ORDER DRIVEN FLEXIBLE SHOP MANAGEMENT

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ABSTRACT

ORDER DRIVEN FLEXIBLE SHOP MANAGEMENT

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The difficulties in responding to variation in product order mixes and load levels effectively in make to order are known. Most of the existing approaches consider releasing jobs to the shop (input control), changing capacity levels (output control) in a controlled way, order acceptance with different definitions of work load and due date assignment. Controlling the processes, routing options and the order accepting capacity with various tool combinations that will decrease tool loading are not considered properly.

However the manufacturing flexibility provided by the computer numerically controlled (CNC) machines, provides both part variety and due date achievement given a reasonable extra capacity. Positive effects of flexibility on the due date achievement of the make to order is shown with a variety of experimental and field studies leaving little doubt. However taking flexibility only as a strategic issue and not considering it as a means of planning and management in either the short term or medium term decisions have been commonplace practice.

In this study, benefits of providing three kinds of flexibility, considering order pool and acceptance probability of the new arrivals in a periodic setting, is the focal issue. If the required flexible environment is provided, the necessity to make a detailed job loading, route planning and scheduling will be reduced to a low level and a high shop congestion and due date achievement will be realized simultaneously. A typical realistic shop with a scaled part mix is assumed in the flexibility management modeling and simulation experiments are conducted applying periodical flexibility planning approach. These experiments briefly support the ideas that worth of anticipation is more than plain expectations and flexibility improves robustness.

Keywords: Make to Order, Flexible Manufacturing System, Manufacturing Flexibility, Order Review and Release, Mathematical Programming

ÖZ

SİPARİŞE DAYALI ESNEK ATÖLYE YÖNETİMİ

Bulut, Aykut
Yüksek Lisans, Endüstri Mühendisliği Bölümü
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Temmuz 2011, 105 sayfa

Siparişe üretimde ürün çeşitliliğine ve yük farklarına verimli bir şekilde karşılık vermenin güçlükleri bilinmektedir. Mevcut yaklaşımların büyük çoğunluğu, atölyeye iş sürmeyi (girdi kontrolü), kapasite düzeyini değiştirmeyi (çıktı kontrolü), çeşitli tanımlarıyla iş yüklerine bağlı sipariş kabulü ve termin tarihi vermeyi önermekle yetinmişlerdir. Atölyenin işlem türlerini, rotalama seçeneklerini ve hazırlık/kurma yükünü azaltan takım kombinasyonlarıyla ürün kabulüne yatkınlığını kontrol etmek fazlaca düşünülmemiştir.

Oysa otomatik takım tezgâhlarıyla temin edilen imalat esnekliği, çeşitlilik ile başarımı makul bir ek kapasite ile bir arada yürütebilmeyi sağlamaktadır. Esneklik var olduğunda, siparişe üretimin başarımının özellikle olumlu etkilediğini çeşitli deneysel ve saha çalışmaları kuşkuya yer vermeyecek biçimde göstermiştir. Ancak bu çalışmaların ortak yanı, esnekliği stratejik bir konu olarak ele alıp, kısa ve orta vadede kontrol edilir, planlanabilir, dolayısıyla yönetimi yapılır bir halde ele almamış olmalarıdır.

Bu çalışmada, sipariş havuzu ve yeni siparişlerin kabul olasılıklarını dikkate alarak, her dönemde yeniden ve bir arada değerlendirilen üç ayrı esneklik türünün kontrollü bir biçimde sağlanmasının yararları incelenmeye odaklanılmaktadır. Gerekli esneklik ortamı sağlandığı ve iyi planlandığı takdirde, ayrıntılı iş yükleme, rota planlama ve çizelgelemeye başvurma gereğini çok azaltarak hem yüksek bir tezgâh doluluğu, hem de üstün bir sipariş temini başarımı sağlanabilir. Dönemsel esneklik planlama yaklaşımı uygulayarak orta ölçekli gerçekçi bir atölye ortamı kabulü ve esneklik yönetimi modellemesine eşlik eden benzetim deneyleri yapılmıştır. Deney sonuçları öncelikle öngörünün düz beklentiden daha kıymetli olduğunu ve esnekliğin tutarlılığı iyileştirdiğini göstermektedir.

Anahtar Kelimeler: Siparişe Üretim, Esnek İmalat Sistemi, İmalat Esnekliği, Sipariş İnceleme ve Sürme, Matematiksel Programlama

To my family

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CHAPTER 1

INTRODUCTION

Make to order (MTO) is a production philosophy/system that produces only after the demand/order is accepted. The production demand may be originated directly from the market or inside the company, from other divisions. Start of the manufacturing after the realization of the order results in a lead time to be waited. But it enables manufacturing of products that match the customer specifications exactly.

Incoming orders wait in a pool called order pool. Order pool acts as a buffer between the market and the shop. This buffer reduces the effects of uncertainty in the market by providing a choice among a set of known orders. Market uncertainty can also thought as the randomness in arriving orders. Orders in the order pool are reviewed by the Order Review and Release (ORR) when a release is triggered.

Many ORR techniques have been proposed for the effective management of MTO systems. An ORR method helps to decide the job that will be released to the shop. Release decision can be made at periodic intervals or may depend on some triggers. The general conclusion about ORR studies in the literature is that the adaptation of an ORR procedure can have several beneficial effects on the shops, including reduced stock carrying costs, shop congestion and flow times [1].

In MTO systems the major production planning activity related to orders is realized by assigning them to the machines of the shop. This is called loading orders to the machines. In this process the operations of orders are assigned to machines. Most of the time orders that will be loaded are selected by a defined ORR method.

In the order review phase, ORR review orders concerning the shop performance in a limited time period ahead. Schedule visibility refers to this planned time period that ORR is concerned with. If order release concerns the performance of the shop in a limited time period, without taking the horizon into account as a whole, this is called limited visibility [1]. If the planning horizon as well as time period ahead is concerned in the order release phase the schedule visibility is called as extended visibility [1].

Another production planning and control concept for make-to-order job shops is workload control (WLC) [2]. The WLC concept sets norms for the work load allowed on the floor. If the job reviewed is not in the allowed norms (in terms of its workload), then the job is held in the order pool [3].

Some researchers (Onur and Fabricky [4], Kingsman and Hendry [5]), argue that controlling the input (workload) to the shop is necessary but not sufficient for a proper management. The output (production capacity) control mechanism is required to improve the control process. Utilizing both the input and output control creates a combined feed-back and feed-forward control aimed at regulating input and output simultaneously [1].

A flexible manufacturing system (FMS) is a manufacturing system that has a high potential to adapt to the changes compared to classical job shop floors. An FMS is ideal in a rapid changing market environment. It consists of machines that can be loaded with tools to process different kinds of operations. It also provides automated part handling by its programming ability.

The research on the management of FMS's attracted many researchers. As FMS's are different from classical job shops since they have the flexibility to adapt to changes rapidly, their management should also be different, it should also concern flexibility. This led to the emergence of the operational flexibility concept [4]. Operational flexibility is a broad concept that relates the management of the FMS rather than the technology installed. According to [4], manufacturing systems can be provided with flexible technology, but still show rigid performance, which is a result of the fact that they have potential flexibility of technology but, due to its poor management, a very low rate, resulting in a rather low flexibility. Management of FMS's is crucial from this point of view.

Flexibility management in MTO is even more critical since MTO's are exposed to uncertainty. Flexible MTO shops should be provided with the flexibility that will help them in responding uncertainty in the incoming orders. The tool loading of the MTO shop should be flexible in order to adapt the changes rapidly.

Definition and classification of the manufacturing flexibilities is well studied in the literature. Three types of flexibility have been specifically addressed in this study. These are process, routing and product flexibilities. The definitions given by Sethi and Sethi [6] are used. These flexibility types constitute the production flexibility aggregate class according to the classification given in [6]. The other aggregate flexibility classes are program and market flexibilities.

The purpose of this study is to propose a management method for flexible shops that will yield both a high shop congestion and due date achievement, without the need to make a detailed job loading, route planning and scheduling. The proposed method is called flexibility management approach. The study also tests the performance of the flexibility management approach and reveals the benefits of the flexibility types provided by the approach in a typical hypothetical shop environment.

A simulation experimentation of the outcome from an optimization methodology is used to fulfill the experimental requirements of the study. The tool loading of the assumed flexible shop is realized by the proposed flexibility management approach. It uses a mathematical model called flexibility model (FM) in determining the tool loading. FM optimizes the balance between flexibility types. After deciding on the periodic loading the shop is simulated for every subsequent period. The simulation model utilizes an ORR method for releasing the orders to the shop. Within ORR, a WLC mechanism is exploited. An experimental analysis is designed with several factors. These factors include the use of a specific flexibility kind, different methods of flexibility allocation and schedule visibility.

This study is an extension to the research conducted by Bekir İlker Süer in his M.S. thesis at the Industrial Engineering Department of METU in 2009 [7]. The following are borrowed from Süer's thesis.

- Modeling basics and some parameters

- Definitions and measures of process and routing flexibility
- Some of the shop simulation parameters

This study extends Süer's work in the following topics.

- Introduction of product flexibility
- A modification in approximating the routing flexibility
- Relieving the flexibility model from workload considerations
- Introduction of the anticipation in order arrivals
- Introduction of the setup of automated machinery on the shop
- Introduction of the setup optimization models
- Comparison of the proposed approach with a naive method from literature
- Enlarging the assumed shop in experimental study
- Testing robustness of the proposed approach

The ultimate purpose of this study is to justify the use of flexibility management in MTO shops in a fairly straight forward manner.

After the introduction, Chapter 2 gives a brief literature about ORR, WLC, FMS and manufacturing flexibility. Then Chapter 3 introduces the flexibility types used in this study and their measurement methods. It also introduces the ORR method used. After introducing ORR, Chapter 4 introduces the flexibility model that is used to load tools to the machines on the shop and setup optimization models that are used to reduce the setup. Chapter 4 also discusses the details of the forward finite loading (FFL) method which is used to evaluate the performance of flexibility models against a naive (but with widespread acceptance) approach. Chapter 5 introduces the simulation model used to create the order arrivals and simulate typical operations of the shop floor. After introduction of the details of the simulation model, Chapter 6 discusses the environment used in the experiments and the results of the comparison and robustness experiments. Finally Chapter 7 concludes the results of this study and indicates future research directions.

CHAPTER 2

LITERATURE REVIEW

The methods used in this study require connections and utilization of different concepts from the literature. The main points that are needed to draw attention to are ORR and flexibility concepts. In this chapter the relevant literature regarding ORR techniques in make-to order shops and operational flexibility on flexible manufacturing systems exploited in this study are discussed. Even though it may be wrong to strictly divide these two concepts, they will be discussed in two different sections here. The first section will introduce ORR literature and the second section will introduce the relevant flexibility literature. If a study from literature includes both ORR and flexibility it will be discussed under the flexibility section. Studies regarding flexibility in make to order (MTO) shops generally consist of the ORR techniques that exploit flexibility concept by default. Hence the first section may be thought as "pure" ORR without use of the flexibility concept and the second as flexibility concept which also covers some form of ORR applications.

2.1 ORR LITERATURE REVIEW

The positive effects of order release mechanism (ORM) is investigated. Lingayat et al. [13] introduce an ORM to be used in flexible flow systems where the primary criterion is the flow time. The mechanism determines the routing, timing and the order to be released based on the batch processing machine and workload balancing at the bottleneck machine. A simulation study is conducted for comparing the mechanism proposed with immediate release. They concluded that the performance of the system with the ORM is significantly better than the performance of the system without ORM. They also indicate that order release mechanism (ORM) is more important than choice of dispatching rule used on the shop floor. They claim that the performance of the ORM depends on the level of shop load, and ORM is more active under high loads.

The workload control (WLC) methods address managing of the workstation loads in MTO environments rather than a straightforward release. Land and Gaalman [8] compare and discuss different WLC concepts. They indicate that WLC concepts try to create a situation on the shop floor of short and stable queues. A pool of unreleased jobs buffers the shop floor against external dynamics, the incoming non-stationary job stream. They claim that the use of workload norms should turn the queuing of orders on the shop floor into a stationary process which is not necessarily aimed at in ORR. It is indicated that release performs a key-role in reaching this stationary situation and it is the most elaborated function within WLC concepts. Therefore, they compare and asses existing WLC concepts from the point of view of releases. The analysis of stationarity requirements within existing production control concepts is proposed to provide guidelines for developing production control concepts for job shops working under dynamic circumstances (i.e. MTO shops).

A major well known study on the ORR literature at the end of 90's is the survey conducted by Bergamaschi et al. [1]. The survey introduces a review and classification framework of the ORR research carried up to 1997. This review is different from Wisner's [9] since it investigates the ORR techniques with their inherent characteristics in order to improve understanding and the implementation of the procedures. Whereas, Wisner [9] focuses on the ability of ORR techniques to achieve better shop effectiveness.

In the survey eight dimensions that describe the fundamental characteristics and properties of the existing ORR techniques are defined. These dimensions are

- Order release mechanism
- Timing convention
- Workload measure

- Aggregation of workload measure
- Workload accounting over time
- Workload control
- Capacity Planning
- Schedule Visibility

It is indicated that effectiveness of the ORR procedure itself is most likely dependent on the amount of information given at the order review phase about future planned orders, that is, it depends on the schedule visibility. Order release may be oriented to optimize the next period (limited visibility) without planning the horizon as a whole. However it can be also oriented to tolerate poor present shop performances on behalf of a global advantage that will be achieved through a more effective management in future periods (extended visibility). It is emphasized that almost all of the reviewed models had implemented a limited visibility approach.

At the end of the survey, one of the future research direction suggested is using the lower and upper bound workload control methods together with continuous timing convention. They claim that it ensures a rather tight level of control, since it allows one to monitor both the occurrence of bottleneck and idle workcentres. It may be viewed as an improvement on both the lower-bound-only and upper-bound-only approaches. They further claim that it allows one to improve workload balance among workcentres, especially when there is a little gap between the upper and the lower bound.

Due date assignment is an important aspect of MTO systems and it is a typical research topic. In a much referred to research Sabuncuoğlu and Karapınar [10] proposes a new due date assignment method that utilizes both job due date and shop load information. The method suggests to complete processing of the jobs on their due date (in line with just in time philosophy). The performance of the new method is compared to different ORR methods under different experimental factors, dispatching rule, system load and due date tightness. The proposed method is found to be more robust to variations in system load and processing times than the other ORR methods examined.

As well as input control suggested in WLC, output control is also well studied. Kingsman and Hendry [5] explore the relative contributions of input control versus output control mechanisms via simulating a real job shop. They use the WLC method that has been developed at Lancaster University. They utilize the input control alone and input and output control together and analyze the results. The experiments result that input and output control mechanisms should be considered as two mechanisms that should be used together. Rather than stopping input when work in process reaches a preset level, an output control should also be considered when needed.

Performances of WLC methods are also investigated. Cigolini and Portioli [11] analyze three workload limiting policies regarding the three objectives; (i) assessing whether the method of workload limiting affects the performances of ORR; (ii) investigating the performances of the workload limiting methods when the mix imbalance changes; (iii) evaluating the robustness of the workload limiting methods considered.

They claim that a better understanding of the real potential of each ORR technique can be achieved by considering the distinctive features one at a time, instead of addressing ORR as a whole. They build a simulation model and carry fractional factorial design to test the workload limiting methods. Their research resulted that the 'upper bound only' method is the best performing workload control method. 'Workload balancing' is proven to be the most robust method.

Selecting parameters of WLC method is also a typical research topic. Land [12] indicates that even though WLC is intended to be a robust concept for dynamic environments, it needs a large number of parameters to be specified. The key decision of order release are specification of workload norms, planned throughput times, a release frequency, and a planning time limit.

He aims to improve parameter setting process by revealing the impact of parameters on performance and analyzing sensitivity. He claims the existence of a fragile balance between average throughput times and variance of due date deviations. A simulation study is conducted to assess the influence of each parameter on this balance. The results indicate that choice of workload calculation method, release frequency and time limit critically effect the performance.

WLC methods in the existence alternative machines have also been studied. Henrich et al. [2] claim that in practice, machines that perform the same type of operations are generally not completely identical but semi-interchangeable. They develop different WLC alternatives to deal with semi-interchangeability and test them in a simulation study. For a low degree of interchangeability they assert that placing semi-interchangeable machines in separate capacity groups and making a routing decision at the order release stage is more attractive than placing them to a single capacity group. This leads to shorter throughput times. They show that postponing the final routing decision until the moment of actual dispatching is advantageous, even if separate capacity groups with a preliminary routing decision (at the time of release) has already been made.

There are significant results of the literature that also utilized in this study. The first result is the conclusion that the ORM is more important than choice of dispatching rule used, by Lingayat et al. [13]. The second result is reached by Land and Gaalman [8]. It is the search developing production control concepts for job shops working under dynamic circumstances and necessity of analysis of stationarity requirements within existing production control concepts to find them.

Another result from literature that is used is schedule visibility. To rescue the flexibility management approach from limited schedule visibility anticipation method is proposed. The method anticipates the order arrivals in the next period and reflects this to the flexibility management approach. Flexibility management approach gains an extended schedule visibility by using anticipation.

Another result from the literature is that a best ORR method does not exists. Performance of the ORR depends on the environment it is used.

2.2 MANUFACTURING FLEXIBILITY LITERATURE REVIEW

The literature regarding the manufacturing flexibility will be introduced in this section.

One of the major studies conducted in manufacturing flexibility is the survey many researchers refer to by Sethi and Sethi [6]. Their study consists of a detailed survey regarding the definition, measurement and classification of the flexibility kinds. They emphasize that the previous studies agree on the complexity, multidimensionality and flexibility as being a hard-to-capture concept.

They give important clues about installed flexibility versus operational flexibility concept discussed in Chapter 1. They assert that in practical terms, flexibility is viewed as a trade-off against efficiency in production and dependability in the marketplace in the literature. They define the flexibility of a system as its adaptability to a wide range of possible environments that it may encounter. They emphasize that a flexible system must be capable of changing in order to deal with a changing environment.

In the light of these discussions they conclude that manufacturing flexibility must, therefore, be a permanent preoccupation and not just an improvisation. It is much more than simply buying an FMS. The idea that flexibility cannot just be bought but must be planned and managed is a crucial one.

They define 11 different kinds of manufacturing flexibility. These are machine, material handling, operation, process, product, routing, volume, expansion, program, production, and market flexibilities. The flexibilities addressed in this study and their definitions given in [6] is as follows.

Process Flexibility: Process flexibility of a manufacturing system relates to the set of part types that the system can produce without major setups.

Product Flexibility: Product flexibility is the ease with which new parts can be added or substituted for existing parts.

Routing Flexibility: Routing flexibility of a manufacturing system is its ability to produce a part by alternate routes through the system.

From Figure 2.1, it can be interpreted that machine, material handling and operation flexibilities are in the basic flexibility category. Process, routing, product, volume and expansion flexibilities are system flexibilities. Finally, program production and market flexibilities are aggregate flexibilities.

