_{23} \leq 1$$ (7)

Where $\tilde{x}_{kj}$ are binary indicators which equals to 1 if the component instance $j$ in generic component $k$ is selected, and 0 otherwise.

4.2. Incorporating manufacturing flexibility

In assemble-to-order production systems, it is often the case that a set of parallel assembly lines are installed. Each production line is capable of performing a number
of production processes, which makes it capable of producing a range of product variants. This characteristic resembles the mix flexibility of the manufacturing system (Sethi and Sethi 1990). As shown in Figure 11, the left hand boxes represent production lines and on the right hand side are different process instances. The directed arrows linking the production lines and process instances represent the capabilities of different lines. As it is possible that different lines could perform the same process in different speed, therefore an efficiency factor is attached to each link.

![Figure 11 Production line capability profile](image)

The interconnection between Figure 10 and Figure 11 establishes the mapping between the customer flexibility and the mix flexibility in the manufacturing system.

Moreover, also considered in this paper is a capped overtime capacity, which enables the system’s volume flexibility.

### 4.3. Mixed-Integer-Programming model formulation

In this section mixed-integer-programming models are developed for the order commitment process. These models incorporate both customer flexibility and
manufacturing flexibility, and provide optimal decisions on product configuration, resource allocation and due date assignment, which maximize customer satisfaction and minimize manufacturing costs.

There are basically two types of mode for conducting order commitment, namely real-time mode and batch mode order commitment (Pibernik, 2005). For real-time mode order commitment, a customer order request is processed immediately after it is received by the company. On the other hand, batch mode order commitment process is carried out after a certain time interval (called batch interval), when a number of new order requests are accumulated and processed together. In general, the response time in real-time mode order commitment process is much shorter than the batch mode. However, with more order requests being processed at the same time, the batch mode process usually performs better in resource allocation and customer service (Chen, 2002).

Two problem scenarios are considered in this section. First, a real-time order commitment problem is considered. The order commitment model is developed for single order commitment. In the second scenario, the model is extended to be able to process multiple customer orders, so that it can be used in more complicated batch mode order commitment processes.

4.3.1. MIP model for single customer order commitment

*Problem description:*
Let us consider an assemble-to-order manufacturing system with a real-time order commitment policy. As new customer order request is processed immediately once arrived, there is only one new customer order being processed by the order commitment model. Therefore this problem is called a single order commitment problem. The planning time horizon is discretized into equal length time periods (a time period is usually equal to a working day). For each time period, the component available-to-promise quantity is known for each component \((k,j)\), where \(k \in K\) denotes the generic component and \(j\) denote the component instance in the generic component. The product assembly process is carried out on a set of parallel assembly lines, denoted by set \(L\). The available capacity of each production line is also known for each time period. It is assumed that the assembly lines are treated as single production units, further detailed modeling for each workstation within the assembly line is not necessary for the order commitment planning purpose.

The customer flexibility can be characterized and represented based on the approach illustrated in the previous chapter. Let \([de, dl]\) denote the customer flexibility range for order due date (\(de\): earliest due date; \(dl\): latest due date). The customer flexibility range for different product attributes can be transformed into the ranges of alternative component instances (denoted by \((k,j)\)) for each generic component, through the mapping process illustrated in Section 4.1. On the other hand, the customer flexibility response is incorporated as the trade-off constraints in the order commitment model. Here in order to preserve linearity of the model, it is assumed
that customer has no flexibility in the order quantity (therefore the order quantity is a constant).

The mix and volume flexibility in the manufacturing system is also incorporated in the order commitment process. Each assembly line possesses multiple capabilities, which resembles the mix flexibility of the production system. Let $\pi_{rl}$ denote the process capability indicator for assembly line $l$, where $\pi_{rl} = 1$ if assembly line $l$ is capable of processing instance $r$, and 0 otherwise. It is assumed that one single order can be split and processed on multiple production lines simultaneously. On the other hand, the volume flexibility is enabled by allowing overtime capacity, which is subject to a maximum overtime cap, denoted by $OT_l$ for line $l$.

The objective of the order commitment model is to best match customer flexibility with manufacturing resource flexibility to determine the product configuration (in terms of component selection) and due date of the new customer order that maximizes the profit function. The profit function consists of the revenue part and the cost part. The order revenue is calculated based on the product configuration and price discount level, while the cost part consists of the following elements. First of all, if the order has to be rejected due to insufficient production resource, there would be a penalty cost associated with the order rejection decision. Furthermore, capacity utilization is another important performance factor in consideration. If the assembly line does not meet the minimum utilization level preset by the company, a penalty cost is incurred. (The reasons behind having the line utilization cost could
have many folds. For example, in many assemble-to-order manufacturing firms, the workers’ salaries are highly tight with the order loadings to the assembly lines. Therefore it is often required to balance the work loads or apply minimum line utilizations among different lines in order to keep up high morale and maintain high production efficiency. In other industries where expansive facilities are used in production lines, the under-utilization penalty would also be an important factor to consider.) In addition, component inventory holding cost is also considered in the order commitment model. In the following, detailed notations and MIP model formulation are presented:

**Notations and detailed formulation:**

Notations:

**Indices:**

- \( t \)  
  time period index, \( t_0 \) denotes the beginning of the planning period
- \( l \in L \)  
  production line index, where \( L \) is the set of all production lines
- \( k \in K \)  
  generic component index, where \( K \) is the set of all generic components
- \( j \in J^k \)  
  component instance index, where \( J^k \) is the set of customer acceptable component instances in generic component \( k \)
- \( (k, j) \in KJ \)  
  the \( j \)th component instance of generic component \( k \)
- \( r \in R \)  
  process instance index, where \( R \) is the set of all alternative processes required to produce the particular customer order
- \( z \in Z \)  
  price discount level index, where \( Z \) is the set of all possible discount levels for this customer order

**Constants:**

- \( Q \)  
  order quantity
- \( B_{kj} \)  
  required number of instance \( j \) of generic component \( k \) to produce one unit of final product
- \( S_{kij} \)  
  scheduled material delivery for
- \( \alpha_{kj} \)  
  unit component price for instance \( j \) in generic component \( k \)
- \( \beta_{z} \)  
  unit price discount for discount level \( z \)
- \( \psi \)  
  customer’s price upper bound
instance \( j \) of generic component \( k \) at the beginning of time bucket \( t \)

\( CR_r \) unit capacity requirement of process instance \( r \)

\( EF_{lr} \) production efficiency of production line \( l \) on process \( r \)

\( C_{lt} \) available regular capacity of production line \( l \) in time \( t \)

\( OT_l \) maximum overtime capacity for production line \( l \)

\( P^a \) base price for one unit of product for the customer order

\( UL_{lt} \) minimum capacity utilization level set by the manufacturer

\( h_{kj}^1 \) unit holding cost for instance \( j \) in generic component \( k \)

\( h^0 \) unit holding cost for finished goods

\( \xi_l \) overtime cost for production line \( l \)

\( \eta \) order rejection penalty cost

\( \gamma_l \) capacity under-utilization penalty

\( \pi_{rl} \) equals 1 if production line \( l \) is capable for process \( r \) (0, otherwise)

\( M \) a big positive number

**Variables:**

\( d_t \) due date indicator, equals 1, if the customer order is committed to be delivered by time \( t \), and =0 otherwise

\( x_{kjt} \) component requirement for instance \( j \) in generic component \( k \) in time \( t \)

\( \tilde{x}_{kj} \) indicator of product configuration, equals 1 if instance \( j \) in generic component \( k \) is selected, and 0 otherwise

\( y_{rt} \) production quantity at time \( t \) by using process instance \( r \)

\( \tilde{y}_r \) process requirement indicator which equals 1 if process instance \( r \) is chosen, and 0 otherwise

\( p \) product unit price, determined mainly by product configuration and discount level

\( g_{lt} \) capacity utilization indicator, which equals 1 if the minimum capacity utilization level is met, and 0 if capacity is under-utilized.

