# MATERIAL FLOW CONTROL IN A SEQUENCE DEPENDENT SETUP JOB SHOP VIA ORDER RELEASE AND DISPATCHING MECHANISMS

by

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ABSTRACT

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Material flow control on the shop floor involves the release and dispatching of orders to meet customer due dates, while minimizing operating costs. The early release of orders to the shop floor does not necessarily ensure delivery performance and often results in unnecessary shop congestion and excessive cost. Thus, determining when order release should occur and how dispatching should be accomplished is critical to the success of a manufacturing organization.

Although there has been a significant amount of research in the material flow control literature regarding the job shop environment, there exists a significant void with respect to order release in a sequence dependent setup (SDS) environment. This research provides comprehensive literature reviews of order review and release (ORR) simulation based studies in job shop environments and dispatching techniques in the SDS job shop. The literature reviews served as the basis for developing practical order release and dispatching mechanisms that can be implemented in a job shop environment where sequence dependent setups exist.

This research investigated the main effects and interactions of several order release and dispatching mechanisms in the benchmark job shop model developed by Ragatz and Mabert (1988). Additionally, experimental treatments were analyzed to determine which combination of dispatching and order release mechanisms yielded the most favorable performance results under the environmental conditions tested. The experimental results demonstrated that the Work Load Control Machine Center (WLCMC) order release and Similar Setup dispatching mechanisms (both mechanisms utilized critical ratio sequencing of queues) yielded superior results, which were robust to the levels of variation and utilization tested.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Preface

There is a need for practical order release and dispatching mechanisms in job shop environments where sequence dependent setups exist. In practice, the effectiveness of a production system can be improved by systematically determining which jobs to release to the shop floor, and when job release is to take place. Further schedule improvements can be made by selecting the next job to process from the queues of waiting jobs at various work stations on the shop floor.

Despite the tremendous number of theoretical studies performed in order release and dispatching, few studies have been implemented in industrial settings. This is partly due to the difficulty in formulating and analytically solving industrial scheduling problems. However, the primary reason that research studies have not been successfully implemented in industry is due to the restrictive assumptions they are founded on. Most industrial scheduling problems are dynamic and stochastic in nature, yet the majority of order release and dispatching research efforts assume static and deterministic conditions. Consequently, the optimal solutions obtained from these efforts, deteriorate quickly in industrial applications.

The stochastic nature of the industrial manufacturing environment is due to deviations that occur during the production process that cause the system to behave differently than what was expected. Deviations can cause the scheduling system to perform its function either incorrectly or inefficiently. Consequently, these deviations may prevent the system from accomplishing its objectives of delivering products in a timely manner and at a reasonable unit cost.

Much of the existing scheduling research also assumes that setup times are negligible or are included in the processing times, and thus are independent of job sequence. This restrictive assumption simplifies the analysis, however adversely affects the solution quality for industrial applications which require the explicit treatment of setup, since sequence dependent setup recognizes that the setup time of a job is a function of the preceding job on the machine and the overall sequence of all jobs. If the setup times are significant and sequence dependent, the failure to adequately address these attributes may lead to inefficient schedules, in terms of resource utilization, including both manpower and equipment.

Such assumptions are inappropriate with respect to many manufacturing environments, including machine shops, plastics, printing, and textile industries. This research is motivated by the need for practical order release and dispatching mechanisms that can be implemented in a job shop environment where sequence dependent setups exist. To date, minimal dispatching research has been conducted with respect to sequence dependent setups in a job shop environment and the research regarding order release in the presence of setup sequence dependency is nearly non-existent.

## 1.2 Problem Statement and Research Objective

Production planning and control in a job shop environment is an inherently complex task, due to the quantity, variety, and type of products produced. The complexity of the job shop is further complicated by the manufacturing task complexity of jobs in this environment. Newman and Maffei (1999) define manufacturing task complexity as "the extent to which parameters of a job shop make it difficult to plan, schedule and control the operation of the job shop". Manufacturing task complexity is impacted by order arrival rates, the number of steps in the manufacturing process, processing time variability, and setup sequence dependency. Nicholas (1997) suggests that although just-in-time (JIT) practices and other techniques have done much to reduce task complexity in manufacturing facilities, these practices have provided limited benefits in job shop environments.