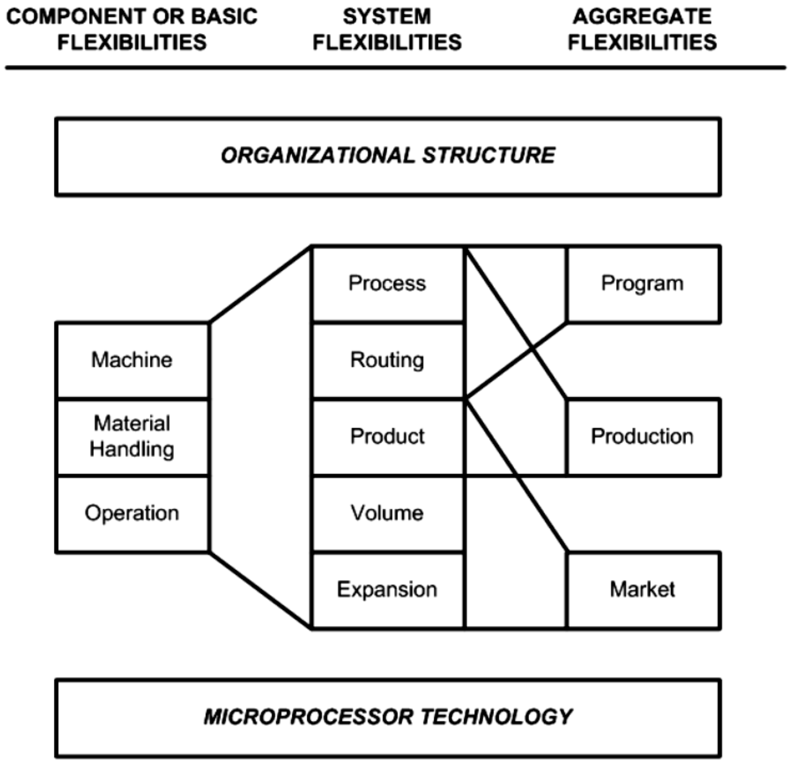

Figure 2.1: Flexibility classification given in [6]

Source of flexibility is another typical research question. Stecke and Raman [14] consider the role of system planning in determining operating flexibility and system performance. They claim that short-term flexibility depends significantly upon planning decisions made during preproduction setup. Different planning objectives lead to different system configurations, and simultaneously yield varying levels of process-oriented flexibility. They also give a classification of different types of flexibilities. They present an illustrative comparison of flexible manufacturing methods for high volume/low variety and low volume/high variety manufacture. They claim that the inverse relationship that exists between flexibility and productivity for conventional manufacturing systems does not necessarily exist on FMS's.

The impact and the essance of flexibility in comparison to other structural properties has also been investigated. Newman and Maffei [15] examine the effects of routing flexibility, simple ORM's, and local job prioritizing rules. They simulate three levels of routing flexibility, four different workload limits and two job sequencing rules.

They state their reasoning to combine the three factors by the proposition that the ORM's and local job sequencing rules play a role in the balance between complexity and workload queues, while the level of flexibility in the process impacts the firm's ability to accommodate complexity.

They conclude that while the impact of each experimental parameter is found to be significant, the impact of flexibility greatly overshadows those of the other parameters. They claim that these results support further examination and more normative understanding of how flexibility and better production planning and control may best be used in various competitive situations.

Using flexibility as a decision making criteria is also investigated. Corsten et al. [16] claim that the aim of releasing orders is to transfer jobs from the planning stage to the realization stage under consideration of economic objectives. They indicate that decision field changes over time and information about these changes are incomplete at the moment of planning and refer to this as open decision field. They characterize this decision problem by time-related, open decision fields. In light of this, they aim to make flexibility an objective in taking decisions. The basic idea of the procedure is utilizing the inherent flexibility of a production system to compensate negative consequences of unexpected changes of the decision field by the decision making capitalizing on flexibility.

Benefits of flexibility have also been studied in many different respects. Chan et al. [17] focus on the physical and operating characteristics of alternative machines (available by the virtue of flexibility), which may not have been explicitly modeled with flexibility. They try to answer the following questions: (a) Does an increase in flexibility have the expected benefits or not? (b) If benefits are present, then up to what level of flexibility?

They provide an approach to identify productive and counterproductive performance zones of an FMS at different flexibility levels while considering physical and operating characteristics. They also demonstrate the need of modeling explicitly the physical and operating characteristics of a system with flexibility, and present a simulation study of these parameters for a given FMS. The results show that expected gains from an increasing level of flexibility may not be present while considering physical and operating characteristics. Flexibility can be increased strategically up to a certain level with benefits when considering the physical and operating characteristic of the system. A further increase in flexibility level may be counterproductive.

Further, they claim that the control strategies may not perform similarly when the flexibility level of manufacturing system is changed. Due to a change in the physical and operating characteristics of a system, the performance of control strategies may also change. The decision-maker may be required to focus on effective decision-making in manufacturing systems with a coordinated view of design (flexibility), planning, scheduling and control issues. They assert that the key challenge, therefore, is to identify the suitable type and level of flexibility in a manufacturing system while considering all other parameters of the system that can affect the performance.

After the simulation study they conclude that at different levels of flexibility, a different control strategy may perform better. Decision-makers should identify a suitable control strategy for a given level of flexibility, and the penalties for these characteristics.

Measuring flexibility is also a typical research topic. Calvo et al. [18] define a flexibility measure based on the utility concept. They define a utility function that is derived from the production objectives which are themselves functions of the state parameters. Next the differential of this utility function with respect to time (where state parameters change in the meantime) is proposed as a measure for flexibility.

A positive variation in the utility function indicates positive flexibility. Null flexibility (no change in utility) corresponds to an interchange of production objectives, conserving utility. A negative variation shows inflexibility. The positive flexibility represent the potential for continuous improvement in manufacturing whereas the null flexibility represents the interchange of production objectives.

The positive effects of flexibility in dynamic job shops have recently been studied. Baykasoğlu and Göçken [19] claim that workload control includes three major decision levels: job entry, job release and priority dispatching. They define several decision points which have impact on the effectiveness of the production planning and control at each decision level (i.e., acceptance/rejection, due date assignment, etc.) They claim that workload control systems should consider all of these decision points simultaneously in order to improve the effectiveness.

They include flexibility of the shop as a fourth decision level. This level allows the shop capacity to be adjusted as new orders enter the system and released to the shop floor. They build simulation models to explore the effect of each decision level. Four experimental factors are defined: pre-shop pool size, OR mechanisms, degree of flexibility and dispatching rules. Three different flexibility degrees are experimented. These degrees are created by allowing the operations be available on more than one workcentre (i.e. routing flexibility). They conclude that simultaneous consideration of decision levels is critical and can improve effectiveness of production planning and control. Another conclusion they reach is that controlled release results better due date reliability in the existence of flexibility.

An important research point indicated in the literature is the installed versus operational flexibility, proposed by Sethi and Sethi [6]. The installed technology on a shop may be flexible but this does not mean that it is operating flexible. Manufacturing flexibility is not only buying an FMS but also operating it flexible. The idea that flexibility cannot just be bought but must be planned and managed is a crucial one.

An important research question addresses flexible operated shops. Moreover using the flexibility leverage at the management of the shop as a decision area. Determining the benefits of flexibility and the limits that its beneficial as underscored in [17] is yet an important issue to inquire about. This may also thought as determining an optimal balance between kinds of flexibility which is also a promise of this study. Another promise is that flexibility will also improve the performance of MTO shops by a better handling of uncertainty of the dynamic environments of MTO.

CHAPTER 3

FLEXIBILITY AND ORDER REVIEW AND RELEASE IN MAKE TO ORDER SHOPS

In this chapter, types of manufacturing flexibility and some of their measurement techniques will be introduced.

Make to order (MTO) companies are exposed to uncertainty and dynamism. One major source of this uncertainty is the randomness in arriving orders as stated in Chapter 1. In this study the uncertainty is managed by providing the shop different kinds of flexibilities and determining an order pool dependent optimal balance between them. For this purpose three flexibility types are introduced and applied under the management control in the shop. These flexibilities are process, routing and product flexibilities.

The flexibilities considered in this study are chosen from the survey that consists definition and classification of manufacturing flexibilities given by Sethi and Sethi [6]. This study covers three of the five system flexibilities defined by them. These three flexibility kinds are production related flexibilities class where the other two (volume and expansion) are market related flexibilities. This study covers all system flexibility types related to production flexibility class, see Figure 2.1.

3.1 FLEXIBLE SHOPS

A flexible shop consists of a set of automated machines and tools that can be loaded to these machines. Each machine has a certain magazine capacity. Machines can process the operations according to the tools loaded and the part programs that run on their processors. We can assume, without loss of generality that each tool corresponds to one and only one operation, ie. there is a one-to-one match between the tools and operations. The flexibility of the shop comes from the flexibility of installing any tool to any machine and free routing among all the machines. Tools are automatically positioned (in negligible time) due to automation of all the machines. Transportation time between machines is negligible. Each part has a unique operation sequence. The operations of a part should be processed only in its sequence. The shop is able to produce a part if tools that correspond to all of its processes are loaded to machines.

The control of flexibility in the flexible shops is a crucial act that is also underlined by Sethi and Sethi [6]. They claim that flexibility is a permanent preoccupation and not just an improvisation [6]. They also emphasize that flexibility is much more than simply buying an FMS, it cannot just be bought but must be planned and managed [6].

In this study a periodic control of flexibility by managerial decision is addressed in order to adopt the dynamism of the MTO shop and achieve a high shop congestion. The tool loading is reviewed periodically for practical changes. After a certain tool set is loaded with a non-negligible setup, the shop starts processing orders for a predetermined time. This preset time is the period. When the end of the period is reached and some orders remain in process the shop continues to production for an amount of time to finish the orders released. This amount of time is considered as overtime during which no new orders arrive to the shop. No new orders are released from the order pool in the overtime. When all released orders are processed the tool set loaded to machines is renewed for the next production period.

The due date assignment for an order is done as soon as the order joins the order pool. We suppose this is done according to Total Work Content (TWK) rule defined in [20]. The reason for this selection is its simplicity and independence from the subsequent period loading and dispatching decisions. The rule assigns due date according to the unit processing time of the corresponding part type and batch size of the order. The formulation of the due date is as given in Equation 3.1.

$$dueDate = F \times partProcessingTime \times batchSize \tag{3.1}$$

where F is the flow allowance parameter. This parameter will be set as we will describe in Chapter 6.

The arriving orders are assumed to have part types at random. We assumed probabilities for each part type arriving. We suppose these are estimated from historical records. For testing the robustness of the flexibility management approach with respect to part probabilities a robustness study will be conducted in Chapter 6.

3.2 TYPES OF FLEXIBILITY

The flexibilities that are regarded when deciding on the tool loading are expressed in this section. These three flexibilities are fundamental and considered adequate, (since all the production related flexibility categories are covered according to categorization given by Sethi and Sethi [6]) for creating a shop that can respond the uncertainty in the demands of the market. Each flexibility makes the shop respond to a fundamental concern with randomness. However each type has its particular emphasis.

3.2.1 Process Flexibility

Sethi and Sethi [6] defined the process flexibility of a manufacturing system to be related to the set of part types that the system can produce without major setups. This definition constitutes the basis for the process flexibility measure used in this study. It corresponds to producible parts without need to modify the set of tools loaded in the flexible shop within a period. The process flexibility is concerned with the number of part types producible. Each producible part contributes to process flexibility. The total number of producible parts gives a process flexibility measure.

We prefer to normalize for a fair treatment. A weighing rule, that represents the needs of the pool better, is introduced.

This procedure uses the classical critical ratio (CR) for each order in the pool. The critical ratio is calculated as in Equation 3.2.

$$CR = \begin{cases} \dfrac{partProcessingTime \times batchSize}{dueDate - nextPeriod} & if\ dueDate > nextPeriod \\ CRmax & otherwise \end{cases} \tag{3.2}$$

where the *CRmax* is a value higher than the maximum *CR* value allowed for a non-tardy order.

The *CR* value increases as due-date approaches. It is also directly proportional with the work content of the order. This *CR* value is the fundamental of the weights of the parts that will be calculated.

Then by summing the *CR* values for part type *p*, total critical value specific to part *p* ($CRtot_p$) is obtained. $CRtot_p$ will be high if the number of orders of type *p* in the pool is relatively larger and their individual *CR* values are high.

The percentage weight of $CRtot_p$ is used as the specific process flexibility weight of part *p* ($intrap_p$).

$$intrap_p = \frac{CRtot_p}{\sum CRtot_p} \tag{3.3}$$

The total process flexibility measure for the shop is calculated as in Equation 3.4.

$$process\ flexibility = \sum_{p \in M} intrap_p \tag{3.4}$$

where *M* is the overall set of producible parts.

3.2.2 Routing Flexibility

Sethi and Sethi [6] defined the routing flexibility of a manufacturing system as its ability to produce a part by alternate routes through the system. This definition constitutes the basis for the routing flexibility measure.

In the flexible shop assumed duplication of a tool creates alternative machines for the corresponding operation, hence alternative routes for the corresponding part type. This improves the performance of the MTO shop by shortening the throughput times of the orders which large workloads.

Routing flexibility values the number of routes. Routing flexibility for a part is maximum when the largest possible number of routes is opened. Regarding this, the routing flexibility of a part is considered to be the ratio of the number of routes opened for that part to the maximum number of routes possible for that part.

A major concern is how to weigh routing flexibility among the parts in the subsequent normalization. The weighing is similar to the process flexibility weighing. The only difference is *CRtot* values are first modified in order to differentiate the parts with different number of operations, see [7]. This is done by multiplying $CRtot_p$ by a factor called route correction factor RCF_p. RCF_p is calculated as in Equation 3.5.

$$RCF_p = |P| \times \frac{count_p}{\sum count_p} \tag{3.5}$$

This factor is used in order to favor the parts with more operations, when allocating routing flexibility between parts. Parts with more operations have the potential to be transferred more times and hence confront more queues. This is why they are favored.

The modified $CRtot_p$ values are called $CRtot'_p$ and calculated as in Equation 4.9.

$$CRtot'_p = RCF_p \times CRtot_p \tag{3.6}$$

The proportion of $CRtot'_p$ to the total $CRtot'_p$'s (for all p) is used as routing flexibility weight of part p ($intrar_p$).

$$intrar_p = \frac{CRtot'_p}{\sum CRtot'_p} \tag{3.7}$$

The total routing flexibility measure for the shop is calculated as in Equation 3.8.

$$routing\ flexibility = \sum_{p \in P} intrar_p \times \frac{NR_p}{maxr_p} \tag{3.8}$$

where NR_p is the number of routes realized by the given tool loading and $maxr_p$ is the maximum number of routes possible for part p respectively.

3.2.2.1 An Illustrative Example

Assume a very simple shop with 3 machines with magazine capacity of 2, 3 part types and 4 operations in total. Let the operation sequences of part type 1, 2 and 3 be 1-2, 3-4 and 1-2-3 respectively. Let all the *intrar* values equal to be 0.33. Assume the tool loading is as in Table 3.1.

Table 3.1: Tool loading for assumed shop (routing flexibility case 1)

machine	slot 1	slot 2
machine 1	1	2
machine 2	2	3
machine 3	2	3

For this loading, number of routes for part type 1, 2 and 3 are 3, 0 and 6 respectively. Maximum number of routes for 1 is realized when operation 1 and 2 are installed on each machine. Then there will be three alternative machines for the first and second operation of part type one. Then total number of routes is 9 (= 3 × 3). Maximum number of routes possible for part type 2 is realized when operation 3 and 4 are loaded to all machines and it is 9 by the same reasoning for type one. Maximum number of routes possible for part type 3 is realized when all of its operations are loaded twice. Then number of routes for part type 3 is 8 (= 2 × 2 × 2).

Routing flexibility for this loading is calculated in Equation 3.9.

$$routing\ flexibility_1 = intrar_1 \times \frac{3}{9} + intrar_2 \times \frac{0}{9} + intrar_3 \times \frac{6}{8} \tag{3.9}$$

Routing flexibility of the shop for this loading is 0.36.

Now assume that the loading is as in Table 3.2.

Table 3.2: Tool loading for assumed shop (routing flexibility case 2)

machine	slot 1	slot 2
machine 1	1	2
machine 2	2	3
machine 3	1	3

The maximum number of routes for all part types are same. Then routing flexibility of the shop is calculated as follows.

$$routing\ flexibility_2 = 0.33 \times \frac{4}{9} + 0.33 \times \frac{0}{9} + 0.33 \times \frac{8}{8} \tag{3.10}$$

The routing flexibility in this loading is 0.48 and it is higher then the routing flexibility in the previous loading. With the new loading same part types are producible with more number of routes.

3.2.3 Product Flexibility

Sethi and Sethi [6] defined the product flexibility as the ease with which new parts can be added or substituted for existing parts. This definition is taken as a basis for the product flexibility concept and measure used in this study.

The product flexibility can be increased by decreasing the number of unloading/loading requirement of non-producible parts to become producible. Product flexibility improves the performance of the MTO shop by favoring tool loading that is easy to modify for including new sets of part types.

Defining a product flexibility measure is more cumbersome than defining process and routing flexibilities. Product flexibility has two major differences from the process and routing flexibilities. First, it involves not only the producible parts but also the non-producible ones. Second, its flexibility concern extends beyond the current period.

It can be claimed that a loading has the product flexibility for the set of part types that can be produced without any or with very limited effort. The product flexibility increases as this set gets larger. One product flexibility measure can be defined as the number of parts that require lower than a predefined threshold level of effort to become producible. This measure weighs all the parts identically (weighing is one). Another proper measure for the product flexibility is the sum of the probabilities of arrival for the part types that can be converted to producible with a limited effort. The effort of converting a non-producible part type into producible can be measured as the number of additional tools needed for that part type. Assume that Q is the set of parts that are producible with a number of additional, which does not exceed a preset threshold, of unloaded tools. It is assumed that all needed tools can be loaded independently.

Then the product flexibility of this current loading is calculated as in Equation 3.11.

$$\sum_{p \in Q} prob_p \tag{3.11}$$

where $prob_p$ is the probability of an arriving order being of type p. It is trivial to see that this measure is bounded from above by unity.

Notice that when the threshold level is 1, the product flexibility measure can be thought as a process flexibility measure weighed with the corresponding part type probabilities. To extend the defined product flexibility measure and make it have a meaning beyond process flexibility, the threshold level must be higher than 1. The threshold value is defined to be 2 in this study. This means that the part types that are producible (i.e. no tool missing) or missing one tool are included in the count for product flexibility. Then the set Q is defined to be the set of part types that are already producible or missing one tool with the current loading.

3.2.3.1 An Illustrative Example

Assume the shop defined in Subsection 3.2.2.1 with the tool loading given in Table 3.3 with all $prob_p$ values equal to 0.33.

Then $Q = \{1, 2\}$ and the product flexibility is calculated as in Equation 3.12.

Table 3.3: Tool loading for assumed shop (product flexibility case 1)

machine	slot 1	slot 2
machine 1	1	4
machine 2	1	4
machine 3	1	4

$$product\ flexibility = prob_1 + prob_2 \tag{3.12}$$

Assume the loading is as in Table 3.4.

Table 3.4: Tool loading for assumed shop (product flexibility case 2)

machine	slot 1	slot 2
machine 1	1	2
machine 2	3	4
machine 3	1	4

Then $Q = \{1, 2, 3\}$ and product flexibility for this loading is 1.

3.3 PROCESS, ROUTING AND PRODUCT FLEXIBILITY RELATIONS

The flexibility types defined should not be considered as irrelevant to each other. Considering them all together with their inter-relations and trade-offs is the fundamental idea of this study. A joint form of these three types of flexibility will be targeted in flexibility management of MTO shops.

The routing flexibility enables the shop to complete the orders faster, whereas the process flexibility provides a faster release opportunity. The product flexibility enables the shop to adapt to the non-producible part types easier.

The process flexibility increases as the number of part types that are producible increases with the current tool loading. The routing flexibility increases as number of routes for any given part type increases. The product flexibility increases as the tool loading permitted to include a non-producible part type becomes easier.

The trade-off between process and routing flexibilities can be explained as follows. When a tool slot will be utilized, there are two alternatives; it can be used for a new tool on a different machine to produce a new type or it can be used for a tool that is already loaded, to open an extra route. In the former alternative the process and routing flexibilities are both increased. Process flexibility is increased since a new type is producible and routing flexibility is increased since a route is opened for a part by making it producible. In the latter alternative the routing flexibility is increased since a new route is opened for an already producible part.

The trade-off between process and product flexibilities is not as clear as the trade-off between process and routing flexibilities. Process flexibility increases as number of producible parts increases. Product flexibility is the ease of including new part types in the producible set. In order to increase process flexibility different tools are loaded in a way that the number of producible part types is made as large as possible. But at this point when the number of producible part types gets so large the tooling is dedicated to a specific set tool slots are occupied and, including brand new part types may demand many tool unloading/loading to achieve a new dedicated tooling.

Product flexibility demands tool loading short of being complete for as many parts as possible. On the other hand process flexibility demands complete set of tools.

A trade-off between routing and product flexibility is also present. Suppose a new slot will be utilized. It can be utilized for opening a new route for an existing part type, or for adding an irrelevant tool for the existing part types so that it will be easier to include a part type just before the next period.