\( \rho_z \) discount level indicator, equals 1 if the \( z \)th discount level is chosen, and 0 otherwise

\( I_{kjt} \) material inventory of component instance \( (k, j) \) at the beginning of time \( t \)

\( F_t \) Finish-good inventory at the end of time \( t \)

\( ca_{lrt} \) capacity allocation from production line \( l \) to conduct process instance \( r \) in time \( t \)

\( ot_{lt} \) overtime capacity required in production line \( l \) in time \( t \)

**MIP model formulation:**

**Objective:**
Maximize $Q \cdot p - \sum_{t=d}^{dl} \eta \cdot (1-d_t) - \sum_{t=0}^{dl} \sum_{(k,j) \in KJ} h_{kj}^1 \cdot I_{kjt} - \sum_{t=0}^{dl} h_0 F_t$

$- \sum_{l=L}^{dl} \sum_{t=t_0}^{dl} \xi_l \cdot t_{lt} - \sum_{l=L}^{dl} g_t \cdot (1-g_t)$

Subject to:

$\sum_{t=d}^{dl} d_t \leq 1 \quad (1)$

$d_t = 0, \text{ for } t_0 \leq t \leq dl - 1 \quad (2)$

$F_t = F_{t-1} + \sum_{r \in R} y_{rt} - Q d_t, \text{ for } t_0 \leq t \leq dl \quad (3)$

$y_{rt} \leq M \cdot \gamma_r, \quad \forall r \in R \quad (4)$

$\sum_{r \in R} \gamma_r \leq 1 \quad (5)$

$y_{rt} = \sum_{j \in J_k} \frac{1}{B_{kj}} x_{kjt}, \quad \forall t_0 \leq t \leq dl \text{ and } \forall k \in K \quad (6)$

$I_{kjt} + S_{kjt} - x_{kjt} = I_{kjt(t+1)}, \quad \forall t_0 \leq t \leq dl \text{ and } \forall (k,j) \in KJ \quad (7)$

$x_{kjt} \leq M \cdot \tilde{x}_{kj}, \quad \forall (k,j) \in KJ \quad (8)$

$\sum_{j \in J_k} \tilde{x}_{kj} \leq 1, \quad \forall k \in K \quad (9)$

$CR_r \cdot y_{rt} = \sum_{l \in L, \tilde{t}_l = t} (c_{arl} \cdot EF_{lr}), \quad \forall t_0 \leq t \leq dl \text{ and } \forall r \in R \quad (10)$
\[
\sum_{r \in R & \pi_{il} = 1} c_{lri} \leq C_{li} + o_{li}, \quad \text{for} \quad t_0 \leq t \leq \Delta l \quad \text{and} \quad \forall l \in L
\] (11)

\[
o_{li} \leq OT_l, \quad \text{for} \quad t_0 \leq t \leq \Delta l \quad \text{and} \quad \forall l \in L
\] (12)

\[
\sum_{r \in R & \pi_{il} = 1} c_{lri} \geq UL_{li} C_{li} g_{li}, \quad \text{for} \quad t_0 \leq t \leq \Delta l \quad \text{and} \quad \forall l \in L
\] (13)

\[
p = \sum_{k \in K} \sum_{j \in J} \alpha_{kj} \bar{x}_{kj} + P^B \sum_{t=d}^{dl} d_t - \sum_{z \in Z} \beta_z \rho_z \leq \psi
\] (14)

\[
\sum_{z \in Z} \rho_z \leq 1
\] (15)

Product configuration constraints
(16)

Product-Process mapping constraints
(17)

Customer trade-off constraints
(18)

\[
\bar{x}_{kj}, \bar{y}_r, \rho_z, d_t \in \{0,1\},
\]
for \( \forall (k,j) \in KJ, \forall r \in R, \forall z \in Z, \quad t_0 \leq t \leq \Delta l \) (19)

\[
x_{kjr}, y_{rt}, c_{lri}, o_{li}, I_{kji}, I_{kj(dl+1)}, F_t \geq 0,
\]
for \( t_0 \leq t \leq \Delta l, \forall r \in R, \forall l \in L, \forall (k,j) \in KJ \) (20)

\[
F_{t_0-1} = 0, F_{dl} = 0
\] (21)

The objective function maximizes the overall operations-based profit function, which equals the sales revenue from the new customer order minus order rejection penalty, inventory holding cost for both components and finished-goods, overtime cost and capacity under-utilization penalty. The order revenue is calculated based on
a product unit price, which is determined by a modular-based price calculation specified in constraint (14). The per-unit inventory holding cost for finished-goods is in general larger than the component holding cost, which ensures a just-in-time production of the order. The capacity under-utilization penalty is used to balance the production line loading in a multi-production line situation.

Constraints (1) and (2) are the due date fulfillment constraints. The customer flexibility in due date is incorporated in this constraint. The finished good inventory is tracked in constraint (3). Finished products for the particular customer order will be stored until the whole order is completed and delivered on the committed due date, which is identified by $d_t$. Constraint (4) sets process instance indicator $\bar{y}_r = 1$ when the production quantity $y_{rt}$ is positive. Constraint (5) makes sure that only one process instance is selected. The component requirements and component inventory constraints (flow conservation constraints) are modeled in (6) and (7). Constraint (8) sets the component instance indicator $\bar{x}_{kj} = 1$ when a particular component $(k,j)$ is required. Constrain (9) makes sure that only one component instance is selected within each generic component. Constraints (10) ~ (12) represent capacity allocation constraints in which mix flexibility (process capability in production lines) and volume flexibility (overtime) of the manufacturing system are incorporated. Constraint (13) reflects the line utilization requirements. Constraint (14) calculates the unit price of the order being committed, and ensures that the final product configuration does not exceed the customer specified budget upper bound. It is assumed that a modular product pricing scheme is adopted. Therefore the product
unit price is calculated based on a base price plus the individual component price of selected component instances, and minus the promised discount. Constraint (15) guarantees the discount level selection is unique. Constraint (16) and (17) models the product and process configuration constraints, respectively. The trade-off constraints in customer flexibility are modeled in constraint (18). The formulations of the above three sets of constraints have been discussed in previous sections. As their formulations are very case dependent, the details are not listed here. Constraints (19) to (20) are integral and non-negativity constraints. Constraint (21) ensures the finish-good inventory before $t_0$ (initial inventory) and after $d_l$ (after order delivery) is zero.