Similarly, Hopp and Spearman (1996) contend that conditions inherent to the job shop production environment preclude the use of constant work in process (CONWIP) or any other pull system. Specifically, they point to problematic issues related to shifting bottlenecks, complex routings, and work in process (WIP) reassignment. Although they do not provide a solution to these complex issues, they do describe how some practitioners use a variation of material requirements planning (MRP) to manage these complex environments. Hopp and Spearman discuss how production researchers and software vendors have increased emphasis on two types of finite capacity scheduling techniques that can be used in conjunction with MRP:

1. Optimization based scheduling.

2. Simulation based scheduling.

With optimization based scheduling, order releases determined by MRP are used in a mathematical programming algorithm to develop a pseudo-optimal schedule. Due to the size and NP hardness of many production environments, optimal solutions cannot be obtained in a reasonable amount of time. Thus, approximation techniques are employed. Hopp and Spearman suggest that these techniques in and of themselves are not bad, however, most optimization based scheduling software is sold in "black box" form (for proprietary reasons) and consequently the effectiveness of the approximations may be difficult for the user to determine. Additionally, the stochastic nature of the job shop environment often renders these approximations obsolete as orders begin processing through the shop floor. Lastly, implementation of optimization based scheduling may be economically infeasible for many organizations.

In simulation based scheduling, a simulator develops a detailed deterministic simulation model of the production system and interfaces it with a WIP tracking system which tracks the status of active jobs. Schedules are generated by running the model forward in time and recording the arrival and departure of jobs at various work centers. Dispatching rules are then applied at each work center, resulting in multiple schedules, whose performance criteria are evaluated in order to obtain the most desirable schedule. An advantage of this approach as explained by Hopp and Spearman is that actual system simulation is an intuitive approach that both planners and operators alike can understand. However, there are two significant disadvantages to the simulation approach. First, simulation modeling requires an extensive amount of data that must be maintained. Secondly, as with the optimization based scheduling approach, simulation does not account for randomness, thus resulting in significant differences between its prediction and actual performance.

Controlling production in a job shop environment remains a NP-hard problem, thus research must focus on finding good solutions, not optimal solutions. As alluded to above, this research is motivated by the void in the existing sequence dependent setup literature and by the need for practical order release and dispatching mechanisms that can be implemented in a job shop environment where sequence dependent setups exist.

Allahverdi's comprehensive surveys of scheduling problems with sequence dependent setup identified over 400 published papers, only 26 of these papers addressed the job shop environment. Additionally, the majority of the research addressing the job shop environment was based on mathematical techniques aimed at obtaining optimal or near optimal solutions. Of the 45 ORR simulation studies identified in Tables 3.1 and 3.2, only one addressed sequence dependent setups in the presence of an order release mechanism. Five of these studies simulated actual production environments. Thus, there is a significant void in the research with respect to the development of practical order release and dispatching mechanisms in a job shop environment with sequence dependent setups. Consequently, the research proposed here has three objectives,

1. Provide a comprehensive literature review of ORR simulation based studies in a job shop environment.

2. Provide a comprehensive review of the job shop scheduling literature that addresses sequence dependent setup.

3. Develop practical order release and dispatching mechanisms that can be implemented in a job shop environment where sequence dependent setups exist.

The literature reviews of ORR simulation based studies and sequence dependent setup will provide researchers and practitioners alike, a comprehensive source of job shop order release and dispatching research. The purpose of developing order release and dispatching mechanisms is not to arrive at optimal or near optimal solutions, but to develop practical mechanisms capable of improving shop floor performance in terms of unit cost, delivery performance, and shop floor congestion. The intent of the mechanisms are not to obtain a set of mechanisms that are used under all shop conditions, but to provide practitioners with the basis for establishing alternatives that can be utilized under appropriate shop floor conditions.

## 1.3 Research Significance

This research represents a significant extension to the work of Kim and Bobrowski (1995), who published the only known work related to ORR/WLC in a sequence dependent setup job shop environment. This research is the first to:

- Evaluate the performance of workload control by machine center for the sequence dependent setup job shop.
- Analyze critical ratio queuing in pre-shop pool and machine queues.

- Evaluate total cost as a dependent variable, where total cost is defined as the sum of production cost, WIP cost, early penalty cost, and late penalty cost.
- Utilize real cost data in the evaluation of performance measures.
- Simulate both hypothetical and operational job shops.
- Evaluate the applicability of non-sequence dependent setup order release findings in a sequence dependent job shops.

Additionally, this research provides a basis for considering WLCMC in a SDS job shop environment, where MRP is utilized.

## 1.4 Overview of Thesis

The report begins with an examination of traditional production planning and control activities. A survey of descriptive and analytical research is then presented, followed by a comprehensive examination of job shop simulation based order review and release and sequence dependent setup dispatching research efforts. The research questions and methodology are presented, followed by the research model development and experimentation processes. Lastly, the conclusions and recommendations for future research are presented.