Both product and routing flexibilities are valid for the current period. They add tools to get the best for the current period. Unfortunately this is a myopic concern. Product flexibility is a flexibility that is concerned with the forthcoming periods. As a result of seeking product flexibility a tool without any direct benefit in the current period can still be loaded for the prospects in the forthcoming period.

3.4 ORDER REVIEW AND RELEASE

Order review and release manages the transition of production orders from the planning to the execution phase [1]. ORR is the procedure to decide which order to release and when to release. Its aim is to improve the shop performance with keeping the orders in a pool (order pool) and releasing in a controlled manner rather than releasing them immediately when the order is realized or holding them in the pool arbitrarily long.

Input control provides the shop floor managers with a feed-back tool to control and reduce lead times, through shop load limitation and balancing [1].

Performance of flexible flow systems with the order release method is significantly better than the performance of the system without ORM, (immediate release) and order release management is more active under high loads, Lingayat et al. [13]. Lingayat et al. also claim that ORM is more important than choice of dispatching rule used on the shop floor.

Some researchers (Onur and Fabrycky [4], Hendry and Kingsman [5]) claim that input control methods alone might be ineffective, since it concentrates only on regulating the amount of load that is in input to the shop. It is also ascertained that by adjusting the amount of production capacity available, even better shop performances can be achieved. In this study, output is controlled by the routing and product flexibilities. Routing flexibility increases the capacity by opening alternative routes. Product flexibility increases output by shortening the setup times. Moreover this study also incorporates the anticipation method which is not utilized in the input/output control suggested by the authors.

3.4.1 Release Triggers

Choice of release frequency and time limit critically affects performance [12].

According to the release timing classification defined in [21], timing convention is continuous or bucketed. Continuous timing convention is used in this study since the inter-arrival time is continuous and processing is taken as continuous.

Order release mechanism can be activated any time during the production period and is triggered by any of the following events.

- Arrival of an order
- Aggregate load drops below a certain level
- Direct load drops below a certain level
- Ending of a setup

Melnyk and Ragatz [21] classify the triggers as shop based and pool based triggers. According to this classification the first trigger is pool based the others are shop based triggers. Since all transportation times are taken negligible these four instances cover all possible decision epochs with an effect on the performance given that preference is given to FIFO among the orders with the same due date.

3.4.2 Workload Control

WLC concepts try to create a situation on the shop floor of short and stable queues. A pool of unreleased jobs buffers the shop floor against external dynamics, the incoming non-stationary job stream [8]. The use of workload norms should turn the queuing of orders on the shop floor into a stationary process [8].

Orders are released to the shop by controlling the load on each machine. In [2], for two work centers that can process some common operations, authors recommend tracking load for each work center instead of grouping work centers. Following a similar argument, load of each machine is tracked and bounded separately in this study.

Workload control method used in this study is adapted from two main ideas. First idea is releasing an order to the shop if it does not cause workload of a machine exceed a certain level. The second idea is releasing an order such that the first operation of the order is on a starving machine. This release is done provided that the released order will not cause a load on machines exceed a second (and higher) workload bound.

The first idea is reviewed in many studies in the literature, see [11]. This method is called ‘upper bound only’. The method of the second idea is called the ‘lower bound only method’. This method is useful in avoiding work center starvation ([11]). The authors argue that even the lower bound only is originally formulated for shop floors that have a fixed bottleneck that is already known, it can be extended to environments when bottleneck station varies. Since the tool loading changes in each period in this study, there may be varying bottleneck machines. Therefore using a lower bound method will be useful for avoiding starvation. The resulting method is called ‘upper and lower bound’ workload control method (see [11]).

The control strategies may not perform similarly when the flexibility level of a manufacturing system is changed [17]. Chan et al. [17] claim that due to a change in the physical and operating characteristics of a system, the performance of control strategies may also change. They further discuss that at different levels of flexibility, a different control strategy may perform better. Hence decision-makers should identify a suitable control strategy for a given level of flexibility and the penalties for these characteristics [17]. In this study, by using an upper and lower bound approach with continuous timing convention a robust workload control with respect to flexibility levels is aimed.

The upper and lower workload bounds approach is also emphasized as a major research path in the review given by Bergamaschi et al. [1]. The authors claim that this method ensures a rather tight level of control, since it allows one to monitor both the occurrence of bottleneck and idle work-centers and it may be viewed as an improvement on both lower-bound-only and upper-bound only approaches. “Moreover, it allows one to improve workload balance among work-centers, especially when there is a little gap between the upper and the lower bound” [1]. “Thus it would be interesting to combine this approach with a continuous timing convention” [1]. “In fact, on the one hand the tight space-wise workload control provided by setting both the bounds could join forces with the frequent time-wise workload control ensured by the continuous timing convention” [1].

Choice of workload calculation method critically effects performance [12]. Two workload load measures are used in this study, aggregate load and direct load. Aggregate load of a machine is found by adding the total processing time of operations of released orders that can be processed on that machine. Direct load of a machine is the total processing time of the operations of the parts in the queue of the machine.

Since the route that will be followed by the released orders are not known at the time of the release, a complication in the aggregate load calculation arises when an operation is installed in more than one machine. Then in this case, the load burden of the duplicated operation to each alternative machine is the processing time of the operation divided by number of redundancies. This way the advantages of routing flexibility is taken by allowing in more orders.

Orders are sorted in the order pool according to the earliest due date rule (EDD). This provides the release method to review the orders with closer due dates first. The purpose of sorting the orders is improving the tardiness of the orders.

When a release is triggered, following steps of the release mechanism are implemented.

Step 0 $i = 1, f = 0$.

Step 1 Calculate the aggregate load of all machines when i^{th} order in the sorted list is released.

- Step 1.1 If aggregate load of all machines are below AL_1 release the i^{th} order, update aggregate and direct loads of the machines on the route of order i, $f = 1$, repeat step 1.

  Else

  If the i^{th} order is the last order in the list and $f = 0$, go to step 2.

  Else $i = i + 1$, repeat step 1.

Step 2 If direct load of any machine is below DL, search the list, find the first order that has the first operation on the starving machine, calculate aggregate load of all machines in case the order is released. If there is no such order, stop.

- Step 2.1 If aggregate load of a machine exceeds AL_2, find the next order that has the first operation on the starving machine, calculate aggregate loads and repeat this step. If there is no such order, stop.

Else release the order, stop.

Note that AL_2 is a second aggregate load norm level that is greater than AL_1. Determining values of AL_1, AL_2 and DL norms will be discussed in Chapter 6.

Since this study omits the output control, the workload control mechanism is aimed to exceed the production cycle limited. The production length can be exceeded for only limited periods of time. For this reason the workload norm levels are updated as the end of the period is approached as proposed in [7]. When the amount of time left to the end of the period is less than AL_1, AL_2 and DL norms, the norms that are greater than the amount of time left are set to the amount of time left. The norms are updated at each release trigger. By updating norms, overloading the shop is prevented such that the need for overtime to finish all the jobs is avoided.

3.5 DISPATCHING

Dispatching rule is noted to effect the shop performance significantly [10]. Once released the orders split and each part selects the machine for its next operation according to the minimum direct load. If the next operation of a part is installed on the same machine and load on the machine queue is less than a threshold, the next operation of the part is processed on the same machine. If load is higher than threshold and an alternative machine with the queue load less than the threshold exists, part moves to that machine.

CHAPTER 4

MATHEMATICAL MODELS

In the scope of this thesis, a flexibility-concerned approach is proposed for the management of a flexible shop. The proposed approach consists of choosing an optimal balance between three kinds of flexibility discussed in Chapter 3.

The model that assigns tools to machines by optimizing a joint criteria for the three flexibility types is called the Flexibility Model (FM).

After optimizing the FM, another mathematical model is solved. This model takes the optimal solution of the FM and optimizes the tool-machine assignment without changing the chosen of tools loaded. It is to make some tool exchanges between machines in order to minimize setup time. This second model is called Setup Optimization Model (SOFM). SOFM also attempts to realize balancing of workloads among machines. In this chapter the FM and SOFM will be introduced in separate sections.

4.1 FLEXIBILITY MODEL

FM addresses three kinds of flexibilities: process, routing and product flexibilities. In its most extended form the model maximizes the process and routing flexibilities for a given product flexibility level. There are trade-offs between flexibility levels, see Section 3.3. The model decides an ideal balance between process and routing flexibilities given a minimum product flexibility level.

The product flexibility level should be decided priori. It is a parameter of the model that should be decided by the decision maker. Two different level of product flexibility is provided and included in the experimental factors of the designed experiment in Chapter 6.

A mixed integer programming (MIP) model is developed that takes the discussed issues into account. The details of the MIP model is discussed in the forthcoming subsections.

4.1.1 Assumptions of the Model

1. There is a one-to-one correspondence between tools and operations.

2. Only one slot is needed for each tool in the tool magazine.

3. Tool life is not a part of this study.

4. All machines have the same magazine (hence tool) capacity and all can perform any operation as long as the corresponding tool is installed.

5. Tool availability and material handling systems are out of the scope of this study.

If an operation requires more than one tool, then this operation can be thought as a series of operations that requires the corresponding tools in sequence. By this method modification assumption 1 can be relaxed easily.

If a tool requires more than one slot, then FM can be modified to adapt this by introduction of a parameter that shows the number of slots the tools require. This parameter is used in the magazine capacity constraint without loss of generality. Assumption 4 can easily relaxed by the change of the magazine capacities constraints of FM.

4.1.2 Notation

The notation used in FM is described in this subsection.

4.1.2.1 Indices

The sets used in the model are defined as follows.

I: set of tools
J: set of machines
P: set of parts
S_p: set of operations of part type p

Indices corresponding to tool, machine and part sets is defined respectively as follows.

$i = 1, 2, \cdots, |I|$;
$j = 1, 2, \cdots, |J|$;
$p = 1, 2, \cdots, |P|$;

4.1.2.2 Variables

The variables used in the model are defined as follows.

x_{ij}: Binary variable that assigns tools to machines, where

$$x_{ij} = \begin{cases} 1 & \text{if tool } i \text{ is loaded to machine } j, \\ 0 & \text{otherwise.} \end{cases}$$

c_p: Binary variable that shows if a part is producible or not, where

$$c_p = \begin{cases} 1 & \text{if } p \text{ is producible,} \\ 0 & \text{otherwise.} \end{cases}$$

d_p: Non-negative variable that is an approximation of the ratio of number of existing routes for part type p to the maximum number of routes possible for part type p.

$ctot$: Non-negative variable that shows total process flexibility.

$dtot$: Non-negative variable that shows total routing flexibility.

z_i: Binary variable that shows if tool i is required to produce a non-producible ($c_p = 0$) part, where

$$z_i = \begin{cases} 1 & \text{if tool } i \text{ is required,} \\ 0 & \text{otherwise.} \end{cases}$$

v_i: Binary variable that shows if a required tool to produce a non-producible ($z_i = 1$) is loaded to at least one machine or not,

$$v_i = \begin{cases} 1 & \text{if } i \text{ is not loaded,} \\ 0 & \text{otherwise.} \end{cases}$$

y_p: Binary variable that shows part types with two or more missing tools,

$$y_p = \begin{cases} 1 & \text{if two or more tools is not loaded,} \\ 0 & \text{otherwise.} \end{cases}$$

4.1.2.3 Parameters

The parameters of the model can be categorized and defined as follows.

Order pool status parameters:

ipf: Weight for process flexibility.

irf: Weight for routing flexibility.

$intrap_p$: Intra-process flexibility weight of part p.

$intrar_p$: Intra-routing flexibility weight of part p.

Flexibility related parameters:

θ: An indicator that determines ipf and irf coefficients given the existing order pool order variety, expressed as an angle.

PFP: Upper bound on the complement of product flexibility level.

Environment related parameters:

$operpart_{ip}$: Operation-part table, 1 if tool i is required to produce part p, 0 otherwise.

$maxr_p$: Maximum number of routes possible for part p.

$prob_p$: Probability of an arriving order to be of part type p.

MTC: Tool capacity for machines (set constant without loss of generality)

MON: Operation number of the part with the largest number of operations.

Parameter θ is a predefined value according to static shop characteristics. Its value will be discussed in Chapter 6.

PFP is the product flexibility related parameter. It is the complement of the decided product flexibility level ($1 - product\ flexibility\ level$). In the MIP model that will be described below the product flexibility is not bounded by a lower bound. Instead its complement, PFP, is bounded from above. This is more convenient for modeling purposes.

Order pool status parameters are calculated from the properties of the orders in the pool at the end of a production period just before the next period starts. Their calculation procedure will be discussed in section 4.1.3. After specifications on the environment are made, values of the environment related parameters will be apparent, in Chapter 6.

4.1.3 Calculation of Pool Status Parameters

At the end of a period there will be some orders at the order pool with assigned due-dates. In this section calculation of the parameters of FM from the status of the order pool at the end of a period will be explained. All the parameters in this section are not directly used in the FM. Some of them are used to calculate parameters that are directly used in the model.

The following parameters are calculated from the current order pool status.

- $entropy$
- ipf
- irf
- CR
- $CRexp$
- $CRant$
- $CRtot$
- $CRtot'$
- $intrap$

- *intrar*

4.1.3.1 Calculation of *entropy*

Entropy is a parameter that shows the part variety of the orders in the pool. Entropy parameter is calculated using the measure proposed in [22]. First the workload for each order in the pool is calculated. Workload for an order is calculated by multiplying the batch size of the order with unit total part processing time of the order type. Then workloads of orders of the same type is calculated and total workload measures for each part type is obtained. Assume the total workload measure for a part type p is wl_p. Then expected workload for each part type ($wlExp_p$) is calculated as in Equation 4.1.

$$wlExp_p = \frac{periodLenght}{IAT} * E(batchSizes) * prob_p * partProcessingTime_p \quad (4.1)$$

Total workload ($wlTot_p$) is the sum of wl_p and $wlExp_p$. Then the *entropy* is calculated as in Equation 4.2.

$$entropy = \begin{cases} -\sum_{p=1}^{|P|} \left(\frac{wlTot_p}{\sum wlTot_p} \times \log \frac{wlTot_p}{\sum wlTot_p} \right) & if \ \sum wlTot \neq 0 \\ -\log \frac{1}{|P|} & otherwise \end{cases} \quad (4.2)$$

The the maximum level of *entropy* is thus $-\log \frac{1}{|P|}$ and this value is achieved when all wl_p levels are equal. As the variance of wl_p values increases *entropy* value decreases. This indicates that when the *entropy* level is high, variety of part types in the pool is larger.

When there is no order in the pool, *entropy* level is again assumed to have the largest value which is $-\log \frac{1}{|P|}$. This assumption is reasonable since all the wl_p levels are equal (all being zero) and there is a perfect balance between part types. This can also be interpreted as the order pool has the maximum part variety that can be achieved.

4.1.3.2 Calculation of ipf

ipf is the inter-process flexibility coefficient. This parameter is the coefficient of the total process flexibility of the shop in FM. The ipf value is directly proportional to entropy value calculated. The ipf is favored when the entropy is high, which means that when the part variety in the pool is high the process flexibility of the shop is favored since ipf is greater. ipf is calculated as in Equation 4.3.

$$ipf = \tan\theta \times entropy \tag{4.3}$$

Maximum value that entropy can take is $-\log\frac{1}{|P|}$. θ is chosen such that ipf is 1 in the maximum entropy value. This value can be found as follows.

$$\theta = \arctan\left[\frac{-1}{\log\frac{1}{|P|}}\right] \tag{4.4}$$

4.1.3.3 Calculation of irf

irf is the inter-routing flexibility coefficient. This parameter is the coefficient of the total routing flexibility of the shop in FM. irf is calculated as in Equation 4.5.

$$irf = 1 - ipf \tag{4.5}$$

As the formula suggests, the irf value decreases when ipf value increases. The irf is favored when the entropy is low, which means that when the part variety in the pool is low, i.e. there is a variance in the workloads of different part types, the routing flexibility of the shop is favored. This would be the case when workload is heavily concentrated on a few part types hence routing flexibility is to help get these part types through the shop as fast as possible.

4.1.3.4 Calculation of CR_p

The critical ratio is calculated for each order (*CRorder*) in the pool according to the formula given in Equation 4.6.

$$CRorder_i = \begin{cases} \dfrac{partProcessingTime \times batchSize_i}{dueDate_i - nextPeriod} & if\ dueDate_i > nextPeriod \\ CRmax & otherwise \end{cases} \tag{4.6}$$

CRorder is assigned to *CRmax* value when the order is tardy. *CRmax* is a value higher than the maximum *CRorder* value allowed for a non-tardy order.

By summing the $CRorder_i$ values of the orders of the same part type, total critical ratio CR_p is found for that part type.

4.1.3.5 Calculation of $CRexp_p$

$CRexp_p$ is a parameter calculated for estimating the critical values of each part type that will result from the order arrivals that will occur in the following period. The expectation of the critical values of each part type is used as an estimation method. The calculation of expected critical value for each part type is given as in Equation 4.7.

$$CRexp_p = \frac{partProcessingTime_p \times E(batchSize)}{\left\lfloor \dfrac{\dfrac{IAT}{prob_p} + F \times partProcessingTime_p \times E(batchSize)}{periodLength} \right\rfloor + 1} \tag{4.7}$$

The numerator is the expected workload of an order. The denominator is the expected due date of the part p arrival. $\frac{IAT}{prob_p}$ is the expected arrival time of part p, and it is added to the due date assigned by TWK.

This formula uses the environment decisions (part type assignment, inter-arrival time of orders, period length, etc.) and due date assignment formula that will be introduced in Chapter 6. The use of the formula will be clearer when these are introduced.

4.1.3.6 Calculation of $CRant_p$

$CRant_p$ is a parameter calculated for taking the critical values of anticipated order arrivals into account.

Inter-arrival time of orders is assumed exponential distributed with mean IAT. The probability of an arriving order be of type p is $prob_p$. Then inter-arrival time between two orders of type p is also exponential and its mean is $IAT/prob_p$.

The probability of having no arrivals of type p during a production period is calculated for each part. If this probability is greater than the probability of having at least one arrival of type p, then $CRant_p$ value for that order is taken as 0. If the probability of having at least one arrival of type p is greater, then an order arrival of type p with expected batch size is taken as one of the anticipated arrivals in the next period and $CRant_p$ value is calculated accordingly. Equation 4.8 shows the calculation of $CRant_p$.

$$CRant_p = \frac{partProcessingTime_p \times E(batchSize)}{\left\lfloor \dfrac{F \times partProcessingTime_p \times E(batchSize)}{periodLength} \right\rfloor + 1} \tag{4.8}$$

F is the flow allowance parameter of TWK. The difference of $CRant_p$ from $CRexp_p$ is that, $CRant_p$ is calculated as if part p will arrive at the beginning of the next period.

Anticipating an order that is not yet realized and changing the model parameters (for example $CRtot_p$, see Section 4.1.3.7) accordingly may lead to poor performance of FM in the current period. However the poor performance of the shop in the current period is taken to be tolerable to obtain a global advantage in the long run. This notion is referred as extended schedule visibility in the ORR review mentioned in Bergamaschi et al. [1]. IT is also emphasized in Chapter 2.

4.1.3.7 Calculation of $CRtot_p$

Three different versions of $CRtot_p$ are calculated for experimenting reasons that will be introduced in Chapter 6. Calculated $CRexp_p$ and $CRant_p$ values are added to CR_p values used.

The first $CRtot_p$ version is without estimated or anticipated term, calculated using Equation 4.9

$$CRtot_p = CR_p \tag{4.9}$$

The second version is generated by adding the estimation term $CRexp_p$ to the CR_p values as in Equation 4.10.

$$CRtot_p = CR_p + CRexp_p \tag{4.10}$$

The third version is constructed by addition of $CRant_p$ term to the CR_p term as in Equation 4.11.

$$CRtot_p = CR_p + CRant_p \tag{4.11}$$

The use of different versions will be made explicit in Chapter 6.

4.1.3.8 Calculation of $CRtot'_p$

$CRtot'_p$ values are calculated from $CRtot_p$ according to the procedure introduced in Section 3.2.2.

4.1.3.9 Calculation of *intrap*

The $intrap_p$ is calculated as in Equation 4.12.

$$intrap_p = \frac{CRtot_p}{\sum CRtot_p} \tag{4.12}$$

It shows the relative criticality level for every part type p. It is used in calculating the process flexibility measure for a given tool loading.