### 4.3.2. MIP model for multiple order commitment

In some cases, particularly in a batch-mode order commitment process, the manufacturer need to handle multiple customer orders all together in one commitment process, and allocate production resources in the most effective way to maximize the overall profit. There are two possible ways to handle multi-order commitment. One way is to first prioritize all new customer orders and process them one by one. In this way, the problem is converted into a single order commitment problem. Criterion for order prioritization can be based on the order size, product pricing and customer relationship, etc. This method can work well when customer prioritization is an easy task. On the other hand, one can also develop optimization model to handle multiple customer order at the same time. This requires more
complicated mathematical model formulation. In this section, we discuss an extension of the MIP model developed in the last section to fulfill the purpose.

**Problem description:**

We consider an order commitment problem similar to the one introduced in the previous section, except in this problem, multiple customer orders are considered. Let \( O \) denote the set of new customer orders and \( i \) denote the order index \((i = 1, 2, ..., n)\). For each new order, the order commitment model need to determine whether accept or reject it, and if accepted, what is the committed due date and product configuration.

Each customer order possesses different level of customer flexibility. Let \( D_i = [d_{e_i}, d_{l_i}] \) denote the due date time window for order \( i \) (\( d_{e_i} \) and \( d_{l_i} \) is the earliest due date and latest due date, respectively), which represent the customer flexibility range in order due date. For each customer order, the customer flexibility range in product configuration can be represented by a set of alternative components and production processes. Similar to single-order commitment model, we use \((k,j)\) to denote the index of component instance and \( r \) for the index of process instance. In order to clearly identify the component instances in a multi-order situation, some specific sets are defined. Let \( K_i \) denote the set of generic components of customer order \( i \) and \( K \) be the set of all generic components derived from all new orders. That is, \( K = \bigcup_{i \in O} K_i \). Let \( J^k_i \) denote the set of component instances which belongs to the generic component \( k \) for order \( i \) (i.e. \( k \in K_i \)), and set \( J^k = \bigcup_{i \in O} J^k_i \) represent the aggregated
component instances of all new orders for generic component \( k \). Therefore, 
\((k, j) \in KJ_i = \{j \in J^k_i \text{ and } k \in K_i\}\) represents the index for a component instance in order \( i \), and \((k, j) \in KJ = \bigcup_{i \in O} KJ_i\) represents the index for the component instance among all new customer orders being processed. Further more, for production processes let \( R_i \) denote the set of alternative process instances for order \( i \).

The production system considered in this multi-order commitment problem is similar to the single-order commitment problem: it is an assemble-to-order production system with parallel assembly lines; mix and volume manufacturing flexibility is incorporated in the order commitment process.

The objective of this order commitment model is to maximize the overall operational profit by accepting new customer orders and assigning due dates and product configurations for each accepted order, and arranging production resources and schedules. The model formulation is presented below:

**Notations and detailed formulation:**

Many of the notations are the same as the single-order commitment model. To distinguish the unique ones for multi-order commitment model, these notations are highlighted in bolded text:

**Indices:**

\( i \in O \) order index, \( O \) is the set of customer order requests to be processed by the order commitment model

\( t \) time period index, \( t_0 \leq t \leq T \),

\( (k, j) \in KJ \) the \( j \)th component instance of generic component \( k \)

\( r \in R \) process instance index, where \( R \) is the set of all alternative processes required to produce the particular
where $t_0$ denotes the beginning of the planning period and $T$ denotes the last planning period, normally

$$ T = \max_{i=O}(d_{l_i}) $$

$l \in L$ production line index, where $L$ is the set of all production lines

$z \in Z$ price discount level index, where $Z$ is the set of all possible discount levels for this customer order

**Constants:**

- $Q_i$ order quantity for order $i$
- $B_{ikj}$ number of component instance $j$ of generic component $k$ required to produce one unit of final product for order $i$
- $CR_{ir}$ unit capacity requirement of process instance $r$ for order $i$
- $P^B_i$ base price for one unit of product for order $i$
- $S_{kjt}$ scheduled material delivery for instance $j$ of generic component $k$ at the beginning of time bucket $t$
- $EF_{lr}$ production efficiency of production line $l$ on process $r$
- $C_{lt}$ available regular capacity of production line $l$ in time $t$
- $OT_{l}$ maximum overtime capacity for production line $l$
- $UL_{lt}$ minimum capacity utilization level set by the manufacturer

**Variables:**

- $\beta_{iz}$ unit price discount for discount level $z$ for order $i$
- $\psi_i$ customer’s price upper bound for order $i$
- $h^0_l$ unit holding cost for finished goods of order $i$
- $h^1_{kj}$ unit holding cost for instance $j$ in generic component $k$
- $\alpha_{kj}$ unit component price for instance $j$ in generic component $k$
- $\xi_l$ overtime cost for production line $l$
- $\gamma_l$ capacity under-utilization penalty
- $\pi_{rl}$ equals 1 if production line $l$ is capable for process $r$ (0, otherwise)
- $M$ a big positive number
**MIP model formulation for multi-order commitment:**

**Objective:**

Maximize  

\[ \sum_{i=1}^{O_i} O_i \cdot p_i - \sum_{i=1}^{O_i} \sum_{t=0}^{d_i} d_i \cdot (1 - d_i) - \sum_{t=0}^{T} \sum_{(k,j) \in K} h_{k}^1 \cdot I_{kjt} - \sum_{t=0}^{T} \sum_{j=0}^{T} h_{j}^0 \cdot F_{it} \]

\[ - \sum_{l=1}^{T} \sum_{t=0}^{T} \xi_{i} \cdot \chi_{i} \cdot \sum_{l=1}^{T} \sum_{t=0}^{T} \gamma_{i} \cdot (1 - g_{i}) \]

**Subject to:**

\[ \sum_{t \in D_i} d_{it} \leq 1 \quad \text{for } \forall i \in O \quad (1) \]

\[ d_{it} = 0 \quad \text{for } \forall i \in O, t \notin D_i \quad (2) \]
\begin{align}
F_{it} &= F_{i(t-1)} + \sum_{r \in R} y_{irt} - Q_id_{it}, \text{ for } \forall i \in O, \ t_0 \leq t \leq dl_i \quad (3) \\
y_{irt} &\leq M \cdot \tilde{y}_{ir}, \text{ for } \forall i \in O \text{ and } \forall r \in R_i \quad (4) \\
\sum_{r \in R_i} \tilde{y}_{ir} &\leq 1, \text{ for } \forall i \in O \quad (5) \\
y_{irt} &= \sum_{j \in J_i^k} \frac{1}{B_{tkj}} x_{ikjt}, \text{ for } t_0 \leq t \leq dl_i, \ \forall i \in O \text{ and } \forall k \in K_i \quad (6) \\
I_{kt} + S_{kt} - \sum_{i \in O, \ (k,j) \in KJ_i} x_{ikjt} &= I_{k(t+1)}, \\
&\text{ for } t_0 \leq t \leq T, \ \forall j \in J^k \text{ and } \forall k \in K \quad (7) \\
x_{ikjt} &\leq M \cdot \tilde{x}_{ikj}, \text{ for } \forall i \in O \text{ and } \forall (k,j) \in KJ_i \quad (8) \\
\sum_{j \in J_i^k} \tilde{x}_{ikj} &\leq 1, \text{ for } \forall i \in O \text{ and } \forall k \in K_i \quad (9) \\
CR_{ir} \cdot y_{irt} &= \sum_{l \in L, \ \pi_i = l} (ca_{ilt} \cdot EF_{ir}), \text{ for } \forall i \in O, t_0 \leq t \leq dl_i \text{ and } \forall r \in R_i \quad (10) \\
\sum_{i \in O} \sum_{r \in R_i, \ \pi_i = l} ca_{irt} &\leq C_{lt} + ot_{lt}, \text{ for } t_0 \leq t \leq T \text{ and } \forall l \in L \quad (11) \\
ot_{lt} &\leq OT_l, \text{ for } t_0 \leq t \leq T \text{ and } \forall l \in L \quad (12) \\
\sum_{i \in O} \sum_{r \in R_i, \ \pi_i = l} ca_{irt} &\geq UL_{lt} C_{lt} g_{lt}, \text{ for } t_0 \leq t \leq T \text{ and } \forall l \in L \quad (13)
\end{align}
\[ p_i = \sum_{(k,j) \in KJ_i} \alpha_{kj} \bar{x}_{kj} + P_i^n \sum_{t=d_{kj}} d_{it} - \sum_{z \in Z} \beta_{iz} \rho_{iz} \leq \psi_i \]

, for \( \forall i \in O \)  \hspace{1cm} (14)

\[ \sum_{z \in Z} \rho_{iz} \leq 1, \; \text{for} \; \forall i \in O \]  \hspace{1cm} (15)

Product configuration constraints  \hspace{1cm} (16)

Product-Process mapping constraints  \hspace{1cm} (17)

Customer trade-off constraints  \hspace{1cm} (18)

\[ \bar{x}_{kj}, \bar{y}_{ir}, \rho_{iz}, d_{it} \in \{0,1\}, \]

for \( \forall i \in O, \forall (k,j) \in KJ, \forall r \in R, \forall z \in Z, \; t_0 \leq t \leq T \)  \hspace{1cm} (19)

\[ x_{ikt}, y_{irt}, c_{irt}, o_{lt}, I_{kit}, J_{kj(l+1)}, F_{it} \geq 0, \]

for \( \forall i \in O, t_0 \leq t \leq T, \forall r \in R, \forall l \in L, \forall (k,j) \in KJ \)  \hspace{1cm} (20)

\[ F_{i(t_0-1)} = 0, F_{i(t_0-1)} = 0, \; \text{for} \; \forall i \in O \]  \hspace{1cm} (21)

Basically this model is a simple extension of the single-order commitment model by introducing a new index \( i \) to denote multiple customer orders. Both the objective function and all constraints are very similar to the single-order commitment model, and therefore the explanation of the objective function and each constraint can be referred to the previous model. However, as multiple customer orders are considered simultaneously, the complexity of this model is increased exponentially.

4.4. Complexity analysis and illustrative example
To understand the complexity of the proposed order commitment models, let us assume a problem scenario, and based on the scenario to calculate the total number of variables and constraints in the optimization model.

For the single-order commitment model, let us consider a customer order which requests a product family consists of $K$ generic components. Considering customer flexibility, each generic component consists of $J$ alternative component instances, and there are $R$ alternative process instances that can be used to produce this order. On the other hand, let us assume the customer expects a due date range of $D$ time periods, and total planning horizon is $T$. The price discount level is $Z$. For the production system, let us assume there are $L$ parallel assembly lines.

For the product and process configuration constraints, since they are constraints related to component and process instances, we assume there are in total $KJR$ constraints. For customer trade-off constraints, since in practice there will not be complicated customer trade-offs between different order attributes, there will only a few trade-off constraints, and can be ignored in approximating the total number of model constraints.

Based on the above variables, the total number of variables and constraints can be approximated as:

Complexity of Single-order commitment model:
Number of variables \( \approx T + KJT + KJ + RT + R + Z + T + LRT + 1 + LT + KJT + LT \)

Number of constraints \( \approx 1 + T + T + R + 1 + TK + KJT + KJ + K + RT + 3LT + 1 + 1 + KJR + KJ + R + Z + T + KJT + RT + LRT + LT + KJT + T \)

For multi-order commitment model, the complexity is much larger as one more index is added to the model. Here is the estimation of the total number of variables and constraints, given the above assumption plus the total number of order = \( N \):

Complexity of multi-order commitment model:

Number of variables \( \approx NT + NKJT + NKJ + NRT + NR + NZ + NT + NLRT + N + LT + KJT + LT \)

Number of constraints \( \approx N + NT + NT + NR + N + NTK + KJT + NKJ + NK + NRT + 3LT + N + N + NKJR + N(KJ + R + Z + T + KJT + RT + LRT + LT + KJT + T) \)

Therefore, approximately, the multi-order commitment model has \( N \) times more variables and constraints than the single-order model. Table 3 lists the approximated complexity of the two models given real numbers. Not surprisingly, it has been observed that the complexity of the model is most sensitive to the number of planning periods, and secondly the number of orders in the multi-order model.

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Problem Scenario</th>
<th>Number of</th>
<th>Number of</th>
</tr>
</thead>
</table>

Table 3  Computational complexity of order commitment model
<table>
<thead>
<tr>
<th>Model</th>
<th>K</th>
<th>J</th>
<th>R</th>
<th>T</th>
<th>L</th>
<th>Z</th>
<th>N</th>
<th>Variables</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-Order Commitment Model</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td></td>
<td>434</td>
<td>729</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>5</td>
<td>4</td>
<td></td>
<td>1940</td>
<td>2958</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>20</td>
<td>10</td>
<td>4</td>
<td></td>
<td>3190</td>
<td>4946</td>
</tr>
<tr>
<td>Multi-Order Commitment Model</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>922</td>
<td>1707</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>7000</td>
<td>11490</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>5</td>
<td>5</td>
<td>20</td>
<td>10</td>
<td>4</td>
<td>10</td>
<td>21100</td>
<td>36860</td>
</tr>
</tbody>
</table>

**Illustrative example:**
For the illustration of the proposed order commitment methodology with the integration of customer flexibility, an illustrative example is presented. This example is based on the single-order commitment model, and assumes infinite capacity for simplification so that it is solvable in Microsoft Excel by the Solver plug-in. A simple product structure is considered with three product attributes. Each attribute contains several alternative options. It is assumed that the product design is modularized so that each attribute option corresponds to a unique component instance. The product-process structure is illustrated in Figure 12 and component unit prices are listed in Table 4. It is assumed that the base unit price is $6 and customer order quantity is 100.

![Product structure for a simple Product Family (PF)](image)

Table 4 Component unit price $\alpha_{kj}$

<table>
<thead>
<tr>
<th>(k, j)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0.80$</td>
<td>$1.78$</td>
<td>$2.77$</td>
</tr>
<tr>
<td>2</td>
<td>$1.81$</td>
<td>$2.86$</td>
<td>$3.97$</td>
</tr>
<tr>
<td>3</td>
<td>$1.98$</td>
<td>$0.84$</td>
<td>$2.81$</td>
</tr>
</tbody>
</table>
The initial component inventory \( I_{kjt_0} \) and the scheduled material arrivals \( S_{kjt} \) are available information from the production management system, which are listed in Table 5 and Table 6, respectively. Each time bucket represent one week.