4.1.3.10 Calculation of *intrar*

The $intrar_p$ is calculated as in Equation 4.13.

$$intrar_p = \frac{CRtot'_p}{\sum CRtot'_p} \tag{4.13}$$

$intrar_p$ shows the relative operation count weighted criticality level for every part type p. It is used in calculating the routing flexibility measure for a given tool loading.

4.1.4 Flexibility Measures

The flexibility measures are defined in Chapter 3. This section will introduce the calculation of the measures with the parameters and variables defined in FM.

The flexibility measure defined in Chapter 3 is a non-linear measure with the defined variables. A linear approximation procedure will be introduced in this section.

4.1.5 Process Flexibility

Calculation of process flexibility measure is introduced in Section 3.2.1. Binary variable c_p is introduced as a variable of the FM that is 1 when the part is producible, 0 otherwise. *ctot* is the variable that represents the total process flexibility realized by a tool loading. Then *ctot* in FM is calculated as in Equation 4.14.

$$ctot = \sum_{p=1}^{|P|} intrap_p \times c_p \tag{4.14}$$

4.1.6 Routing Flexibility

Routing flexibility measure is calculated as in Section 3.2.2.

<u>**Approximation of Routing Flexibility**</u>

The routing flexibility for a specific part type is found by dividing the number of opened routes of the corresponding part type (NR_p) to the maximum number of routes possible ($maxr_p$)for that part type.

Using the variable x_{ij} defined for NR_p, the routing flexibility for part p can be defined as follows. Let this ratio be RR_p.

$$RR_p = \frac{NR_p}{maxr_p} = \frac{\prod_{i \in S_p} \sum_{j=1}^{|J|} x_{ij}}{maxr_p} \tag{4.15}$$

Thus the routing flexibility measure is non-linear. For the sake of linearizing this expression, two approximations are made. The first is approximating this expression by inserting the logarithms of the nominator and denominator as in Equation 4.16.

$$RR_p^{'} = \frac{\sum_{i \in S_p} \log \sum_{j=1}^{|J|} x_{ij}}{\log maxr_p} \tag{4.16}$$

The second approximation comes from linearizing the logarithm function. For a producible p and fixed i, x_{ij} takes values of $1, 2, \cdots, |J|$. A linear approximation for logarithm function can be found using linear regression where $1, 2, \cdots, |J|$ are independent and $\log(1), \log(2), \cdots, \log(|J|)$ are dependent variables. When a linear regression model is fitted, the linear approximation function for logarithm of number of routes is found. The approximation of the total routing flexibility is named *dtot* and calculated as in Equation 4.17.

$$dtot = \frac{\sum_{i \in S_p} \alpha \left(\sum_{j=1}^{|J|} x_{ij} \right) + \beta}{\log maxr_p} \tag{4.17}$$

Where α is the slope and β is the intercept of the fitted line by linear regression model.

Figure 4.1 shows the approximated line by linear regression and the natural logarithm curve for 4 machines ($\alpha = 0.456, \beta = 0.347$).

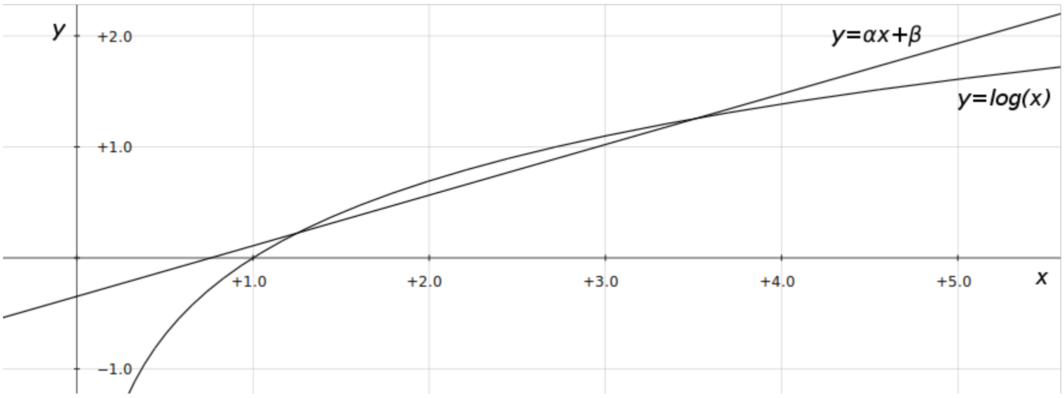

Figure 4.1: Approximation of natural logarithm

4.1.7 Product Flexibility

Product flexibility is not maximized in the model. The solutions of the model is forced to have certain level of product flexibility by a constraint added. This constraint is called the product flexibility constraint. It makes sure that the sum of the arrival probabilities of the part types that miss 2 or more tools is below a certain level. This constraint assures that in the next period, the shop will be easily changed to cover the part types that are not producible at present, in case it is needed.

4.1.8 Objective Function of the Model

The objective function f_{FM} accounts for the process and routing flexibility measures defined.

$$maximize\ f_{FM} = ipf \times ctot + irf \times dtot \tag{4.18}$$

4.1.9 Constraints of the Model

The set of constraints of FM can be listed as follows

- Process flexibility related constraints
- Routing flexibility related constraints
- Product flexibility related constraints
- Tool capacity constraints
- Variable restrictions

Process Flexibility Related Constraints

$$ctot - \sum_{p=1}^{|P|} \left(intrap_p \times c_p \right) = 0 \tag{4.19}$$

$$c_p - \sum_{i \in S_p} \sum_{j=1}^{|J|} x_{ij} <= 0 \qquad \forall p \in P \tag{4.20}$$

Routing Flexibility Related Constraints

$$dtot - \sum_{p=1}^{|P|} \left(intrar_p \times \left(\frac{d_p}{maxr_p} \right) \right) = 0 \tag{4.21}$$

$$d_p - \log \left(maxr_p \right) c_p <= 0 \qquad \forall p \in P \tag{4.22}$$

$$d_p <= \sum_{i \in S_p} \left(\alpha + \beta \times \left(\sum_{j=1}^{|J|} x_{ij} \right) \right) + 1 - c_p \qquad \forall p \in P \tag{4.23}$$

Product Flexibility Related Constraints

$$\sum_{i=1}^{|I|}(operpart_{ip} \times z_i) >= \sum_{i=1}^{|I|} operpart_{ip} - MON\, c_p \qquad \forall p \in P \qquad (4.24)$$

$$v_i >= z_i - \sum_{j=1}^{|J|} x_{ij} \qquad \forall i \in I \qquad (4.25)$$

$$MON\, y_p >= \sum_{i \in S_p} v_i - 1 \qquad \forall p \in P \qquad (4.26)$$

$$\sum_{p=1}^{|P|} y_p \times prob_p <= PFP \qquad (4.27)$$

Tool Capacity Constraints

$$\sum_{i=1}^{|I|} x_{ij} <= MTC \qquad \forall j \in J \qquad (4.28)$$

Variable Restrictions

$$x_{ij} \text{ binary} \qquad \forall i \in I,\ \forall j \in J \qquad (4.29)$$

$$c_p \text{ binary} \qquad \forall p \in P \qquad (4.30)$$

$$z_i \text{ binary} \qquad \forall i \in I \qquad (4.31)$$

$$y_p \text{ binary} \qquad \forall p \in P \qquad (4.32)$$

$$ctot \geq 0 \qquad (4.33)$$

$$dtot \geq 0 \qquad (4.34)$$

$$d_p \geq 0 \qquad \forall p \in P \qquad (4.35)$$

$$v_i \geq 0 \qquad \forall i \in I \qquad (4.36)$$

FM has $|I| \times |J| + 2|P| + |I|$ binary variables and $|P| + |I| + 2$ non-zero continuous variables. It has $5|P| + |I| + |J| + 3$ many constraints.

Constraint 4.19 assigns total process flexibility to *ctot*.

Constraint 4.20 assures that c_p is not 1, when one of its operation is not loaded. The objective function forces it to be 1 when all tools are loaded.

Constraint 4.21 assigns total routing flexibility to $dtot$.

Constraint 4.22 assures that d_p is 0 when c_p is 0.

Constraint 4.23 assures that when c_p is 1 (part is producible), upper bound of d_p is the approximation of the logarithm of the number of routes for p.

Constraint 4.24 assigns 1 to z_i, if operation i is an operation of a part p such that $c_p = 0$ (non-producible part). It gives a non-positive lower bound for z_i otherwise (hence $z_i = 0$ otherwise).

Constraint 4.25 assigns 1 to v_i, if $z_i = 1$ and tool i is not loaded to any machine. It gives a non-positive lower bound for v_i otherwise (hence $v_i = 0$ otherwise).

Constraint 4.26 assigns 1 to y_p, if two or more operations of part p are not loaded to any machine.

Constraint 4.27 assures that total probability of parts with $y_p = 1$ is not to exceed PFP (non-producible part with at least two tools missing).

Constraint 4.28 assures that at most MTC tools can be loaded to any machine.

4.2 SETUP OPTIMIZATION AFTER FLEXIBILITY MODEL

SOFM makes tool interchange between machines in order to minimize setup time without changing the tool set loaded to the shop. When making tool interchanges it also preserves a balance of tools of producible and non-producible parts.

4.2.1 Assumptions of the Model

1. It takes time to unload/load a tool from a machine, this time is deterministic and the same for each tool.
2. Making more than one loading or unloading simultaneously on a machine is not possible.
3. Setup time is equal to the longest total loading-unloading time interval across

the machines.

Each machine is thought to be set independently. It is assumed that the shop has the enough resources for this. Automated machines are easier to unload/load tools as most work is done by programmed tasks. Hence machine operators can set up themselves. If the shop does not have enough resources, then the model can be updated by the change of the objective function. The new objective function should be the sum of setup times of the machines. Assumption 3 can be relaxed easily.

4.2.2 Notation

4.2.2.1 Variables

The variables used in the model are as follows.

y_{ij}: Binary variable that shows new tool-machine assignment, where

$$y_{ij} = \begin{cases} 1 & \text{if tool } i \text{ is assigned to machine } j, \\ 0 & \text{otherwise.} \end{cases}$$

a_{ij}: Binary variable that shows whether tool i is unloaded from machine j or not, where

$$a_{ij} = \begin{cases} 1 & \text{if } i \text{ is unloaded from } j, \\ 0 & \text{orherwise.} \end{cases}$$

b_{ij}: Binary variable that shows whether tool i is loaded to machine j or not, where

$$b_{ij} = \begin{cases} 1 & \text{if } i \text{ is loaded to } j, \\ 0 & \text{orherwise.} \end{cases}$$

$setupTime$: Nonnegative variable that shows the setup time.

$nOper$: Integer variable that corresponds to largest difference in the number of tools loaded on two different machines for any producible or non-producible part.

4.2.2.2 Parameters

The parameters used in the model are as follows.

z_{ij}: Binary parameter that shows the tool-machine assignment of the previous period, where

$$z_{ij} = \begin{cases} 1 & \text{if tool } i \text{ is assigned to machine } j, \\ 0 & \text{otherwise.} \end{cases}$$

x_{ij}: Binary parameter that shows the tool-machine assignment after FM is solved, (FM's decision variable becomes Setup Model's parameter).

$$x_{ij} = \begin{cases} 1 & \text{if tool } i \text{ is assigned to machine } j, \\ 0 & \text{otherwise.} \end{cases}$$

x_{ij}'s are the targeted tool set.

c_p: Binary parameter that shows the producible and non-producible parts after FM is solved, where

$$c_p = \begin{cases} 1 & \text{if } p \text{ is producible,} \\ 0 & \text{otherwise.} \end{cases}$$

UT: Time required to unload a tool from a machine.

LT: Time required to load a tool to a machine.

TBP: Tool balance (between machines) parameter

4.2.3 Objective Function of the Model

The objective is to minimize the setup time. $nOper$ is also in the objective function with a small coefficient to ensure that if there are alternative solutions with the same setup time, the one with the small $nOper$ value, more balanced in terms of tool dispersion, is favored.

$$minimize f_{SOFM} = setupTime + \epsilon \times nOper \tag{4.37}$$

4.2.4 Constraints of the Model

$$setupTime \geq UT \times \sum_{i=1}^{|I|} a_{ij} + LT \times \sum_{i=1}^{|I|} b_{ij} \qquad \forall j \in J \tag{4.38}$$

$$\sum_{j=1}^{|J|} y_{ij} = \sum_{j=1}^{|J|} x_{ij} \qquad \forall i \in I \tag{4.39}$$

$$y_{ij} = z_{ij} - a_{ij} + b_{ij} \qquad \forall i \in I,\ \forall j \in J \tag{4.40}$$

$$\sum_{i=1}^{|I|} y_{ij} \leq MTC \qquad \forall j \in J \tag{4.41}$$

$$\sum_{\substack{i=1 \\ operpart_{ip}=1}}^{|I|} y_{i,j1} - \sum_{\substack{i=1 \\ operpart_{ip}=1}}^{|I|} y_{i,j2} - nOper \leq 0 \qquad \forall j1, j2 \in J, j1 \neq j2 \quad \forall p \in P \tag{4.42}$$

$$nOper \leq TBP \tag{4.43}$$

$$y_{ij}, a_{ij}, b_{ij}\ binary \qquad \forall i \in I,\ \forall j \in J \tag{4.44}$$

$$setupTime \geq 0 \tag{4.45}$$

$$nOper\ integer \tag{4.46}$$

ϵ is chosen to be 0.01 considering the tool load and unload times that will be introduced in Chapter 6.

SOFM has 1 integer, 1 non-zero continuous and $3 \times |I| \times |J|$ many binary variables. It has $|J| \times |J-1| \times |P| + |I| \times |J| + 2 \times |J| + |I|$ many constraints.

Constraint 4.38 ensures that $setupTime$ is greater than the total tool load-unload time of each machine.

Constraint 4.39 ensures that the new loading will have the same number of tools from each type as in the output of FM.

Constraint 4.40 assigns 1 to a_{ij} if tool i is unloaded from machine j and assigns 1 to b_{ij} if tool i is loaded to machine j.

Constraint 4.41 assures that at most MTC many tools are loaded to each machine.

Constraint 4.42 assures that difference between number of tools of part p loaded to each machine is less than $nOper$.

Constraint 4.43 assures that $nOper$ is less than TBP.

FM and SOFM run in dynamic environments. The order pool changes through periods. Tool distribution between machines is balanced for creating a balanced workload between machines. This notion is proposed by Land and Gaalman [8].

Workload control strategy by means of load balancing is also emphasized in [1]. Bergamaschi et al. [1] further claim that smoothing loads both space-wise and time-wise can be a powerful weapon to improve the absolute performances of the shop as well as its robustness against the environment perturbations. The tool balancing target of SOFM is to provide the superiority indicated by these authors.

4.3 FORWARD FINITE LOADING

Loading orders to a shop in the dynamic environment of MTO has been shown to be critical in both WLC and ORR [8], [12], [1], [13]. For the sake of comparing the flexibility management method with a loading method from literature, forward finite loading method is used.

Forward finite loading is a well known method in the literature, for loading jobs to machines, see [23] for example. In a flexible shop environment different than loading in classical job shops, machines can process some common operations (tools may be duplicated on different machines). The forward finite loading algorithm is modified to allow for loading on multiple machines due to the tool duplication when loading orders. This is realized by assigning as many copies of a tool as needed/can fit to the available tool slots of the identical flexible machines in the shop.

This modified forward finite loading method will be introduced in this section.

4.3.1 Forward Finite Loading Method

When loading orders with constrained machine capacities in the forward direction in time, first the orders are sorted in the order of nondecreasing due dates.

After sorting the orders, operations of orders are loaded to machines starting from the first one, and remaining capacity of machines are updated after loading each operation. When the total machine capacity available is below a threshold or the end of the list is reached, the method stops loading.

Figure 4.2 summarizes the classical forward finite loading method.

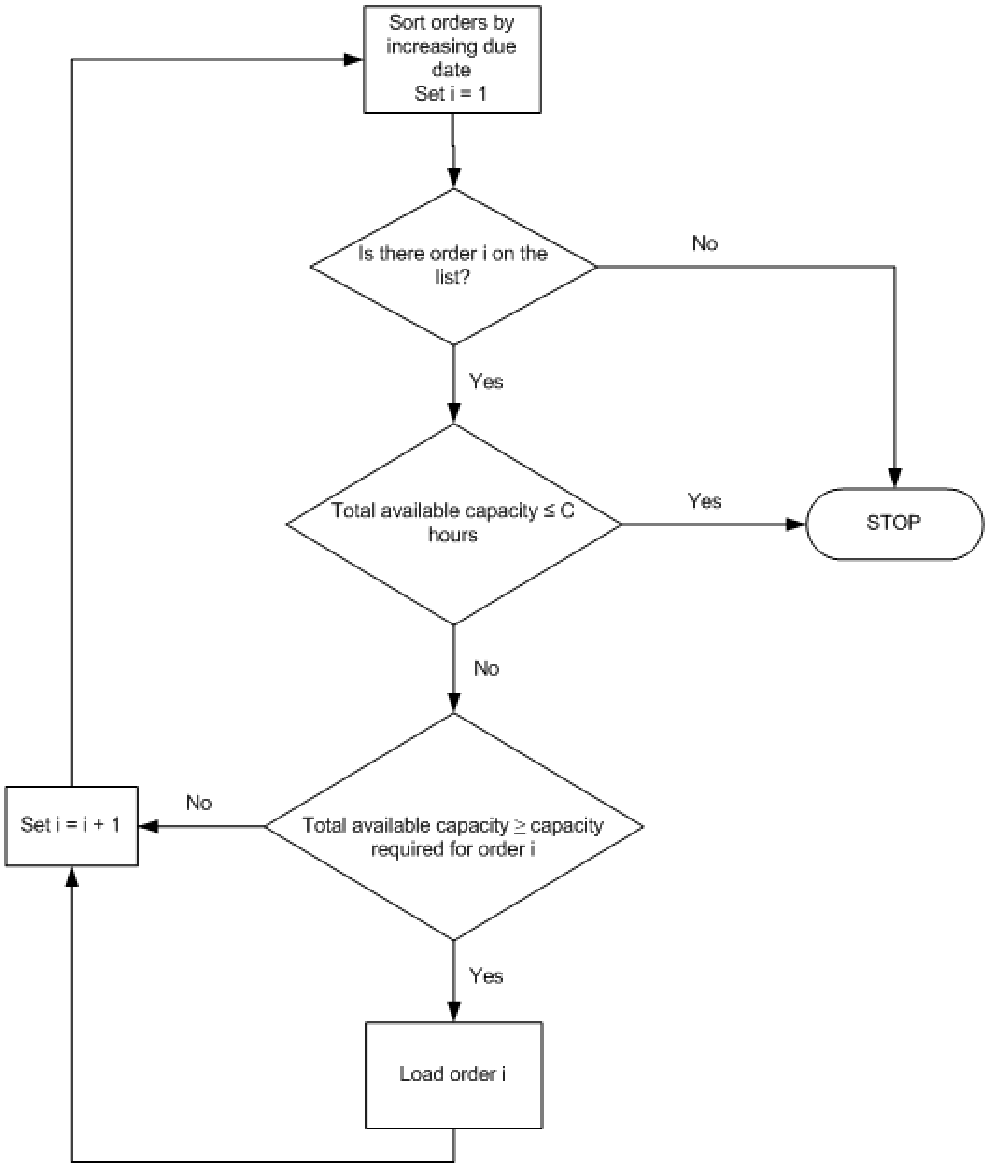

Figure 4.2: Classical forward finite loading flow chart

4.3.2 Modified Forward Finite Loading Method

The classical forward finite loading method is modified for the requirements of the flexible shop. It is modified to allow setting up the different machines for common operations (tool duplications).

The steps of the modified forward finite loading method can be listed as follows.

Step 1 Sort the orders in ascending order of the due dates. For the orders with the same due date, put the ones with fewer number of operations to ahead of the others in the list (This is done to save as many tool slots as possible while serving urgent orders first).

Set $i = 1$.

Step 2 Update machine capacities and tool slots if i^{th} order in the list is loaded.

If total capacity is less than C, STOP.

Else, if no tool slot is available, STOP.

Else, if there is no capacity on the machine that the required tool loaded, load a duplicate for that tool.