### Table 5 Initial material inventory

<table>
<thead>
<tr>
<th>(k,j)</th>
<th>(1,1)</th>
<th>(1,2)</th>
<th>(1,3)</th>
<th>(2,1)</th>
<th>(2,2)</th>
<th>(2,3)</th>
<th>(3,1)</th>
<th>(3,2)</th>
<th>(3,3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial inventory</td>
<td>70</td>
<td>40</td>
<td>100</td>
<td>10</td>
<td>0</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

### Table 6 Scheduled material arrivals \( S_{kjt} \)

<table>
<thead>
<tr>
<th>Skjt</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>80</td>
<td>70</td>
<td>40</td>
<td></td>
<td></td>
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<tr>
<td>12</td>
<td>60</td>
<td>70</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>90</td>
<td>80</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>20</td>
<td>80</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>80</td>
<td>200</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>0</td>
<td>100</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>0</td>
<td>200</td>
<td>50</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>32</td>
<td>100</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Four problem scenarios are considered in a sequence. In the first scenario, it is assumed that customer requires very specific product configuration and due date. In other words, no customer flexibility is considered. In scenario 2 and 3, customer flexibility is considered in order due date and product attribute respectively. In scenario 4, more realistic customer flexibility is considered which takes customer trade-off constraint into account. Numerical illustration of customer flexibility integration in single-order commitment is given below:

**Scenario 1: (Base case)**
In this scenario, no customer flexibility is considered. Suppose the customer specifies his product configuration as $\tilde{x}_{11}$, $\tilde{x}_{21}$ and $\tilde{x}_{31} = 1$, and $d_4 = 1$ (i.e. due date = week 4). Based on the single-order commitment model, no commitment solution can be found due to the shortage in material inventory.

**Scenario 2: (Flexible due date)**

In this scenario, customer due date requirement is set to a range: {4, 5, 6}, the product specification remains the same as in scenario 1. In this setting, an optimal commitment solution can be found with due date assigned to week 5, and total profit = $470.

**Scenario 3: Full customer flexibility**

In this scenario, in addition to the flexible due date, the customer requirements on all three product attributes are relaxed. Therefore, there are in total 27 product variants which can satisfy the customer demand. In this case, the order commitment model found the best profit of $1116, with the commitment solution being: $\tilde{x}_{13} = \tilde{x}_{23} = \tilde{x}_{33} = 1, d_4 = 1$ (due in week 4).

**Scenario 4: Considering reduced customer flexibility range**

Let us assume the customer has a tradeoff consideration which involves three product attributes and would have the following minimum tradeoff requirement (tradeoff constraint):

$$0.2 \sum_{j} u_{1j} \tilde{x}_{1j} + 0.3 \sum_{j} u_{2j} \tilde{x}_{2j} + 0.5 \sum_{j} u_{3j} \tilde{x}_{3j} \geq \mu = 0.3$$
By integrating this constraint into the order commitment model, a new solution is obtained with profit of $994 and order configuration being: $\tilde{x}_{13} = \tilde{x}_{23} = \tilde{x}_{31} = 1$ and $d_5 = 1$.

Actually, by changing the minimum utility level $\mu$, different solutions can be obtained. The results are plotted in Figure 13, which shows the profit is increasing with more customer flexibility (less restriction on trade-off constraint).

![Figure 13 Impact of customer flexibility on profit](image-url)
CHAPTER 5
CASE STUDY AND SIMULATION ANALYSIS

5.1. Case study background

A garment manufacturing company is considered in this case study. The shirt manufacturing is a high variety industry now facing dramatic market changes characterized by decreasing order volume and shortened time to market. In addition, it has been observed that there are many configurable product attributes for a simple shirt product and there existing different level of customer flexibility among different buyers. All of the above industry characteristics make this industry very suitable for the case study in this research.

The following figure shows some examples of the shirt product family being considered in this case study. Basically they are all men’s casual shirts. The reason to choose this product family is mainly because that this product family is relatively simple in terms of product attributes, styles (attribute options) and the production process.

Figure 14  Men’s knit casual shirt – the product family chosen for the case study
The objectives of this case study are as the following:

(1) To verify the proposed approaches

(2) To study the interactions between customer flexibility and manufacturing flexibility with regards to the impacts on system performances

In order to verify the proposed approaches for customer flexibility characterization and order commitment, these approaches are applied step-by-step throughout the case study. The effectiveness of the approaches is demonstrated through qualitative and quantitative studies (simulation). At the same time, this case study also studies the interactions between customer flexibility and manufacturing flexibility regarding the system performance. As both customer flexibility and manufacturing flexibility are considered in the order commitment process, improvements can be made to the system performance (e.g. in terms of service level improvement, manufacturing cost reduction, etc.) by might be interactions between the two different types of flexibility. The final result of their interaction will not simply be a cumulative effect. Instead, sometimes the two types of flexibility can be complementary, and sometimes one of the flexibility might be redundant. To this end, this case study tries to find out the interrelationship between manufacturing flexibility and customer flexibility, so that managerial insight can be derived on how to better position the manufacturing system flexibility and how to create incentives for customer to share the information of their potential flexibilities in their demand.
5.2. The order fulfillment system overview

The order fulfillment system of the garment manufacturing company can be summarized as the following: as an industry leader in the garment manufacturing industry, the company is facing challenges of increased product variety, reduced time to market and market competition. An assemble-to-order business model is adopted for the men’s shirt product family in the company. As illustrated in Figure 15, there are basically two major processes in a men shirt production: the production of fabric and the production of garment. For fabric production, the company follows a make-to-stock strategy (since the customer required order delivery lead time is usually around 1 ~ 3 weeks, it is impossible to incorporate fabric production in the make-to-order process. Fortunately, for this product family there is relatively small number of fabric types, so that applying make-to-stock strategy for fabric is a viable solution). Finished fabrics are stored in the fabric inventory. When customer order arrives, the company first commits the due date and product configuration (shirt design) with the customer, and then produces the order with the fabric already stored in fabric inventory. For the order commitment process, the major production process focused is the garment production, particularly the sewing operation as this is the bottleneck process of the whole make-to-order production process. As Figure 16 shows, there are five parallel sewing lines being considered in this garment factory. Each line may possess different sewing capabilities. In this case study, we will show how customer flexibility is incorporated in the order commitment process, and how
to integrate both manufacturing flexibility (mainly process flexibility) and customer flexibility to achieve better service level and lower manufacturing cost.

Figure 15   General production framework in the case study

5.3. Simulation study

Through interviews with the sales team and production management team in the case study company, it is confirmed that there exists customer flexibility in the incoming customer orders. For example, sometimes the customer would agree on a spec change in the shirt design, or they would accept a different order delivery date. However, the current order commitment process does not take customer flexibility into consideration. Customer order requests are processed and committed based on their original specification. Although there could be some change-of-order-spec
during the order enquiry stage, the process is rather ad hoc and time consuming with a lot of back-and-forth communication and negotiation. One of the contributions of this research is to shorten the order commitment process and to improve the order commitment quality through the integration of both customer flexibility and manufacturing flexibility in the order commitment decision making process. In order to study the impact of such integration in this garment production system, simulation study is carried out. In the following, the customer flexibility is characterized for this garment manufacturing firm. After that, design of experiment is carried out for this simulation study. A discrete event simulation model is then developed based on the actual production system. An order commitment process with the integration of both customer flexibility and manufacturing flexibility is incorporated in the simulation model. The results are analyzed at the end of this section.