Else, if there is no capacity for the i^{th} order, set $i = i + 1$, repeat Step 2.

Else, if no slot is available for the i^{th} order, set $i = i + 1$, repeat Step 2.

Step 3 Remove the i^{th} order from the list, go to 2.

Figure 4.3 presents the steps of the modified FFL method in a flow chart.

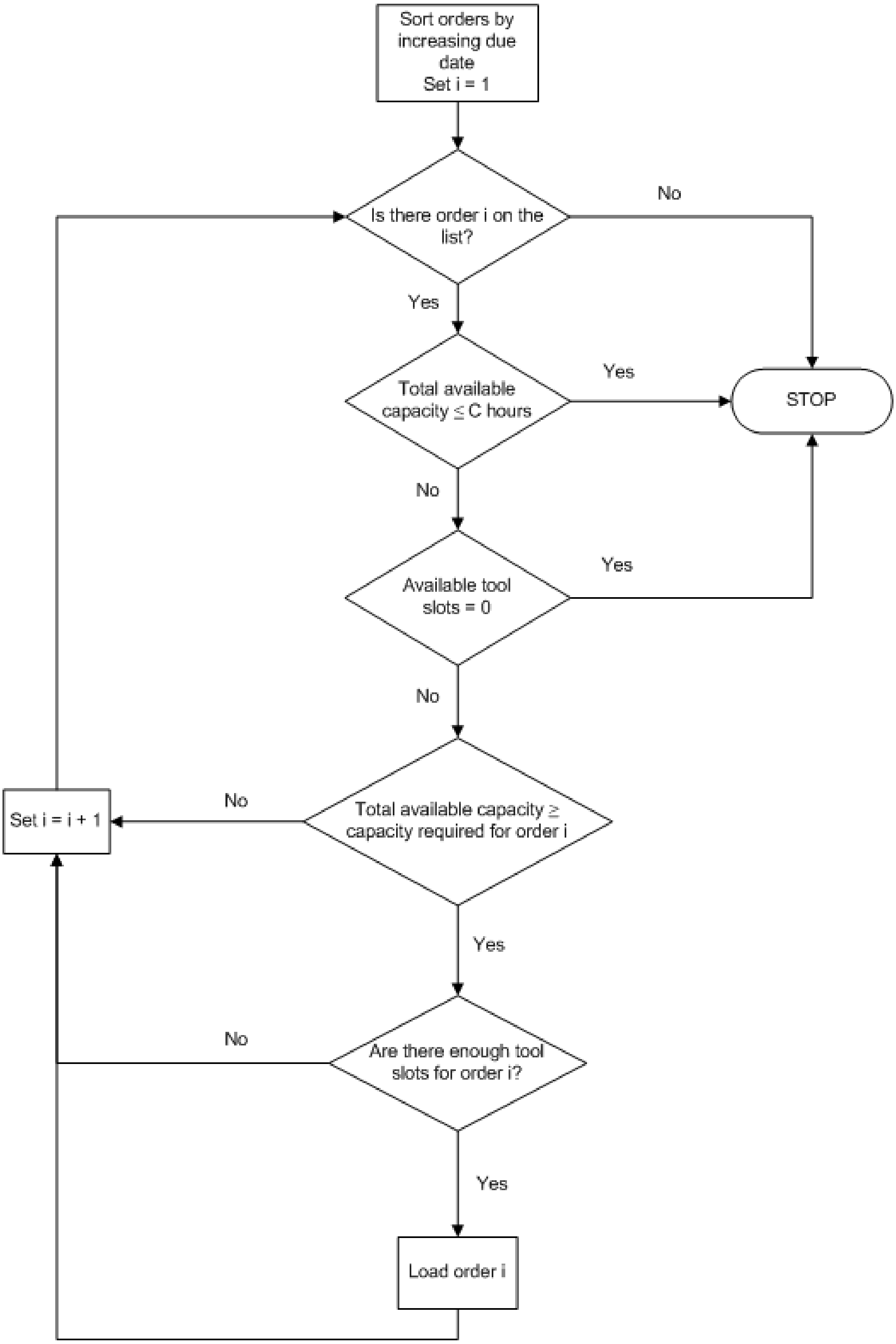

Figure 4.3: Modified forward finite loading flow chart

4.4 SETUP OPTIMIZATION AFTER FFL

As in the case of FM (Section 4.1), a setup optimization model (SOFFL) is run after the tool loading is determined by the modified FFL method. SOFFL is different from SOFM in Section 4.2.

SOFM model makes tool interchanges between machines without changing the set of tools loaded to the set of machines on the shop. This approach can not be used for FFL method. Since FFL uses machine capacities when assigning tools to machines, changing tools between machines may result in over-capacity or under-capacity loaded machines. A setup optimization model that does not change the specific tool set assigned to a machine, but decides which machine this predetermined tool set is to be loaded on. The main reason for this is the existing tool set on every machine. An existing tool set on a machine may be more appropriate for the loading of another machine in terms of the setup (tool swaps). This results in a more restrictive model compared to SOFM, and the source of the restriction is the capacity consideration of machines when loading with FFL.

4.4.1 Assumptions of the Model

All assumptions of the SOFM (Section 4.2) are valid for this model. Additionally capacities determined by the FFL method should not be changed by the SOFFL as stated in Section 4.4.

Variables

x_{ij}: Binary variable that assigns order loading of machine i entirely to machine j, where

$$x_{ij} = \begin{cases} 1 & \text{if loading of machine } i \text{ is loaded to machine } j, \\ 0 & \text{otherwise.} \end{cases}$$

$setupTime$: Nonnegative variable that shows the setup time.

mc_j: Nonnegative variable that shows the setup time of machine j.

Parameters

y_{ij}: Parameter that shows the total setup time required to install tool loading of machine i entirely to machine j due to the required tool replacements. This is calculated before the SOFFL is run by comparing the existent and needed tools for loading from the solution of FFL.

4.4.2 Objective Function of the Model

Objective function of the model is minimizing the resultant setup time.

$$minimize\ f_{SOFFL} = setupTime \tag{4.47}$$

4.4.3 Constraints of the Model

$$setupTime \geq mc_j \qquad \forall j \in J \tag{4.48}$$

$$mc_j = \sum_{i=1}^{|J|} x_{ij} y_{ij} \qquad \forall j \in J \tag{4.49}$$

$$\sum_{i=1}^{|J|} x_{ij} = 1 \qquad \forall j \in J \tag{4.50}$$

$$\sum_{j=1}^{|J|} x_{ij} = 1 \qquad \forall i \in J \tag{4.51}$$

$$x_{ij}\ binary \qquad \forall i \in J, \forall j \in J \tag{4.52}$$

$$setupTime \geq 0 \tag{4.53}$$

In fact this is a standard bottleneck assignment model as it is in the minmax form, with a set of assignment constraints.

Constraint 4.48 ensures that the setup time is greater than the tool replacement (loading/unloading) time of any machine.

Constraint 4.49 constraint assigns mc_j the total tool loading/unloading time of machine j.

Constraint 4.50 ensures that a resultant loading is assigned to only one of the machines.

Constraint 4.51 ensures that a machine is loaded with only one entire machine loading. This is needed to maintain loading feasibility realized in FFL.

Constraints 4.52 and 4.53 are variable restrictions.

CHAPTER 5

SIMULATION MODEL

This chapter will introduce the simulation model developed to represent a typical flexible shop. Understanding the power and limitations of the flexibility management approach for MTO is aimed at using this simulation model. The simulation model simulates shop operations as a series in production periods. The period refers to a production cycle such as a shift, a day or a week. This study requires a periodic approach (as mentioned in Chapter 3 since the FMS modeled will be loaded for a specific time interval and at the end of this interval a new loading will be installed. This approach is referred as time bucketing in [1].

The simulation model interacts with the flexibility model at period transactions. At each period end the flexibility model is solved and resulting tool loading is given to the simulation model as input. Then simulation model is run and a new pool situation is supplied to the FM for the next period. Figure 5.1 shows this interaction.

The functions of the simulation model consists of the all operations that are maintained at the shop floor and the order arrivals to represent the passing of the production cycle. These operations include order release, processing of orders, dispatching, pool management and computation of performance measures during simulation.

Orders are released to shop according to the ORR defined in Section 3.4. When orders are released to the shop they are split and each part moves independently. By allowing split and independent part move, advantage of routing flexibility and immediate start on the next machine is used. The parts dispatch according to the minimum load as indicated in Section 3.5. Release procedure defined in Section 3.4.2 is activated when one of the release triggers defined in Section 3.4.1 occurs. Orders are released to the shop until the end of the production period. When the end of the period is reached the orders in progress are waited to finish. When all the orders on the shop get processed the simulation ends.

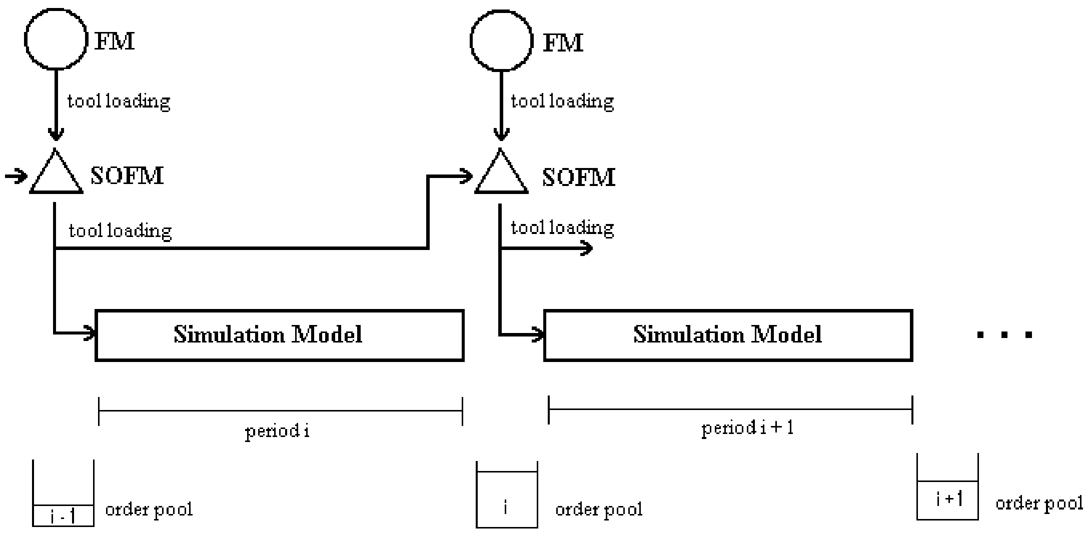

Figure 5.1: Flexibility model and simulation model interaction

5.1 ASSUMPTIONS OF THE MODEL

Some simplifying assumptions are made in simulating the flexible shop. These assumptions are as follows.

1. Machines are assumed to be reliable and do not break down. They do not require preventive maintenance.
2. Operation processing times are deterministic and do not vary by the machine.
3. Orders can be split to get processed in parallel on different machines.
4. A part does not need a transporter to move from a machine to another, and transfers dot not take any time.

5. Machines have infinite buffer space.

6. All orders released to the shop must be completed at the end of the simulation. Orders are not allowed to get processed partially.

7. Machine setups are done independently.

Since the simulation model is developed to test the flexibility management approach, machine breakdown is left out of the scope. Orders are allowed to split to reveal the routing flexibility effect. Including material handling system and finite buffer capacity machines with a change in the flexibility management approach may be topic of another research. They are out of the scope of this study. Partial processing of orders are not allowed. This assumption is essential since set of tools loaded is changed in each period. Enough resource is assumed available (due to programmable automation and simplified tool changeovers in advanced flexible machines) to make machine setups in parallel.

5.2 ORDER ARRIVAL

Inter-arrival time of orders are assumed to be independent, identical and exponentially distributed. Exponential inter-arrival times are assumed and used frequently in the literature, see [2], [24], [21], [3] and [7].

Each order is assumed to be of a specific part type with a certain known probability. As a result given the number of arrivals in a production cycle counts of part types of arrived orders follow multinomial distribution.

Batch size of an order is assigned using a discrete uniform distribution as in [24]. In the absence of information uniform distribution is often preferred. Each order batch is treated separately however it can be freely split to its elements or joined through the flow.

5.3 DUE DATE ASSIGNMENT

Due date is assigned according to total work content (TWK) discussed in [20]. As its name implies TWK utilizes the total work content of orders to assign due dates. For this study TWK is modified to respond the periodic production system utilized in this thesis. Due dates are assigned in units of production periods according the following formula.

$$dueDate_i = ArrivalPeriod_i + \left\lfloor \frac{arrivalTime_i + F \times partProcessingTime_i \times BS_i}{periodLength} \right\rfloor + 1 \tag{5.1}$$

where F is the flow parameter ($F \geq 1$) and BS is the batch size. TWK is believed to assign due date effectively, see [25].

Figure 5.2 illustrates the extra safety in due date assignment procedure.

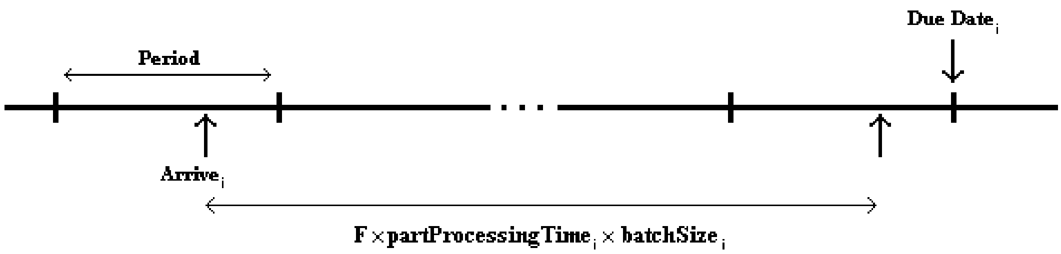

Figure 5.2: Due date assignment

A shop or pool dependent due date rule is not chosen on purpose. Due dates as demanding (tight) as TWK can singly get are aimed. This is reflected in tardiness calculation.

5.4 PERFORMANCE MEASURES

Several performance measures are gathered during the simulation-optimization cycles. These performance measures are as follows.

- Batch Size Weighted Average Periods Waited
- Number of Tardy Orders
- Batch Size Weighted Percentage of Tardy Orders
- Batch Size Weighted Percentage of No-period-wait Orders
- Realized Setup Times
- Machine Utilization Levels
- Realized Lengths of Production Period

The calculation of performance measures and their purpose will be introduced in Chapter 6.

CHAPTER 6

EXPERIMENTAL STUDY

In this chapter, the experimental study conducted to test of the proposed flexibility management approach is introduced.

The parameters of the flexibility and simulation model are determined first. The principles in setting these parameters have been either reasonable choices relative to the existing literature or meaningful levels for the desired tests. Next experimental runs are conducted following pilot runs to set some experimental run properties.

After the experimental runs, a robustness study is carried out. It tests the behavior of the flexibility management approach in the existence of wrong probability distribution information. The robustness of the approach to probability information is tested since in most of the cases probability information is estimated and it is exposed to error.

Following sections explain the details of the environment and the results of experimental runs and robustness study.

6.1 ENVIRONMENT

When determining the environment of the models developed two major points are taken into account. The first is the environments of the models of the studies conducted in the literature and the second is the necessity of creating an environment that gives the opportunity to test the capabilities of the flexibility management approach proposed.

The environment parameters are chosen such that the resulting flexible shop has an adequate range for three kinds of flexibility defined in Chapter 3.

6.1.1 Size of the Shop

[24] explains that 4 or 5 number of machines is recommended for FMS. A 4-machine shop is assumed in [25]. 4-machine shop is also found suitable for the scope of this study.

6.1.2 Magazine Capacity

Magazine capacity is taken as 5 in [24]. To create a larger range for routing flexibility magazine capacity of each machine is set to 10 slots. With 10 tool capacity machines, number of routes possible for a part is higher.

Another reason for choosing tool capacity as 10 is to create a shop with enough number of part types and operations so that the role of different flexibility levels will become evident. Moreover magazine capacity of 10 is closer to the realistic CNC machine tool capacities.

6.1.3 Part Types and Operations

20 different part types with distinct operation sequences are defined. The part types also vary in the number of operations. Number of operations a part requires is chosen from a broad range to represent a shop with a large number of job types.

Having different number of operations also differentiates the parts in terms of the different flexibility potentials. A part with small number of operations requires fewer tools slots. This creates a situation where some parts increase process flexibility with fewer number of slots compared to others.

Parts with different number of operations also differ in terms of their potential of asking more routing flexibility. Parts with more operations have a larger likelihood to realize routing flexibility potential since a larger number of opportunities to add routes are possible. Maximum number of routes is larger so the ratio is harder to increase but more tool requirement contribute to offering new routes.

This situation creates an imbalance among part types in terms of flexibility potentials. This may be expected to maintain a part-mix to realize flexibility types at a reasonable level for each simultaneously.

When deciding on the total number of different operations and operation sequences of parts; number of machines, tool capacity of machines and number of part types are taken into account.

50 different operation types are defined in total. This exceeds the largest sum of operation variety possible (i.e. 40 with 4 machines × 10 slots). Hence not all operations can be loaded concurrently. The operation processing times (in hours) are given in table 6.1.

Table 6.1: Operation processing times (in hours)

oper	time	oper	time	oper	time	oper	time	oper	time
1	0.120	11	0.144	21	0.104	31	0.120	41	0.132
2	0.164	12	0.168	22	0.176	32	0.164	42	0.168
3	0.144	13	0.132	23	0.104	33	0.056	43	0.196
4	0.184	14	0.180	24	0.184	34	0.184	44	0.180
5	0.088	15	0.100	25	0.128	35	0.144	45	0.100
6	0.044	16	0.120	26	0.056	36	0.104	46	0.120
7	0.176	17	0.164	27	0.168	37	0.176	47	0.164
8	0.044	18	0.132	28	0.088	38	0.044	48	0.088
9	0.196	19	0.180	29	0.196	39	0.128	49	0.196
10	0.128	20	0.088	30	0.100	40	0.144	50	0.056

In Table 6.1, oper stands for operation number and time stands for unit operation processing time in hours.

The number of operations for a part is chosen to be uniformly distributed between 4 and 12. A uniform distribution is used to create a part types with varying number of operations. A set of part types with varying number of operations is aimed.

The operation sequences of part types are as is Table 6.2.

Given the operation sequences, tool sharing among part types is investigated. Common number of operations is important since it shows the tool sharing between part

Table 6.2: Operation sequences of part types

	operations in sequence number											
part type	1	2	3	4	5	6	7	8	9	10	11	12
1	17	3	19	9	10	34	45	2	5	11	22	35
2	35	11	19	3	16	31	32	21	48	41	42	14
3	41	3	19	25	33	34	35	11	44	45	5	-
4	25	11	34	16	18	41	26	35	28	50	38	-
5	31	35	5	11	44	10	19	17	39	30	-	-
6	10	3	7	35	19	1	5	18	15	47	-	-
7	1	10	35	29	17	20	11	19	47	-	-	-
8	28	17	14	3	35	27	45	7	10	-	-	-
9	17	12	3	27	15	11	7	32	-	-	-	-
10	29	17	35	36	20	45	10	16	-	-	-	-
11	4	19	17	46	47	6	39	33	-	-	-	-
12	19	40	4	6	35	47	21	-	-	-	-	-
13	35	24	4	13	33	43	49	-	-	-	-	-
14	40	19	13	24	47	46	33	-	-	-	-	-
15	6	10	33	19	47	49	-	-	-	-	-	-
16	43	3	9	17	45	11	-	-	-	-	-	-
17	45	3	19	7	9	-	-	-	-	-	-	-
18	47	45	3	35	23	-	-	-	-	-	-	-
19	47	45	3	37	-	-	-	-	-	-	-	-
20	3	47	8	45	-	-	-	-	-	-	-	-

types. Common operations also complicates the problem of tool loading since it effects the flexibility measures. If a tool is duplicated for opening extra routes for a part type, number of routes for other parts that has the same operation also increases. The process flexibility can be increased easily for the set of parts that have common operations. This is true for product flexibility as well.