5.3.1. Customer flexibility characterization

Through the interviews with the sales team and production management team, the customer flexibility is revealed in the garment manufacturing firm. Although the men’s causal shirt is a relatively simple product in the fashion industry, it still involves a lot of different product design attributes that are configurable for customers. As shown in Figure 17, to precisely define a product variant, there are at least 30 different product attributes needed to be specified.

The customer flexibility actually exists in many attributes of a customer order, ranging from fabric type to shirt style (e.g. collar style, stitching style and button
type) and to order due date. However, based on the attribute selection principles developed in section 3.3.1 (see Figure 8), only a few of the order attributes are critical for the order commitment process. Besides order due date which is definitely a critical attribute, three product attributes are identified to be critical for the order commitment decision making, which are listed in Table 7.

![Figure 17 A sample of a men’s shirt product specification](image)

Product attributes listed in Table 7 all belong to the type IV attribute category, i.e. customer is less sensitive to the attribute value changes, and manufacturing resource is tightly connected with these attributes. For example, the selection of fabric type is directly linked with the fabric inventory availability. Different collar style of a shirt may require different processing technique and tooling, and therefore has an impact on both the required sewing line capability and sewing capacity. Similarly, the customer may require some special stitching to create fashionable style on the shirt.
These special stitching effects may require additional sewing cycle time to finish, and therefore can affect the capacity requirement for the sewing line.

Table 7  Selected product attributes important for customer flexibility modeling

<table>
<thead>
<tr>
<th></th>
<th>Customer flexibility</th>
<th>Impacts on resource requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric type</td>
<td>Customer may compromise</td>
<td>Fabric availability</td>
</tr>
<tr>
<td>Collar style</td>
<td>Customer may compromise</td>
<td>Sewing line capability &amp; capacity</td>
</tr>
<tr>
<td>Special stitching</td>
<td>Customer may compromise</td>
<td>Sewing line capacity</td>
</tr>
</tbody>
</table>

5.3.2. Design of experiment

The purpose of the simulation experiment is to demonstrate how to integrate both customer flexibility and manufacturing flexibility in the order commitment process, and to understand the impact of the flexibility integration to the order commitment performance for the manufacturing firm. Three major performance indicators are selected: (1) customer service level, (2) resource utilization and (3) line loading balance. All of them are key performance indicators commonly used in garment manufacturing firms. The customer service level is measured by the order acceptance ratio, which is calculated by the number of accepted orders divided by the total number of incoming order requests. The resource utilization is measured by the ratio of the total production capacity allocated to customer orders vs. the total installed capacity in the sewing production system. The line loading balance is a
measure of the evenness of the production line work load among all sewing lines. It is calculated by the following equation:

\[
LB = 1 - \frac{1}{L} \sum_{i=1}^{L} |LU_i - ALU|
\]

, where \( LB \) denotes the line loading balance index, \( LU_i \) denotes the line utilization of sewing line \( i \), and \( ALU \) represents the average line utilization among all sewing lines.

The three performance indicators are very critical for the evaluation of the effectiveness of matching customer demand with production resources in an order commitment process. By observing the three KPIs, the impacts and interaction of customer flexibility and manufacturing flexibility in an order commitment process can be revealed. Specifically, we are investigating the following questions:

(1) How much will the system performance be improved if customer flexibility is considered in order commitment process?

(2) Can customer flexibility compensate manufacturing flexibility?

(3) How can we better structure the two flexibility types (namely customer flexibility and manufacturing flexibility) to improve performance?

To answer the above questions, simulation experiments are conducted with different settings of manufacturing flexibility and customer flexibility being input to the simulation model. The major focus of the manufacturing flexibility is on the process capabilities in different sewing lines (this can be categorized as mix flexibility,
which is one of the most important types of manufacturing flexibility). Three different levels of manufacturing flexibility are defined: low, medium and high. As shown in Table 8, Table 9 and Table 10, the major capability difference among different sewing lines is the capability of processing different collar styles. Different collar style (even for the “No Collar” option) requires different operational skill for the worker, and some of the styles require special tooling. In the low flexibility setting, each sewing line possesses no more than two types of process capabilities. And in the high flexibility setting, each line is capable of making more than three types of collar styles.

Table 8  Sewing line process capability (low manufacturing flexibility)  
(marked “✓” if the sewing line can perform the particular collar style)

<table>
<thead>
<tr>
<th>Collar style</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>#1 No collar</td>
<td>✓</td>
</tr>
<tr>
<td>#2 Kent - Straight</td>
<td>✓</td>
</tr>
<tr>
<td>#3 Button Down</td>
<td>✓</td>
</tr>
<tr>
<td>#4 Piccadilly - Round</td>
<td>✓</td>
</tr>
<tr>
<td>#5 London Spread</td>
<td>✓</td>
</tr>
<tr>
<td>#6 Half Spread</td>
<td></td>
</tr>
</tbody>
</table>

Table 9  Sewing line process capability (Medium manufacturing flexibility)
On the other hand, five customer flexibility profiles are defined in the simulation experiment, namely “flexible stitching only”, “flexible fabric only”, “flexible collar only”, “flexible due date only” and “hybrid”. Since there are four critical order attributes, namely “special stitching”, “fabric type”, “collar style” and “due date”, the first four profiles assume the customer is only indifferent to one of the order attribute. For example, the profile named “flexible fabric only” specifies that the customer would only accept alternative fabric type, but no alternatives in other order attribute(s). The last profile named “hybrid” represents a more flexible case, which
assumes the customer can accept alternative option in either one of the four attributes. It is assumed that the customer has the same level of flexibility response in all the five profiles. This assumption can be explained as the following: suppose there are two customers, each belongs to a different flexibility profile. If both of their orders have one level of attribute value change, the customers will perceive the same level of change in the degree of satisfaction. This assumption is very important to guarantee a fair comparison of different customer flexibility scenarios. Because, suppose the customer service level is 95% given the “flexible due date only” customer flexibility profile and 90% under the “flexible stitching only” profile, then we can claim that the “flexible due date only” profile offers more help to the service level improvement with the same level of customer satisfaction (due to the same level of customer flexibility response). In addition, there is one more benchmark profile named “no customer flexibility”, which represent the case when customer flexibility is ignored in the order commitment process. Six customer flexibility profiles are used as different input scenarios for the simulation experiment. The combination of different customer flexibility profiles and manufacturing flexibility creates 18 different scenarios. Through the simulation study of all the 18 scenarios, the interaction of customer flexibility and manufacturing flexibility can be analyzed.

5.3.3. Simulation modeling

Overall logic flow of the simulation model

The simulation model is developed using ARENA® 7.0, which is a widely used discrete event simulation tool. The logic flow of the simulation model is illustrated
in Figure 18, which consists of two parts. The upper part simulates the order commitment process, in which incoming customer orders are processed through the Order Commitment Engine. Customer orders will be either rejected or accepted with promised due date and product configuration. The lower part of the model simulates the order execution process. Committed orders are first kept in the order waiting pool, and then released to the production shop floor. The performance data is then collected based on the output of both parts, which measures the order acceptance ratio (service level), production line utilization and the line loading balance.

Figure 18 The logic flow in the simulation model

The Order Commitment Engine

In this simulation model, the Order Commitment Engine is the most critical and sophisticated component, which incorporates both manufacturing flexibility and customer flexibility into the order commitment decision making process. The logic
flow within this order commitment engine is illustrated in Figure 19. Basically it is implemented based on the order commitment algorithm.