Assume that $commonOper_{ij}$ is a parameter that shows number of common operations of part type i and j. Let μ_1 be the expected number of common operations of any two part type. It is calculated using the Equation 6.1. Let σ_1 is the standard deviation of the number of common operations for any of the two part types, then it is found using Equation 6.2.

$$\mu_1 = \frac{\sum_{i=1}^{20} \sum_{j=1}^{20} commonOper_{ij}}{400} \tag{6.1}$$

$$\sigma_1 = \sqrt{\frac{\sum_{i=1}^{20}\sum_{j=1}^{20}\left(commonOper_{ij} - \mu_1\right)^2}{400}} \tag{6.2}$$

The number of common operations are also investigated excluding the comparison of same type of parts. Let μ_2 and σ_2 be the expected value and standard deviation define for this measure. Their calculation is given in Equation 6.3 and 6.4 respectively.

$$\mu_2 = \frac{\sum_{i=1}^{20}\sum_{\substack{j=1 \\ i \neq j}}^{20} commonOper_{ij}}{380} \tag{6.3}$$

$$\sigma_2 = \sqrt{\frac{\sum_{i=1}^{20}\sum_{\substack{j=1 \\ i \neq j}}^{20}\left(commonOper_{ij} - \mu_2\right)^2}{380}} \tag{6.4}$$

For the defined operation sequences μ_1 is 2.32 and σ_1 is 1.94. μ_2 is 2.03 and σ_2 is 1.99. When μ_2 increases a larger set of part types can be produced with the limited magazine capacity. μ_2 shows that for the defined operation sequences number of common operations for any two different part type is around 2. The standard deviation (σ_2) is around 1.99 which can be considered high relative to the μ_2. This underscores a set of parts with varying number of common operations.

Unit part processing times (in hours) calculated from operation sequence of part types and operation processing times are given in Table 6.3. Average and standard deviation of part processing times are 1.11 and 0.36 respectively. Standard deviation is large releative to the mean. This indicates part processing times vary and they are from a large range.

6.1.4 Product Mix at Arrivals

Two distinct probability values (0.025 and 0.075) are used in the discrete probability distribution of part types. This generates equal changes of arrival among two groups.

Table 6.3: Unit part processing times (in hours)

part type	processing time	part type	processing time
1	1.812	11	1.040
2	1.688	12	0.964
3	1.480	13	1.092
4	1.228	14	0.980
5	1.376	15	0.768
6	1.376	16	0.944
7	1.328	17	0.796
8	1.292	18	0.656
9	1.228	19	0.584
10	1.044	20	0.452

This is to increase variability within the two groups of part types and to make part types with larger workloads to be less likely to arrive in aggregate (i.e. 25% larger, 75% smaller). Table 6.4 shows the probability of an arriving order to be of the corresponding type.

Table 6.4: Probability distribution of part types

part type	probability	part type	probability
1	0.025	11	0.075
2	0.025	12	0.075
3	0.025	13	0.075
4	0.025	14	0.075
5	0.025	15	0.075
6	0.025	16	0.075
7	0.025	17	0.075
8	0.025	18	0.075
9	0.025	19	0.075
10	0.025	20	0.075

6.1.5 Production Period

The production period is determined as a week. Assuming 8 hour shift in a day, the production period length is taken as 40 hours in regular time to resemble the real life operation.

6.1.6 Size of the Batch

A discrete uniform distribution is used for determining the batch size of orders. The batch size of an order is between 5 and 15 as in [24].

6.1.7 Order Arrival

Inter-arrival time of orders are taken exponential distributed as indicated in Chapter 5. The mean of the exponential distribution is taken as 3.1 hours. The mean is selected as 3.1 in order to satisfy a medium level of shop congestion (78%).

With the defined inter-arrival time, product mixture and part processing times, shop congestion (γ) is calculated using Equation 6.5.

$$E(\gamma) = \frac{E(arrivals\ in\ a\ period) \times \left(E(BS_i) \times \sum_{i=1}^{20} probability_i \times PPT_i \right)}{total\ machine\ time\ available\ in\ a\ period} \tag{6.5}$$

where PPT is the unit part processing time. Equation 6.6 shows the formula when some environment variables (number of arrivals, expected batch size) are inserted.

$$E(\gamma) = E(Utilization\ of\ a\ machine) = \frac{\frac{40}{3.1} \times \left(10 \times \sum_{i=1}^{20} probability_i \times PPT_i \right)}{4 \times 40} \tag{6.6}$$

The shop congestion calculated using this formula is 78%. This average value is realistic given the high variance in part type arrivals. Note that net utilization levels of the machines will be higher since the value calculated in Equation 6.6 ignores setup time.

6.1.8 Due Date

Due date is assigned according to the TWK rule as described in Chapter 5. The flow parameters F is taken as 6. This value is considered as a moderate value in terms of the tightness of the resulting due date, see [26]. For an arriving order after the part type and batch size is assigned, due date is assigned according to the Equation 6.7.

$$dueDate = ArrivalPeriod + \left\lfloor \frac{6 \times PPT \times batchSize}{40} \right\rfloor + 1 \qquad (6.7)$$

6.1.9 Tool Load and Unload Time

Tool load time and unload time are taken as 0.7 and 0.1 hours. Expected load of an order is the product of expected batch size and expected part processing time of a part. Expected batch size is 10 and expected part processing time is 0.97 hours. Then expected load of an order is 9.7 hours. A moderate part has 8 number of operations. Loading a moderate part will last 5.68 hours (8×0.7) where expected part processing time of an order is 9.7 hours.

6.1.10 Workload Norms

AL_1 and AL_2 levels are taken as 15 and 25 respectively. The DL_1 level is 3. The values of the norms are updated according to the method explained in Chapter 5. These levels of the workload norms were tested found reasonable by Süer [7].

6.1.11 CRmax, TBP and C

CRmax should be greater than the largest possible CR. Unit processing time of the part type with the largest unit processing time is 1.812, see Table 6.3. The largest batch size possible is 15, see Section 6.1.6. Then the maximum critical ratio possible is 27.18 (1.812×15). *CRmax* is taken as 30 as it should be greater than 27.18.

After the pilot runs the tool balance parameter (TBP) is chosen as 2.

C is the only parameter of the modified FFL method. It should be less than the order with the least possible workload. Unit processing time of the part type with the shortest unit processing time is 0.452 hours. The smallest batch size is 5. Then the least possible workload for an order is 2.26. C is chosen as 2 to be an integer not larger than 2.26.

6.2 OBJECTIVES AND EXPERIMENTAL FACTORS

Evaluating the power of flexibility management approach proposed is the main objective of the experimental study. 6 different versions of FM are developed. These models differ in terms of three factors; use of product flexibility, use of expectation, anticipation and inclusion product flexibility level. These factors are explained in the following sections.

6.2.1 Use of Product Flexibility

Two FM versions are constructed that are only restricted to process and routing flexibility to reveal the impact of product flexibility in flexibility management approach. This is done to perform a controlled experiment.

6.2.2 Expectation and Anticipation

Constructed models differ in terms of using the extra terms in calculating $CRtot_p$. These extra terms are $CRexp_p$ and $CRant_p$. When the expectation method used, $CRexp_p$ is used in calculating $CRtot_p$. When anticipation method used, $CRant_p$ is used. Calculation of $CRexp_p$ and $CRant_p$ are defined in Section 4.1.3.5 and 4.1.3.6 respectively. Calculation of different versions of $CRtot_p$ is defined in Section 4.1.3.7.

There is no test model in which both of the terms $CRexp_p$ and $CRant_p$ are used. Although there is a test model where neither of them is used. Creating a test model with neither of the estimation terms used is reasonable and will reveal the effect of the estimation methods. Using both of the estimation terms ($CRexp_p$ and $CRant_p$) is meaningless since both of them aim to take the next order arrivals into account and both make this estimation with different methods independently.

6.2.3 Product Flexibility Level

Two different levels of product flexibility are used to test the effect of product flexibility level in the flexibility management approach.

6.2.4 Categorization of the Models Constructed

Using the experimental factors defined the following versions of FM are constructed.

The first version is the FM with only the process and routing flexibility. There is no anticipation or expectation term added to $CRtot_p$ values calculated from pool. This model is abbreviated "wo".

The second version is the FM with only the process and routing flexibility but $CRest_p$ is added to $CRtot_p$. This makes the model sensitive to the expectation of the new arrivals only. This model is abbreviated "w".

The third version is the FM with all three kinds of flexibility types and with the first level of product flexibility. This level is achieved via setting PFP parameter to 0.10. This will result in a shop that has at least product flexibility level of 0.90, see Section 4.1.2.3. No extra term is added to $CRtot_p$ value. This model is abbreviated "pf90".

The forth version is the same with the third version in the sense of restricting the solution to satisfy a threshold for product flexibility. The only difference is the PFP parameter set to 0.15. The resultant shop will have at least 0.85 product flexibility level. This model is abbreviated "pf85".

The fifth version is again the same as the third version. The only difference is $CRant_p$ term is added to $CRtot_p$. This makes the model sensitive to the anticipated tool discrepancy due to new arrivals. This model is abbreviated as "pf90ant".

The sixth version is same as the fifth version. The only difference is the PFP parameter set to 0.15. This model is abbreviated "pf85ant".

Table 6.5 summarizes these versions of FM defined.

In addition to the FMs defined, the FFL method explained in Chapter 4 is also in-

Table 6.5: Versions of FMs

model version number	model version	use of product flexibility	additional term to $CRtot_p$	PFP level
1	wo	missing	-	-
2	w	missing	$CRexp_p$	-
3	pf90	exists	-	0.10
4	pf85	exists	-	0.15
5	pf90ant	exists	$CRant_p$	0.10
6	pf85ant	exists	$CRant_p$	0.15

corporated in the tests. This enables to compare the FMs with a well known method from the literature, see [26].

With the 7 models defined objective of the experiment is to reveal the characteristics of the FM'S and comparing the results with the FFL model as a base case.

By comparing model versions wo and w with model versions pf90 and pf85, the effect of product flexibility will be revealed. By comparing the model version pf90 with version pf85 the effect of product flexibility level will be revealed. By comparing versions pf90 and pf85 with versions pf90ant and pf85ant the effect of anticipation term added will be understood.

6.3 EXPERIMENT PLAN

Each loading model (FFL and versions of FM) are used to load tools all at once. The simulation and loading model interaction is as explained in Chapter 5.

The loading model and simulation model will be run for 100 periods. 100 period is found adequate in the pilot runs. The pf90ant model is run for 500 periods and resulting number of tardy orders at the end of each period is examined. Figure 6.1 shows the number of tardy orders at the end of each period for 500 periods.

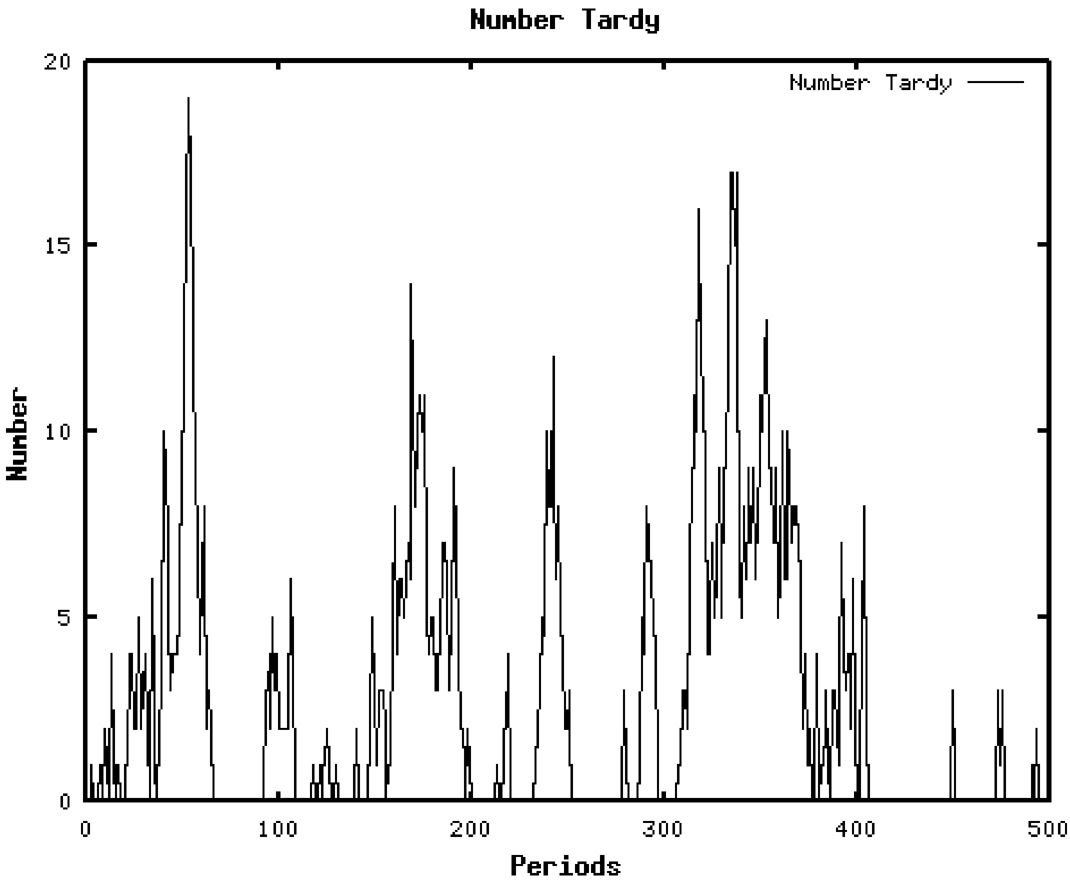

Figure 6.1: pf90ant model, 500-period run

A cyclic behavior of this key performance indicator is apparent in the run. There happens one major peak every 100 periods. This is also indicative of the responding character of flexibility to the pool size and composition.

With the help of this pilot run, 100 periods is found adequate to reflect the typical behavior of the system in the long run.

During the pilot runs the performance of the methods is observed to change dramatically from replication to replication, see Appendix. To study this situation with variability it is preferred to conduct 10 replications in each setting. Identical seeds leading to identical job arrivals are used when comparing different models. This resulted in identical order streams arrive in the same period for each method. This can be taken as an application of common random numbers for variance reduction in simulation, see [27].

6.3.1 Decisions in a Period

Two decisions are made in each period. The first decision is the specifying set of tools that will be loaded to the shop. This is made by FM or FFL. The second decision is tool-machine assignment. This decision is made by SOFM or SOFFL, using decided tool loading by FM/FFL and the previous tool-loading information.

6.4 PERFORMANCE MEASURES

At the end of each replication statistics are collected to judge the performance of the loading models. These statistics constitutes the performance measures that will be introduced in this section. There are seven different performance measures defined.

6.4.1 Batch Size Weighted Average Periods Waited

This performance measure shows the number of periods an order waited in the order pool. This is a statistics that is recorded for each order. If an orders arrived in the i^{th} period and released in the $(i + 1)^{th}$ period, then “periods waited” statistic for that order is 1. This statistic is 0 if an order is released in the period it arrived.

At the end of the replication the statistics is calculated by taking batch size weighted average of periods waited. The weighing is done to reflect the impact of batch (hence workload) sizes.

This performance measure can be considered similar to the conventional flow time measure.

6.4.2 Number of Tardy Orders

An order is tardy if it is released in a period that is strictly greater than its due date. This performance measure shows the total number of tardy orders throughout a replication.

At the end of the replication tardiness statistics is formed by the total number of tardy orders.

This statistics measures the performance of the method in processing orders on time. It also gives an idea about the performance of the due date assignment method.

6.4.3 Batch Size Weighted Percentage of Tardy Orders

This performance measure shows the batch size weighted percentage of tardy orders. It is calculated by dividing the sum of batch sizes of tardy orders to the total batch size of all orders arrived during each replication.

The number of tardy orders shows total number of tardy orders whereas this performance measure shows the batch size weighted percentage of tardy orders. It measures the percentage of number of parts that are tardy. This makes the measure sensitive to order batch sizes at arrivals.

6.4.4 Batch Size Weighted Percentage of No-Period-Waited Orders

This statistics shows the percentage of no-period waited orders. An order is a no-period waited order if it is released to the shop in the same production period it arrives. The performance measure is calculated by dividing the sum of the batch sizes of no-period waited orders to the total batch size of all orders that have arrived during a replication.

Period waited measures the time orders waited in pool whereas this measure assesses the readiness of the shop to the incoming order arrivals.

6.4.5 Realized Setup Times

At the beginning of each production period the tool loading is potentially changed. This includes the unloading and loading operations. A certain time is required to load and unload tools. As a result of this activity a setup period occurs. The setup times are recorded during the replication and a statistics is computed by taking their average.

This statistics shows the average of the setup times during the replication.

This performance measure will show the time loss due to setup. It is expected that a shop with a certain product flexibility level will have less setup times, since new parts inclusion is easier. When setup times of different FM versions are compared, the effectiveness of product flexibility on improving setup times will be revealed.

6.4.6 Machine Utilization Levels

The net utilizations of machines are recorded at each period through the replication. Setup period is not included in calculating net machine utilization levels. At the end of the replication, average utilization is found by taking the average of machine utilizations.

This performance measure determines the processing potential for the tools loaded. Low levels of the machine utilization measure indicates inadequate tool loading decision.

6.4.7 Realized Lengths of Production Period

In Chapter 5, it is indicated that a production period does not end unless all the released orders are fully processed. This creates a random production period length. There are times when producible orders deplete before the production period ends. In these cases realized lengths period is less than the determined production period length. There are also cases which need overtime to process all the orders released. At the end of each period the realized production period length is recorded. At the end of the replication, average production period length is calculated from the recordings.

This performance measure helps to evaluate the release procedure used together with the effect of routing flexibility.

6.5 RESULTS

The results of the experiments are introduced in this section. In each subsection four statistics are given. These are average, standard deviation, minimum and maximum for each measure across the 10 replications.

The results include all the experimental factors defined in Section 6.2. Different models constructed are FFL, w, wo, pf90, pf85, pf90ant and pf85ant, see Section 6.2. In the discussions the phrase ”flexibility models” refers to the collection of six different versions of FMs, w, wo, pf90, pf85, pf90ant and pf85ant.

For the observations of each performance measure Dunnett test [28] is conducted to compare the mean of the corresponding performance measure of FFL to flexibility model versions. Dunnett test is used for comparing means of populations that do not have a common variance. The null hypothesis of the test is that the compared populations have equal means.

The reader may refer to Appendix A for the results of the individual replications.

6.5.1 Process and Routing Flexibility Values

Figure 6.2 shows the process and routing flexibility allocated by flexibility model version pf85ant for a 100-period replication. It is common to all the periods to have process flexibility exceeding the routing flexibility levels. 100% process flexibility means that all the part types in the pool can be produced. This case has occurred in several periods (e.g. 1, 6, 54, 69). There are periods that indicate the trade-off between the two flexibility types. Like in periods 18, 24, 59, 68, 71 they move in opposite directions. However there are periods where the two types move in parallel, like periods 9, 53, 65, 98. These show that order pool status affects the trade-off between the types in the optimal mix of flexibilities.

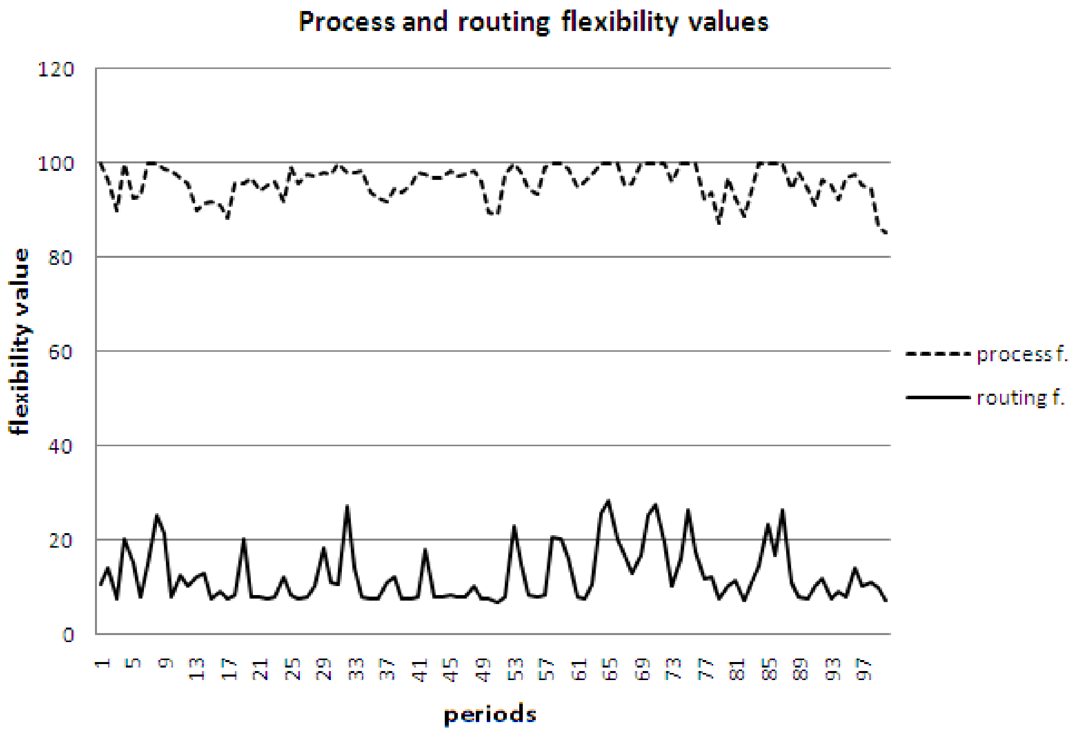

Figure 6.2: Process and routing flexibility values (pf85ant)

6.5.2 Batch Size Weighted Average Periods Waited

Batch size weighted average of periods waited is calculated at the end of the each replication. By using these calculated values of each replication the statistics represented in Table 6.6 are calculated.

Table 6.6: Batch size weighted average periods waited statistics

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	2.80	1.52	1.54	1.53	1.44	1.39	1.31
stdev	1.12	0.52	0.36	0.45	0.30	0.42	0.35
min	1.22	0.80	1.09	1.10	1.00	0.81	0.71
max	4.37	2.36	2.42	2.53	1.86	2.03	1.86

FFL performs the worst in terms of the average periods waited. w, wo, pf90, pf85, pf90ant and pf85ant perform close to each other. pf85, pf90ant and pf85ant perform slightly better than w and wo. Among the models with product flexibility pf90ant and pf85ant perform better than pf90 and pf85. The average number of periods waited for an order in a shop that any of the flexibility models being used, is less than 1.6 periods. This value is 2.8 for FFL method. When FFL method is used the orders nearly wait twice as much compared to the flexibility models.

The standard deviation of FFL model is high when compared to the flexibility models. This indicates that performance of FFL is unpredictable when compared to the flexibility models. Standard deviations of the flexibility models are close to each other.

Dunnett test result for comparison of mean of average period waited of FFL to means of flexibility model versions is given in Table 6.7. Test indicates that means of average periods waited for flexibility model versions pf90ant and pf85ant are less than mean average periods waited for FFL method at 5% significance. The means of other flexibility model versions (w, wo, pf90 and pf85) are less than mean of FFL method only with 10% significance. Hence one has stronger evidence for including anticipation.

Table 6.7: Dunnett test for batch size weighted averaged periods waited

(I)Group	(J)Group	Mean Difference(I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower B.	Upper B.
FFL	w	1.272	.39	.100	-.1545	2.6985
	wo	1.254	.37	.095	-.1491	2.6571
	pf90	1.269	.38	.094	.1443	2.6823
	pf85	1.351	.37	.061	-.0474	2.7494
	pf90ant	1.409	.38	.050	.0001	2.8179
	pf85ant	1.486	.37	.035	.084	2.8880

Multiple comparison of flexibility models versions in terms of average periods waited performance measure is made using Tukey test at 5% significance level. Test resulted 0.758 p-value, which indicates that performance of the flexibility models are not different in this significance level.

6.5.3 Number of Tardy Orders

The statistics related to number of tardy orders is presented in Table 6.8. The table includes the average, standard deviation, minimum and maximum statistics of the total number of tardy orders at the end of each replication. The average number of orders arrived in a replication is over 1286.

Table 6.8: Number of tardy orders statistics

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	378.90	125.70	112.70	104.60	80.00	104.40	88.00
stdev	220.85	112.23	88.79	108.51	66.90	78.09	61.43
min	29	3	8	7	1	0	1
max	650	319	331	346	199	222	173

In terms of this measure the flexibility models are superior to the FFL method. Within flexibility models, w and wo perform close to each other. pf90 and pf90ant also perform close to each other and they also perform better than w and wo. pf85 and pf85ant perform better than all flexibility model versions. Standard deviation of flexibility models is less than standard deviation of FFL.

Dunnett test result for comparison of mean of number of tardy orders of FFL to means of flexibility model versions is given in Table 6.9. Test indicates that means of number of tardy orders for pf85 and pf85ant are less than mean of number of tardy orders for FFL method at 5% significance. wo, pf90 and pf90ant perform better than FFL at 10% significance level.

Table 6.9: Dunnett test for number of tardy orders statistics

(I)Group	(J)Group	Mean Difference(I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower B.	Upper B.
FFL	w	253.2	78.34	.101	-30.93	537.33
	wo	266.2	75.27	.067	-13.07	545.47
	pf90	274.3	77.81	.061	-8.88	557.48
	pf85	298.9	72.97	.031	22.04	575.76
	pf90ant	274.5	74.08	.054	-3.37	552.37
	pf85ant	290.9	72.49	.037	14.38	567.42

Multiple comparison of flexibility models versions in terms of number of tardy orders statistics is made using Tukey test at 5% significance level. Test resulted 0.879 p-value, which indicates that performance of the flexibility models are not different in this significance level.

6.5.4 Batch Size Weighted Percentage of Tardy Orders

The statistics of the weighted percentage of tardy orders is presented in Table 6.10.

Table 6.10: Batch size weighted percentage of tardy orders statistics

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	0.34	0.12	0.10	0.10	0.07	0.10	0.08
stdev	0.19	0.10	0.08	0.09	0.06	0.07	0.05
min	0.03	0.00	0.01	0.01	0.00	0.00	0.00
max	0.58	0.29	0.30	0.30	0.19	0.20	0.15

For this performance measure the flexibility models perform close to each other and they perform better than FFL method.

Note that among the flexibility models, even though the difference in the number of tardy orders statistics seem significant in Subsection 6.5.3, the statistics for this measure in the weighted version is close to each other. This may be due to two things. First, tardiness of small batches may be suppressed in the weighted measure. Second, the difference in the percentages is small since difference in number of tardy orders is small compared to the total number of orders arrived.

Standard deviation of FFL model is high when compared with flexibility models. This indicates that FFL has a fluctuating performance in terms of this statistics. Standard deviations of flexibility models are close to each other.

Dunnett test result for comparison of mean of percentage of tardy orders of FFL to means of flexibility model versions is given in Table 6.11. Test indicates that means of percentage of tardy orders for pf90, pf85, pf90ant and pf85ant are less than mean percentage of tardy orders for FFL method with 5% significance level. Other flexibility model versions (w and wo) perform better with 10% significance level.

Multiple comparison of flexibility models versions in terms of percentage of tardy orders performance measure is made using Tukey test at 5% significance level. Test resulted 0.861 p-value, which indicates that performance of the flexibility models are not different in this significance level.

Table 6.11: Dunnett test for batch size weighted percentage of tardy orders statistics

(I)Group	(J)Group	Mean Difference(I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower B.	Upper B.
FFL	w	.229	.069	.087	-.0211	.4791
	wo	.238	.066	.060	-.0073	.4833
	pf90	.248	.068	.050	-.0001	.4961
	pf85	.269	.064	.026	.0259	.5121
	pf90ant	.250	.065	.043	.0062	.4938
	pf85ant	.265	.064	.029	.0225	.5075

6.5.5 Batch Size Weighted Percentage of No-Period-Waited Orders

The statistics related to the weighted percentage of no-period-waited orders is presented in Table 6.12.

Table 6.12: Batch size weighted percentage of no-period-waited orders statistics

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	0.13	0.26	0.18	0.19	0.19	0.29	0.30
stdev	0.04	0.08	0.02	0.03	0.02	0.08	0.08
min	0.09	0.17	0.14	0.14	0.15	0.19	0.18
max	0.19	0.40	0.21	0.23	0.23	0.38	0.44

FFL method is again not favorable in terms of this performance measure either . In the tests with FFL setting, around 13% of the orders are released within the period of arrival. This value increases to around 19% for wo, pf90 and pf85 flexibility models. w performs better than wo, pf90 and pf85. The models that use the anticipation, pf90ant and pf85ant, method perform better than other flexibility models.

In replications that pf90ant and pf85ant models used, around 30% of the orders are released in the period they arrived.

Dunnett test result for comparison of mean of percentage of no-period-waited orders of FFL to means of flexibility model versions is given in Table 6.13. Test indicates that means of percentage of no-period-waited orders for all flexibility model versions are greater than mean percentage of no-period-waited orders for FFL method with 5% significance. The significance of the test with w, pf85, pf90ant and pf85ant is notably small. This is a very strong indicator of the superiority of these models in this performance measure.

Table 6.13: Dunnett test for batch size weighted percentage of no-period-waited orders statistics

(I)Group	(J)Group	Mean Difference(I-J)	Std. Error	Sig.	95% Confidence Interval Lower B.	95% Confidence Interval Upper B.
FFL	w	-.126	.027	.008	-.2248	-.0272
	wo	-.054	.013	.021	-.1018	-.0062
	pf90	-.058	.015	.024	-.1106	-.0054
	pf85	-.064	.014	.006	-.1138	-.0142
	pf90ant	-.154	.026	.001	-.2506	-.0574
	pf85ant	-.172	.027	.000	-.2697	-.0743

Multiple comparison of flexibility models versions in terms of percentage of no-period-waited orders statistics is made using Tukey test at 5% significance level. Test resulted 0.000 p-value, which indicates that performance of flexibility models vary. Figure 6.3 shows the confidence intervals generated by multiple comparison of flexibility model versions using Tukey test. The results of the test indicate that pf85ant performs best in terms of this statistics. The sorting of the models form best performer to worst is pf85ant, pf90ant, w, pf85, pf90 and wo.

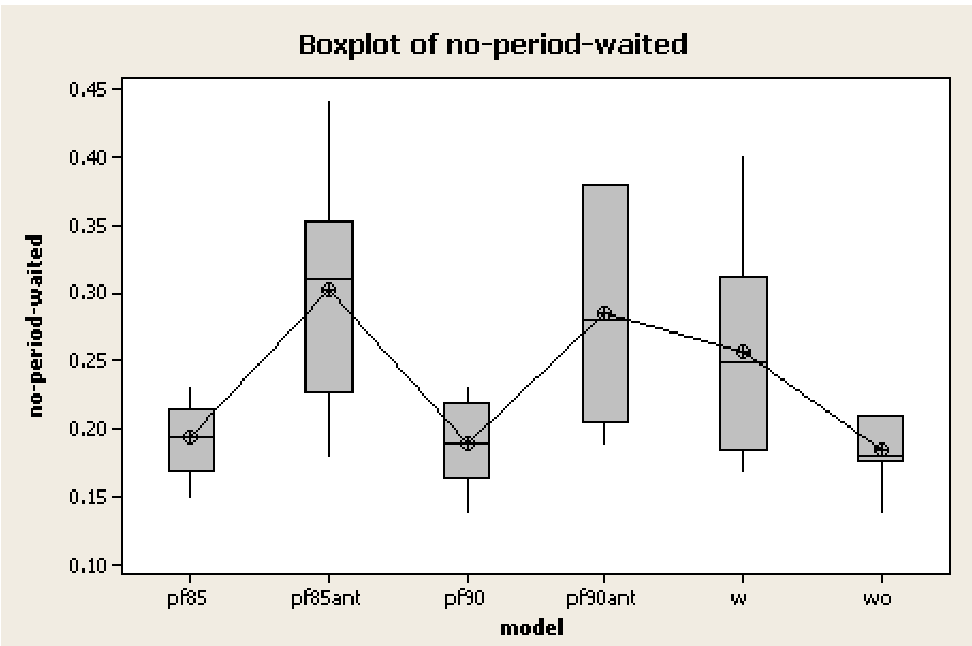

Figure 6.3: Confidence intervals found using multiple comparison (no-period-waited)

6.5.6 Realized Setup Times

The setup time statistics are presented in Table 6.14. The table includes the average and standard deviation of replication averages of setup times. The minimum and maximum for setup time are not the minimum and maximum of the replication averages. They are calculated by taking the averages of the maximum and minimum setup times realized during a replication of 100 production periods.

Table 6.14: Realized setup time statistics (in hours)

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	5.50	1.78	2.81	2.43	2.61	1.92	2.14
stdev	0.08	0.08	0.42	0.35	0.29	0.13	0.15
min	3.57	0.00	0.72	0.88	0.64	0.40	0.48
max	6.57	3.68	5.44	4.48	4.64	3.36	3.84

Time loss due to setup is the largest with the FFL method. It is significantly larger than time loss of flexibility models.

Setup duration of wo is larger than the w and flexibility models with product flexibility (pf90, pf85, pf90ant and pf85ant). w performs better since it includes expectation method. Using expectation method results in similar tool sets through periods. pf90, pf85, pf90ant and pf85ant performs better as a result of utilizing product flexibility. Since the tool loading created using product flexibility models are flexible, making setup is easier at the forthcoming period.

When the effect of the anticipation is investigated between same product flexibility level models, it can be observed that anticipation improves setup times.

Unloading a tool takes 0.1 hours and loading a tool takes 0.7 hours, (see Section 6.1.9). 1.92-hour setup time corresponds less than 3 tool changeovers (unload and load) in the bottleneck machine. 5.50-hour setup time corresponds to more than 6 tool changeovers.

Dunnett test result for comparison of mean setup time of FFL to means of flexibility model versions is given in Table 6.15. Test indicates that means of setup times for all flexibility model versions are less than mean setup time for FFL method with almost perfect significance.

Table 6.15: Dunnett test for setup time statistics

(I)Group	(J)Group	Mean Difference(I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower B.	Upper B.
FFL	w	3.718	.03632	.000	3.5922	3.8438
	wo	2.689	.13447	.000	2.1673	3.2107
	pf90	3.064	.11240	.000	2.6311	3.4969
	pf85	2.883	.09580	.000	2.5173	3.2487
	pf90ant	3.578	.04857	.000	3.4051	3.7509
	pf85ant	3.360	.05211	.000	3.1727	3.5473

Multiple comparison of flexibility models versions in terms of setup time statistics is made using Tukey test at 5% significance level. Test resulted 0.000 p-value, which indicates that performance of flexibility models vary. Figure 6.4 shows the confidence intervals generated by multiple comparison of flexibility model versions using Tukey test. The results of the test indicate that w performs best in terms of this statistics. The sorting of the models form best performer to worst is w, pf90ant, pf85ant, pf90, pf85 and wo.

Figure 6.4: Confidence intervals found using multiple comparison (setup time)

6.5.7 Machine Utilization Levels

The machine utilization statistics are presented in Table 6.16.

Table 6.16: Machine utilization level statistics

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	0.86	0.80	0.82	0.80	0.81	0.80	0.81
stdev	0.02	0.02	0.02	0.02	0.02	0.02	0.02
min	0.82	0.76	0.78	0.76	0.78	0.76	0.76
max	0.88	0.84	0.84	0.84	0.85	0.84	0.85

Machine utilization level statistics for FFL is slightly higher than the machine utilization levels of flexibility models. Machine utilization levels of flexibility models are close to each other.

Note that even though machine utilization level of FFL method is higher than flexibility models, the tardiness measures are worse for FFL method, see Subsection 6.5.3 and 6.5.4. This is due to the larger setup durations of FFL method compared to flexibility models, see Subsection 6.5.6.

Standard deviation of all test models are very low. This indicates that performance of the models in terms of machine utilizations is stable around averages.

Dunnett test result for comparison of mean utilization level of FFL to means of flexibility model versions is given in Table 6.17. Test indicates that means of utilization levels for all flexibility model versions are lower than mean utilization level for FFL method with almost perfect significance.

Table 6.17: Dunnett test for machine utilization level statistics

(I)Group	(J)Group	Mean Difference(I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower B.	Upper B.
FFL	w	.057	.00872	.000	.0265	.0875
	wo	.042	.00789	.001	.0146	.0694
	pf90	.053	.00932	.001	.0202	.0858
	pf85	.044	.00830	.001	.0151	.0729
	pf90ant	.059	.00872	.000	.0285	.0895
	pf85ant	.053	.00907	.000	.0212	.0848

6.5.8 Realized Lengths of Production Period

The statistics related to the realized lengths of production period are presented in Table 6.18. Minimum and maximum for setup time is calculated as in the case of setup times, see Section 6.5.6. They are calculated by taking the averages of the maximum and minimum realized production period length occurred during a replication.

Table 6.18: Realized length of production period statistics

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	39.75	39.88	39.33	39.47	39.31	39.80	39.71
stdev	0.31	0.24	0.57	0.52	0.66	0.31	0.33
min	33.35	36.25	26.00	28.32	26.49	34.25	33.69
max	43.23	43.72	43.63	44.29	44.42	43.79	44.46

The realized lengths of production periods of all models are close to 40, which is the production period length. The standard deviations are relatively small (maximum coefficient of variation, for pf85, is less than 0.02). This is a result of input controlled release and update of norms through the simulation, see Chapter 5.

Maximum of the production period lengths for FFL and for flexibility models are 43.23 and 44.46 respectively. This indicates that at most 3.23 hours of overtime is realized when FFL model is used. At most 4.46 hours of overtime is realized when a pf85 is used. However, by interpreting the standard deviations it can be reached that overtime is seldom.

Dunnett test result for comparison of mean realized length of production period of FFL to means of flexibility model versions is given in Table 6.19. The test fails to reject the null hypothesis, that flexibility models have different mean realized length of production period than mean of FFL method. Flexibility models fills up the whole time more often as in a finite loading case although utilization is not in the objective function. FFL favors high utilization, see Table 6.16.

Table 6.19: Dunnett test for realized length of production period statistics

(I)Group	(J)Group	Mean Difference(I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower B.	Upper B.
FFL	w	-.125	.12301	.998	-.5553	.3053
	wo	.425	.20566	.590	-.3160	1.1660
	pf90	.280	.19230	.931	-.4068	0.9668
	pf85	.442	.23105	.691	-.4029	1.2869
	pf90ant	-.045	.13782	1.000	-.5225	.4325
	pf85ant	.044	.14273	1.000	-.4507	.5387

6.5.9 Robustness Analysis

Additional simulation experiments are conducted to test the robustness of the flexibility management approach to the probability of orders being from a specific part type. In most of the FMS studies part type distribution is assumed either uniform [24], or estimated from the production data [7]. The robustness of the flexibility management approach to the probability of part types is analyzed in order to test the approach to errors that may occur in estimating the part mix probabilities.

In the robustness analysis experiments, part type assignment probabilities are left the same in the simulation model, as defined in Table 6.4. Order arrivals in robustness experiments are maintained. However, in robustness experiments, part probabilities assumed by the flexibility models have been deliberately set to erroneous values as in Table 6.20. Note that part mix probability distribution assumed by flexibility models is different than the distribution used in assigning part types in simulation model.

FFL does not utilize the part type probability information. FFL results do not change since exactly the same order arrivals occur, results are the same as in Section 6.5.

Note that the flexibility model versions w and wo do not utilize product flexibility. All flexibility models including wo use part type probability information in the entropy calculation, see Section 4.1.3.1. Version w uses part type probability information in calculating CR of expected orders as well as in entropy calculation.

Flexibility model versions pf90, pf85, pf90ant and pf85ant use the part type probability information in calculating product flexibility measure. These flexibility models

Table 6.20: Probability distribution assumed by FMs in robustness experiments

part type	probability	part type	probability
1	0.025	11	0.075
2	0.075	12	0.025
3	0.025	13	0.075
4	0.075	14	0.025
5	0.025	15	0.075
6	0.025	16	0.025
7	0.025	17	0.075
8	0.025	18	0.025
9	0.025	19	0.075
10	0.075	20	0.025

will be exposed to the same arrivals (as in Section 6.5) however tool loading (by FM) is performed by the erroneous part type probability estimates. The results will give an indication on the robustness of modelling to the part type probability information.