The order commitment algorithm is a search-based algorithm which incorporates flexible manufacturing resources and flexible customer needs into the search space. It is designed for real-time single-order commitment process. As shown in the logic flow chart, after receiving a new customer order, an order due date is quoted based on the initial order specifications (specified by the product specification, order quantity and the expected due date). The process for order due date quotation is conducted by a separate algorithm, which is discussed in the next section. Based on the initial quotation, the profit function is calculated. If there is flexibility in the customer order, alternative order configurations are constructed based on the customer flexibility model. Due date is quoted and order profit is calculated for each alternative order configuration. After that, the best solution is selected and manufacturing resource availability is updated. Notice, the best solution could be a commitment of order due date and product specification. It could also be an order rejection decision.
The order due date quotation algorithm

The due date quotation algorithm is basically a capacity available-to-promise algorithm (Jeong, 2002) that searches for the best due date quotation based on both available material inventory and production capacity on the shop floor.

For the illustration of the algorithm, let us define some variables:

*EFRD*(i): Earliest Fabric Ready Date for order *i*; This can be obtained from fabric inventory status

*ES*(i): Earliest Start Date for order *i*;

*EF*(i): Earliest Finish Date for order *i*;

*LS*(i): Latest Start Date for order *i*;

*LF*(i): Latest Finish Date for order *i*;

*DD*(i): Due Date for order *i*;

---

**Figure 19** The logic flow of the order commitment engine
For each production line, there could be some already loaded orders in the queue, waiting to be processed (denote $QueLength$ as the total number of orders in the queue). Let us assume their sequence is consistent with their order index, (that is the order index $i$ also represent its sequence in the queue) For these existing orders, we can calculate their $ES(i)$, $EF(i)$, $LS(i)$ and $LF(i)$ as the following:

$$ES(1) = EFRD(1);$$

$$ES(i) = \min \{EFRD(i), EF(i-1)\}; \quad \text{for } i = 2 \text{ to } QueLength$$

$$EF(i) = ES(i) + \text{order processing time}(i); \quad \text{for } i = 1 \text{ to } QueLength$$

$$LF(i) = \min \{DD(i), LS(i+1)\}; \quad \text{for } i = 1 \text{ to } QueLength - 1$$

$$LS(i) = LF(i) - \text{order processing time}; \quad \text{for } i = 1 \text{ to } QueLength$$

$$LF(QueLength) = DD(QueLength)$$

The logic of this order due date quotation algorithm is similar to the finite capacity promising algorithm developed by Taylor (1999), which searches for enough capacity slack on each production line that is capable of processing the new order $i'$, and then quote order due date accordingly. The pseudo code for the due date quotation algorithm is written as the following:

INITIATE $BestProfit = 0; NewOrderDD = 0; NewOrderLoadLine = Empty$;

//This initiates some variables at the beginning. Particularly, the $NewOrderDD$ remembers the Due Date for the new order and the $NewOrderLoadLine$ remembers the decision of which line the new order is loaded to.
FOR EACH sewing line \( l \) that is capable of processing order \( i' \), DO:

\{
    FOR EACH existing order \( i \) on line \( l \), DO:

    \{
        Calculate \( ES(i') = \min \{EFRD(i), EF(i-1)\} \);
        Calculate \( EF(i') = ES(i') + \text{order processing time}(i') \);
        IF \{ \( EF(i') < LS(i+1) \) OR \( i == \text{QueLength} \) \} \AND \( EF(i') \leq DD(i') \) THEN {insert the new order \( i' \) after order \( i \); quit this FOR EACH} ELSE next \( i \)
    \}

    IF order \( i' \) is inserted in line \( l \)
    THEN Calculate \( \text{Profit} = \text{Order Price} - \text{Inventory Cost} - \text{Line Under-Utilization Penalty} - \text{Overtime Cost} \)
    ELSE Calculate \( \text{Profit} = -\text{Order Denial Penalty} - \text{Inventory Cost} - \text{Line Under-Utilization Penalty} - \text{Overtime Cost} \)
    IF \( \text{BestProfit} < \text{Profit} \) THEN \{\( \text{BestProfit} = \text{Profit}; \)
    \text{NewOrderDD} = DD(i');
    \text{NewOrderLoadLine} = l;\}
    ELSE next \( l \)
\}

Return \( \text{NewOrderDD}; \text{NewOrderLoadLine}; \)

**Simulation setup**

It is assumed there are 10 fabric types (digitized from 1 to 10), 6 collar styles (digitized from 1 to 6) and 3 levels of special stitching (digitized from 0 to 2) for the shirt product family being considered in the simulation (in total 180 different stock-keeping-units (SKUs)). Each new order arrives into the system with a random order specification that requests any one of the 180 SKUs with equal probability and
expected delivery lead time to be either 2 weeks or 3 weeks. The customer demand is set up to be a Poisson arrival process with average order arrival rate of 1.4 orders per day. The order processing time (capacity requirement) is dependent on the product specification, which can be calculated by the following equation:

\[ CR_i = \text{order qty} \times \text{SAM} \times (1+\text{collar style}/10) \times (1+\text{special stitching}/5) \]

In the above equation, \( \text{SAM} \) is the Standard Allowance Minute for making one piece of standard shirt. This standard processing time is modified by two style difficulty multipliers. The first multiplier represents the collar style difficulty and the second multiplier represents the difficulty caused by the special stitching requirements in the order.

The simulation runs for three replications for each experiment scenario. In each replication, 100 days of warm-up period and 600 days of replication length are used. (This replication length is chosen because it simulates the manufacturing system for about a two-year period, which is long enough to eliminate all noise factors so that we can get more statistically stable results.)

5.3.4. Results and discussion

Figure 20 shows the impacts of different customer flexibility profiles on the three system performance variables, given the situation of low manufacturing flexibility. It can be seen that except for the customer flexibility profile of “flexible stitching only”, other kinds of customer flexibility will have significant impacts on order acceptance % and resource utilization level (in the case of low manufacturing
flexibility). The “no-impact” result for the “flexible stitching only” profile can be explained as the following: although some customers may be flexible in certain changes in the style requirements on special stitching, this flexibility is very limited as the shirt style change would be too significant for customer to accept if the stitching style changes too much. And given the stitching style changes within the customer allowed range, the capacity gain along with the change might be too little to allow the order to be accepted.