The flexibility model versions pf90ant and pf85ant utilize the probability distribution information in calculating model parameters ($CRtot_p$) as well as in calculating product flexibility measure, see Section 4.1.3.7. The method pf90ant and pf85ant use to account for anticipation is sensitive to part type probability distribution. Since the probability distribution information is false the model parameters of pf90ant and pf85ant are also calculated erroneously.

For each test model, 10 replications, each with 100 periods, is made. The results are given in the following sections.

6.5.9.1 Batch Size Weighted Average Periods Waited

The statistics in this section is calculated identical to that in Section 6.5.2. The results are given in Table 6.21.

FFL performs worse compared to flexibility model versions even though it does not utilize part type probability information.

The statistics is also increased for the flexibility models according to the previous probability distribution except wo, see Table 6.6. wo performs close to its previous

Table 6.21: Batch size weighted average periods waited statistic (robustness analysis)

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	2.80	1.68	1.47	2.35	1.62	1.97	1.86
stdev	1.12	0.60	0.38	0.86	0.49	0.79	0.71
min	1.22	0.87	1.09	1.08	1.11	1.15	1.00
max	4.37	2.70	2.42	3.60	2.91	3.70	3.44

performance since it does not use probability information (except entropy calculation). With wrong information, w and pf85 models perform better than pf90, pf90ant and pf85ant respectively.

Even though flexibility model versions pf85, pf90ant and pf85ant utilize wrong information about probabilities they still perform close to flexibility models w and wo. For each FM version, average periods waited resulted from robustness experiments (results in this section) are compared to the results obtained from true probability used experiments (results in Section 6.5.2). Dunnett test is conducted for comparison of means. At 5% significance level, the test failed to reject that the means are different (null hypothesis) for all FM versions.

6.5.9.2 Number of Tardy Orders

The statistics in this section is calculated as in Section 6.5.3. The results are given in Table 6.22.

Table 6.22: Number of tardy orders statistics (robustness analysis)

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	378.90	166.10	89.70	274.30	118.90	198.00	186.10
stdev	220.85	129.76	93.74	188.14	108.05	159.15	151.91
min	29	14	12	7	14	37	6
max	650	410	331	500	399	506	521

The number of tardy orders for flexibility models are less than the number of tardy orders for FFL. wo again performs best. All flexibility models except wo are negatively effected. pf90, pf90ant and pf85ant are the most negatively effected flexibility models. This is because of the anticipation and tight product flexibility level calculated by wrong information. w and pf85 are effected less compared to pf90, pf90ant and pf85ant.

At 5% significance level, Dunnett test failed to reject the equality of the mean number of tardy orders of robustness results and true probability results for all FM versions.

6.5.9.3 Batch Size Weighted Percentage of Tardy Orders

The statistics in this section is calculated as in Section 6.5.4. The results are given in Table 6.23.

Table 6.23: Batch size weighted percentage of tardy orders statistics (robustness analysis)

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	0.34	0.15	0.08	0.26	0.11	0.18	0.17
stdev	0.19	0.12	0.08	0.16	0.09	0.14	0.14
min	0.03	0.01	0.01	0.01	0.01	0.04	0.01
max	0.58	0.37	0.30	0.44	0.35	0.45	0.47

Flexibility models perform better than FFL model in terms of this performance measure. wo performs best among flexibility models and its performance is close to its previous performance. Performance of other flexibility models worsens, see Table 6.10. pf90, pf90ant and pf85ant are the most affected models.

At 5% significance level, Dunnett test failed to reject the equality of the mean percentage of tardy orders of robustness results and true probability results for all FM versions.

6.5.9.4 Batch Size Weighted Percentage of no-period-Waited Orders

The statistics in this section is calculated as in Section 6.5.5. The results are given in Table 6.24.

w performs best in terms of this statistics. All models except wo, perform worse in terms of this statistics compared to previous results, see Table 6.12. Even though the pf85, pf90ant and pf85 uses wrong probability distribution information, they perform

Table 6.24: Batch size weighted percentage of no-period-waited orders statistics (robustness analysis)

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	0.13	0.24	0.19	0.15	0.18	0.19	0.21
stdev	0.04	0.08	0.02	0.04	0.02	0.06	0.06
min	0.09	0.14	0.14	0.10	0.13	0.10	0.11
max	0.19	0.38	0.23	0.22	0.21	0.28	0.32

close to flexibility model versions w and wo. Flexibility model versions pf90ant and pf85ant performs better than pf90 and pf85 even they use the wrong probability distribution when anticipating orders.

At 5% significance level, Dunnett test failed to reject the equality of the mean percentage of no-period-waited orders of robustness results and true probability results for all FM versions.

6.5.9.5 Realized Setup Times

The statistics in this section is calculated as in Section 6.5.6. The results are given in Table 6.25.

Table 6.25: Realized setup times statistics (robustness analysis)

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	5.50	1.81	2.84	2.01	2.37	1.91	2.00
stdev	0.08	0.07	0.42	0.22	0.24	0.12	0.09
min	3.57	0.00	0.88	0.80	0.72	0.72	0.56
max	6.57	3.68	5.59	3.76	4.48	3.36	3.82

Average of the setup times of the models are close to their setup times in the previous environment, see Table 6.14.

w performs best and its performance is close to its previous performance. Models with anticipation (pf90ant and pf85ant) perform better than models without anticipation (pf90 and pf85). wo performs worse in this measure even though it is the model that is sensitive to the probability information the least among the flexibility models.

At 5% significance level, Dunnett test failed to reject the equality of the mean of setup times of robustness results and true probability results for all FM versions.

6.5.9.6 Machine Utilization Levels

The statistics in this section is calculated as in Section 6.5.7. The results are given in Table 6.26.

Table 6.26: Machine utilization levels statistics (robustness analysis)

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	0.86	0.80	0.82	0.79	0.80	0.80	0.80
stdev	0.02	0.02	0.02	0.02	0.02	0.02	0.02
min	0.82	0.75	0.78	0.74	0.76	0.75	0.76
max	0.88	0.83	0.84	0.82	0.82	0.82	0.82

The average utilization levels are very close to their previous values, see Table 6.16.

6.5.9.7 Realized Lengths of Production Period

The statistics in this section is calculated as in Section 6.5.8. The results are given in Table 6.27.

Table 6.27: Realized lengths of production period statistics (robustness analysis)

	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
average	39.75	39.87	39.18	39.59	39.49	39.75	39.81
stdev	0.31	0.19	0.61	0.57	0.54	0.34	0.28
min	33.35	35.83	24.98	29.02	24.54	33.76	32.91
max	43.23	44.01	43.59	44.51	44.23	43.88	43.98

Average realized production period statistics is close to the previous results, see Table 6.18.

6.6 OVERALL INTERPRETATION OF THE RESULTS

Models that exploit flexibility performed better in all performance measures except machine utilizations and realized lengths of production period. FFL performed better in machine utilizations because of the accumulation of orders in the order pool. This accumulation is due to the ineffective loading of FFL compared to flexibility models. The longer realized production periods of the flexibility models is due to the process flexibility provided. With the process flexibility provided by the flexibility models, ORR finds more chance to release orders to the shop. Even though the flexibility models causes overtime in production period, this overtime is in reasonable limits, 4.46 hours in a 40 hour period at most.

Model with expectation method performed best in setup times. Since w uses expectation method, tool sets loaded through periods is close to each other. This results is shorter setup times. Models with anticipation perform better in setup time (after w) and percentage of no-period-waited orders performance measures. They perform similar to other flexibility models in terms of other performance measures. From this result it can be concluded that anticipation improves flexibility models in terms of setup times and percentage of no-period-waited orders performance measures, even though it does not worsen the performance in other terms.

pf90 performs better than pf85 in setup time statistics where pf85 performs better than pf90 in average periods waited and tardiness statistics. Tighter product flexibility level of pf90 results is shorter setup durations. From this result it can be concluded that setup times can be reduced through higher level product flexibility.

In average periods waited and tardiness performance measures pf85 performed better than pf90. This shows that more flexibility is not necessarily better.

The standard deviation statistics of the performance measures show that flexibility stabilizes the performance. This indicates that flexibility models provide loading which is more robust compared to FFL. Loading with flexibility model also builds up the pool in every 100 periods, see Figure 6.1.

w performs better than wo in setup time and no-period-waited orders performance measures where they perform close in other performance measures. This indicates that incorporating the expected value as an estimation together with the use of flexibility models in loading MTO shops improves setup times and release of orders in the period they arrived. Models with anticipation method performed better than models with expectation method in average periods waited, tardiness and no-period-waited performance measures. This shows that anticipation is likely to be more useful which indicates the potential for paying attention to risks, discrepancies explicitly, becomes advantageous in at least some areas although performs similar in others.

Results of robustness analysis indicate that wo is the most robust flexibility model. This is because of the fact that it is the model that depends upon the probability information the least among all the flexibility models. Dunnett test shows that not all flexibility settings are the same. pf90, pf85, pf90ant and pf85ant performs close to wo and w even though they use wrong information. They performed similar or better than w and wo in terms of performance measures defined. Models with high product flexibility level (pf90 and pf90ant) were affected more compared to other flexibility models. Robustness analysis also revealed that anticipation is still useful and improves the performance of the flexibility models when the part type distribution is estimated wrong.

CHAPTER 7

CONCLUSION

This study shows that both high shop congestion and due date achievement can be satisfied by providing different types of flexibility to the shop. It provides measures for the three types of manufacturing flexibility defined in the literature and proposes a management methodology for flexible shops, that uses the measures defined. In addition to the measures defined it gives a flexibility allocation procedure and a method that extends the schedule visibility of the flexibility allocation procedure. The study not only suggests all the mentioned procedures but also includes experiments that test the benefits and drawbacks of the suggested procedures. It also includes additional experiments that test the robustness of the measurement of a specific flexibility kind and flexibility allocation procedure.

A mixed integer mathematical model that optimizes the balance between process and product flexibility measures for a given product flexibility, is provided. The model decides the tool loading of the machines on a MTO shop. A simulation model is developed for testing the loading provided by the mathematical model. The simulation model includes the arrivals of the orders, release to the shop and processes on the shop.

Mathematical modelling is not necessarily meant to be proposed for direct application. Its main purpose is to inquire about the potential of the best mix of flexibility. An ORR is defined to release orders to the shop. It utilizes continuous timing convention and an upper and lower bound WLC methodology. Periodic production is assumed and production period is chosen as a week. Mathematical model loads tools to flexible machines, a period is simulated and mathematical model decides the loading of the next period. In each replication approximately 2 years is simulated (100 periods/weeks). Experimental factors include the use of product flexibility, provided product flexibility level and use of anticipation.

Experimental results indicated that the use of product flexibility in the flexibility management approach should be favored. Use of product flexibility improves setup time performance measure, without worsening other performance measures. Anticipation as an approach to extent schedule visibility, improves the performance of the flexibility management approach. Anticipation improves the performance of the product flexibility used models in average periods waited, no-period-waited orders and setup times performance measures without worsening the others. Expectation is also effective as an approach to extend schedule visibility but it is surpassed by anticipation. Another experimental factor was the effect of product flexibility level. It is observed that setup time is very sensitive to product flexibility level and tighter product flexibility levels lead to shorter setup times. It is also observed that the anticipation improves the flexibility model more in the case of loose product flexibility level. This is reasonable since both product flexibility and anticipation have concerns beyond the next period. The robustness analysis indicated that product flexibility measure, its use and anticipation method proposed are robust to part type probability distribution.

This study provides a guide in use of manufacturing flexibilities as a means of shop planning. It provides measures for three types of manufacturing flexibility and a method that manages shop using these flexibilities. Shop managers can benefit from this study by modifying the proposed approach for requirements of their flexible shops. Even if the proposed method does not respond their requirements, they can get an intuition about benefits of flexibility from the results of this study.

Proposed flexibility management approach optimizes the process and routing flexibility measures for a given bound for product flexibility level. An extension of the approach proposed may be optimizing the product flexibility measure as well as process and routing flexibility measures. The difficulty is that the requirement of the shop for each flexibility level should be determined and reflected to the mathematical model appropriately. This requires not only a prioritizing between process and routing flexibility measures as given in this study, but also a prioritizing between all three flexibility measures.

This study experiments the flexibility approach in an assumed flexible shop. The potential for a good flexibility mix adjusted by the order pool can be an attractive choice with the use of a heuristic to replace the loading and the later setup optimization. This way the benefits of flexibility in realistic size problems can be studied.

For the sake of obtaining a linear model, an approximation is proposed for the defined non-linear routing flexibility measure. This may be improved by defining a linear routing flexibility measure or with a better approximation. Even a different routing flexibility measure can be proposed. A nonlinear model with the routing flexibility measure defined can also be another research direction.

The ORR procedure in this study utilizes only input control. Integration of a mechanism that also utilizes output control techniques into the flexibility management approach beyond the capacity facilitated by routing and product flexibilities, is another research direction.

Infinite buffer is assumed for the machines in the shop. Testing the effectiveness of the ORR and flexibility management approach with the finite buffer capacity machines may be another research direction.

A material handling system is not considered either in the FM, SOFM or the simulation of the flexible shop. Testing the effectiveness of the flexibility management approach at a flexible MTO shop with material handling system is another research path.

Machines are assumed to be reliable and they do not require preventive maintenance. This assumption may be relaxed and benefits of routing flexibility in the case of machine breakdowns may be investigated.

The availability of the tools is not considered in this study. It is assumed that the tools are always available and they do not break. This assumption may be relaxed and a decision methodology regarding the tool availability and tool life may be integrated to the flexibility management approach proposed.

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APPENDIX A

DETAILED RESULTS

Table A.1: Batch size weighted averaged periods waited statistics for each replication

replication	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
1	2.65	1.72	1.50	1.55	1.40	1.53	1.41
2	4.10	2.36	1.49	1.98	1.50	1.85	1.59
3	1.90	1.03	1.43	1.20	1.33	0.81	1.15
4	4.23	1.69	1.59	1.57	1.79	1.73	1.70
5	2.37	1.29	1.55	1.10	1.86	1.36	1.33
6	1.22	0.80	1.09	1.11	1.00	0.86	0.71
7	1.58	0.99	1.12	1.18	1.09	0.96	0.90
8	2.90	1.86	1.69	1.63	1.32	1.28	1.22
9	2.63	1.32	1.53	1.41	1.35	1.45	1.22
10	4.37	2.17	2.42	2.53	1.80	2.03	1.86

Table A.2: Number of tardy orders statistics for each replication

replication	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
1	399	168	104	113	76	122	101
2	650	319	84	227	55	199	126
3	224	3	90	28	44	0	87
4	621	152	114	104	160	177	173
5	317	87	126	11	199	108	109
6	29	3	17	7	1	9	1
7	75	6	8	15	8	33	1
8	471	197	151	111	43	67	39
9	389	61	102	84	65	107	72
10	614	261	331	346	149	222	171

Table A.3: Batch size weighted percentage of tardy orders statistics for each replication

replication	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
1	0.36	0.15	0.09	0.10	0.07	0.11	0.09
2	0.58	0.29	0.08	0.21	0.05	0.18	0.11
3	0.21	0.00	0.08	0.03	0.04	0.00	0.08
4	0.55	0.14	0.11	0.10	0.15	0.15	0.15
5	0.29	0.08	0.12	0.02	0.19	0.10	0.10
6	0.03	0.00	0.02	0.01	0.00	0.01	0.00
7	0.08	0.01	0.01	0.01	0.01	0.03	0.00
8	0.43	0.19	0.15	0.10	0.04	0.06	0.04
9	0.36	0.06	0.10	0.08	0.07	0.10	0.07
10	0.55	0.23	0.30	0.30	0.13	0.20	0.15

Table A.4: Batch size weighted percentage of no-period-waited orders statistics for each replication

replication	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
1	0.12	0.20	0.17	0.19	0.19	0.27	0.30
2	0.09	0.17	0.18	0.15	0.17	0.19	0.23
3	0.18	0.31	0.21	0.22	0.21	0.38	0.35
4	0.09	0.23	0.18	0.17	0.19	0.21	0.22
5	0.13	0.31	0.18	0.23	0.17	0.29	0.33
6	0.19	0.40	0.21	0.21	0.23	0.38	0.44
7	0.16	0.32	0.21	0.22	0.23	0.38	0.36
8	0.13	0.19	0.19	0.17	0.20	0.29	0.30
9	0.13	0.27	0.18	0.19	0.21	0.27	0.32
10	0.09	0.17	0.14	0.14	0.15	0.19	0.18

Table A.5: Setup time statistics (in hours), for each replication

replication	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
1	5.61	1.65	2.86	2.55	2.73	1.87	2.13
2	5.48	1.74	2.63	2.10	2.47	1.82	2.04
3	5.43	1.81	2.93	2.63	2.63	2.12	2.18
4	5.54	1.79	2.61	2.28	2.29	1.84	2.05
5	5.39	1.84	2.73	2.94	2.38	1.87	2.13
6	5.39	1.88	3.56	2.75	3.12	2.05	2.38
7	5.57	1.67	3.23	2.70	2.87	2.05	2.29
8	5.58	1.90	2.71	2.33	2.76	1.93	2.19
9	5.53	1.75	2.86	2.27	2.74	1.96	2.13
10	5.45	1.76	1.96	1.78	2.15	1.68	1.85

Table A.6: Machine utilization level statistics for each replication

replication	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
1	0.87	0.80	0.82	0.82	0.82	0.80	0.81
2	0.86	0.82	0.84	0.82	0.83	0.81	0.82
3	0.85	0.79	0.80	0.80	0.80	0.79	0.80
4	0.87	0.82	0.83	0.82	0.83	0.82	0.82
5	0.85	0.80	0.81	0.77	0.80	0.79	0.79
6	0.82	0.76	0.78	0.76	0.78	0.76	0.76
7	0.86	0.79	0.81	0.80	0.80	0.78	0.80
8	0.87	0.80	0.82	0.81	0.81	0.80	0.80
9	0.85	0.79	0.81	0.81	0.82	0.80	0.80
10	0.88	0.84	0.84	0.84	0.85	0.84	0.85

Table A.7: Realized length of production period statistics for each replication

replication	FFL	w	wo	pf90	pf85	pf90ant	pf85ant
1	39.77	39.89	39.62	39.57	39.46	39.76	39.76
2	40.13	39.88	39.71	40.15	39.83	40.32	40.14
3	39.50	39.84	39.52	39.61	39.27	39.60	39.44
4	39.90	40.25	39.73	39.89	39.91	40.12	39.95
5	39.67	39.89	39.14	38.70	39.37	39.87	39.55
6	39.11	39.34	37.94	38.49	37.78	39.22	38.96
7	39.74	39.96	38.93	39.43	39.20	39.55	39.74
8	39.96	39.71	39.33	39.46	38.82	39.73	39.82
9	39.60	40.02	39.40	39.46	39.32	39.87	39.81
10	40.14	39.99	39.95	39.96	40.14	39.93	39.91

APPENDIX B

COMPUTATIONAL DETAILS

B.1 PROGRAMMING ENVIRONMENT

All the computational tasks are carried on Python programming language version 2.6.6. The computations are done on a machine that runs Ubuntu 10.10 (Maverick Meerkat).

B.2 MIP SOLVER

Python bindings of GNU Linear Programming Kit (GLPK) version 4.43 is used for solutions of the MIP models.

B.2.1 Solver Options

Table B.1: Solver options used in flexibility models

Option	Use
Branching	heuristic by Driebeck and Tomlin
Backtracking	best local bound
Preprocessing	perform an all levels
Feasibility pump heuristic	Off
Gomory mixed integer cut	On
Mixed integer rounding cut	Off
Mixed cover cut	On
Clique cut	On
Gap tolerance	0.0
Time limit	100 seconds

Table B.2: Solver options used in setup optimization models

Option	Use
Branching	heuristic by Driebeck and Tomlin
Backtracking	best local bound
Preprocessing	perform an all levels
Feasibility pump heuristic	Off
Gomory mixed integer cut	On
Mixed integer rounding cut	Off
Mixed cover cut	On
Clique cut	On
Gap tolerance	0.0
Time limit	60 seconds

B.3 SIMULATION TOOL

SimPy simulation package version 2.1.0 is used at simulating the flexible shop. It is a discrete-event object-oriented simulation package for Python.