Among all the single-attribute flexibility profiles, the “flexible due date only” profile gives the maximum improvement in service level and line utilization. And the hybrid flexibility profile (i.e. the multi-attribute flexibility profile) gives even more significant performance improvement in terms of the service level (acceptance rate). This actually shows the importance of multi-attribute customer flexibility. In current order fulfillment practices, due date postponement is the most common approach in order negotiation to acquire customer orders when resource limitation is reached. From this experiment result, it shows that there would be better to explore different alternative solutions among multiple order attributes. It further demonstrates the critical impact of this research by modeling the customer flexibility in multiple attributes and dimensions.
Figure 20  Impact of customer flexibility

From Figure 21 to Figure 24 are simulation results showing the interaction between customer flexibility and manufacturing flexibility. In general, it can be shown that when the manufacturing flexibility is at a low level, the impact of customer flexibility is very significant. However, when manufacturing flexibility (in this case, the process flexibility of sewing lines) is increased, the impact of customer flexibility reduces. This actually partially answers that question “Can customer flexibility compensate manufacturing flexibility?” and the answer is yes. Basically we can name this effect as the complementary effect between customer flexibility and manufacturing flexibility. The following discussion is carried out to further understand this effect.
Although the customer flexibility and manufacturing flexibility come from different domains, they are interconnected through manufacturing resources, which simply have two basic forms, namely materials and capacity. From this perspective, the manufacturing flexibility basically enables sufficient materials and capacity of specific types to meet customer needs in the dynamic environment. On the other hand, the customer flexibility basically enables the easy adjustment of resource requirements in materials and capacity. Using manufacturing resource as a common currency, the two flexibility types are interchangeable. This indicates that the shortage in manufacturing flexibility can be compensated with an increment of customer flexibility under certain dimension and attributes, and vice-versa. Such understanding has significant implications not only in order fulfillment practices, but also in manufacturing system design and marketing. One good example is the Dell Computer’s demand management system (www.dell.com). Based on its component inventory, the online computer configuration system dynamically adjusts its promotion plans and discounts on some specific items to attract demand for components with sufficient inventory and release demands for those with insufficient inventory. With the multi-attribute and multi-dimension customer flexibility concept, we can now further apply the demand shaping concept into product families with more complicated product structures and manufacturing systems.
Figure 21 Interaction between customer flexibility and manufacturing flexibility

(impact on service level)

Figure 22 Interaction between customer flexibility and manufacturing flexibility

(impact on line utilization)
Figure 23  Interaction between customer flexibility and manufacturing flexibility  
(impact on line loading balance)

Figure 24  Interaction between customer flexibility and manufacturing flexibility  
(impact on the total number of order fulfilled)
CHAPTER 6
SUMMARY AND FUTURE WORK

6.1. Summary

Customer flexibility has been recognized as a critical supplement to manufacturing flexibility in achieving adaptability and high performance in high variety manufacturing. This research focused on the integration of customer flexibility in order commitment process. The research is focused on two critical issues: (1) How to characterize and represent customer flexibility? (2) How to integrate customer flexibility in order commitment process?

It is widely accepted that flexibility is a multi-dimensional concept. Range and Response are two mostly used dimensions for flexibility characterization. Due to the conceptual similarity and interconnection between customer flexibility and manufacturing flexibility, this research adopts Range and Response as the two critical dimensions for customer flexibility characterization. The Range of customer flexibility refers to the total number of different options in each order attribute that are acceptable by a customer. On the other hand, as the customer often has different preferences towards different alternative options, the Response of customer flexibility refers to the change in the degree of customer satisfaction in response to the changes in order attribute values. Following this conceptual characterization of customer flexibility, quantitative method for customer flexibility modeling is developed.
While the range of customer flexibility can be represented as discrete or continuous value sets, the representation of customer flexibility response is more complicated. Here the utility theory is adopted to measure customer’s satisfaction towards different order configurations, and to derive customer flexibility response. Based on the formulation of customer preference functions of each order attribute, the overall customer utility can be obtained by assigning a weight to each order attribute and aggregating all preference functions. The partial derivative of this utility function over any order attribute gives the customer flexibility response in relation to that particular attribute. Customer’s trade-off over different order attributes can also be formulated with such utility function. Methods to obtain critical parameters for accurate customer flexibility formulation are proposed, which is based on customer grouping (based on empirical or historical data) and the establishment of customer flexibility profiles.

The potential value of customer flexibility can be realized if it can be fully considered and aligned with manufacturing capabilities in the order commitment process. Based on the quantitative representation of customer flexibility, the customer flexibility range and trade-offs are modeled as constraints in an order commitment optimization model developed in mixed-integer-programming formulations. The essence of the model is to simultaneously decide customer order configurations and resource allocations that best utilize both customer flexibility and manufacturing flexibility to meet customer needs and minimize cost. A variation of
the model is also developed to handle situations with multiple customer orders in a batch commitment setting.

An industrial case study in a garment manufacturing company is conducted to verify the proposed approaches and to study the interactions between customer flexibility and manufacturing flexibility with regards to the impacts on system performances. Simulation studies are carried out to analyze the sensitivity of system performances in relation to different system inputs, such as demand rate, product mix, and different levels of customer/manufacturing flexibility. The case study and simulation not only demonstrate the effectiveness of the proposed approach, but also reveals system interactions between customer flexibility and manufacturing flexibility. It has been demonstrated that a better positioning of manufacturing flexibility together with a proactive management of customer flexibility can help the manufacturer better shape the manufacturing capability and customer demand, so that to achieve improved demand-supply matching in the high mix low volume production environment.

6.2. Research contributions

The contributions of this research can be summarized into two aspects. From the academic point of view, this research provides a totally different perspective to solve demand fulfillment challenges in high mix low volume production. The new perspective, the customer flexibility, is a phenomenon that has been identified in previous literature, but never studied systematically and being incorporated with equal importance as the flexibility from the manufacturing side. The research also
bridges the research areas between customer preference and advanced planning, which were studied separately in previous papers, but is extremely important to be looked at holistically in the new production era.

From the industry point of view, this research has developed order commitment models and algorithms with consideration of both customer flexibility and manufacturing flexibility, which can fit the practical use. Also to be noticed is that, this study developed managerial insights for firms to better position their manufacturing flexibility and shape customer demands.

6.3. Future works
The research could be extended in many directions.

First of all, the customer flexibility model requires further development. An potential alternative is to apply fuzzy logic and fuzzy set theory in the modeling of customer flexibility. Although, conceptually both the utility theory and fuzzy theory resembles the uncertain and subjective nature of the customer preference, there are well established mathematical models and optimization tools available for fuzzy set modeling. In this aspect, modeling customer flexibility as a fuzzy set could be a viable future extension of this research.

Secondly, in terms of the solution technology for order commitment model, it is necessary to develop efficient heuristic algorithms to facilitate fast and promising order commitments, especially when encountering large scale problems. The order
commitment problem in general can be categorized as NP-hard problems with similar as the well-known bin-packing problems. Therefore, it is recommended that specific algorithms can be developed to solve problems in some special cases. For example, in situations with single order, small number of planning horizon and production lines, simple tree-based search algorithms will provide satisfying performance.

Furthermore, the research can also be extend to create good mechanism and system of learning customer flexibility and developing knowledge base. As mentioned in chapter 3, the order commitment system can be designed into a close loop learning process with the integration of customer flexibility profiles and knowledge base. Depending on the customer feedback on each order quotation, the order commitment system record and analyze the customer behavior and keeps on updating the customer flexibility knowledge base. Gradually, the model can be more accurate in prediction the customer flexibility and provide more appropriate solutions to meet customer’s true needs and shorten the lead time of the order quotation process.

Last but not least, it is suggested that except for order commitment research, the integration of customer flexibility can be extended to even the product design phase, which is to consider and incorporate customer flexibility and its interaction with manufacturing system during the product family design phase. The key is to design certain product features that can provide alternative product options that will satisfy customer needs equally and will relief manufacturing constraints on the other hand.
Knowledge accumulated from the customer flexibility model can help the company obtain more accurate information in this aspect.
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