# CHAPTER 2

# PRODUCTION PLANNING AND CONTROL

In today's competitive business environment, manufacturing managers seek on time delivery, minimal lead times, and minimal work in process, while attempting to maximize resource utilization. Unfortunately, these objectives are conflicting. It is much easier to finish jobs on time if resource utilization is low. It is also much easier to eliminate delivery delinquencies and reduce customer lead times if large amounts of work in process are maintained. Thus, a primary goal of manufacturing management is to strike a profitable balance amongst these conflicting objectives. An essential tool for achieving this profitable balance is an effective production system.

## 2.1 Facility Layout

Facility layout is the physical arrangement of all the processes needed for the production of goods. An efficient layout will result in a smooth work flow through the production facility. The quantity, variety, and type of products produced dictates the layout employed.

In traditional production facilities, there are three principal layout types:

1. Fixed position layout.
2. Product layout.
3. Process layout.

With the fixed position layout, the product remains in one location and manufacturing equipment and personnel are brought to the product. Examples of the fixed position layout include large aircraft assembly and ship building production environments.

In production facilities utilizing a product layout, equipment and processes are arranged according to the progressive steps by which a product is made. Production lines, assembly lines, flow lines, and group technology are examples of product layouts. Production lines and assembly lines are examples of product layouts, in which large volumes of narrow product lines are produced, often utilizing special equipment. With flow lines, the facility is arranged to make the dominant products flow easier. Flow lines differ from production and assembly lines three ways:

1. Wider product range.
2. Less specialized equipment.
3. Production in batches rather than a mixed continual sequence.

Group technology is a manufacturing philosophy in which similar parts are grouped together to take advantage of manufacturing similarities. Part families are established by grouping parts with similar manufacturing characteristics, thus the processing of each part within a given family would result in manufacturing efficiencies. These efficiencies are realized by grouping production equipment into machine cells to facilitate work flow.

In a process layout, production machines that perform similar functions are physically grouped. In this layout, shop production can be characterized as low volume and high product mix. The open shop and job shop are examples of process layouts. These shops are similar in that they group similar machines to form machine centers. In both shops there are as many machine centers as there are types of machines. When an operation on a particular type of machine is specified, any available machine of that type may perform the specified process at the machine center, since the machines are interchangeable. However, the flow of work within the job shop and open shop differ dramatically. In the job shop layout, each job has a given machine routing in which some machines may be missing and some may repeat. In contrast, in the open shop each job is processed once on each of the machines, passing them in any order.

The proposed order release and dispatching research addresses the job shop facility layout. The proposed research will however investigate some of the principles of the group technology production philosophy, related to the establishment of part families and incorporate them into the proposed mechanisms. The production facility that serves as the motivation of this research is configured as a job shop. The job shop configuration utilized in this facility is necessitated by the vast product mix and variable lot size quantities experienced in daily operations. These production attributes make other facility layouts such as fixed position and product layouts infeasible. Additionally, these shop attributes have a significant influence on the production system utilized in the job shop.

## 2.2 Production Systems

Typical functions of a production planning and control system include:

- Demand management.

- Planning the requirements for materials.
- Inventory accounting.
- Scheduling and sequencing jobs.
- Planning and balancing capacities.
- Order release.
- Tracking performance and taking action when necessary.

Production systems are often characterized as either push systems or pull systems. In a push production system, production is authorized when the computed start date of a job is reached, regardless of the state of the shop floor. MRP is a push based system. With a pull production system, production is authorized as inventory is consumed. Thus, with pull production, authorization depends on the state of the shop floor. According to Nicholas (1997), there are five general requirements for pull system application:

1. Continuous flow production.
2. Limited product mix.
3. Short setups.
4. Low demand variability.
5. Limited interruptions due to equipment, quality, or setup problems.

Examples of pull production systems include Kanban and CONWIP.

Stevenson et al. (2005) classified MRP, Manufacturing Resource Planning (MRP II), Kanban, and Theory of Constraints (TOC) as classic approaches to production planning and control. They consider approaches such as Workload Control

(WLC), CONWIP, Advanced Planning and Scheduling (APS), and Paired cell Overlapping Loops of Cards and Authorization (POLCA) as emerging production planning and control techniques. Each of these production planning and control approaches can be effective under the right shop conditions.

## 2.3 Material Requirements Planning

Despite being labeled a "classic approach" to production planning and control and despite the vast amount of enterprise resource planning (ERP), CONWIP, and APS research and commercial production planning and control software currently available, MRP is still an important production planning and control approach. Sower and Abshire (2003) found that one third of all manufacturing companies surveyed used production planning and control systems such as MRP.

MRP is a push based system, designed for complex production planning environments. Complex environments often preclude the use of pull based production systems such as Kanban, CONWIP, POLCA, and TOC. Researchers and practitioners alike recognize MRP as a valid production planning and control system alternative under the appropriate shop conditions. For example, Hopp and Spearman (1996) state that shifting bottlenecks and complicated routings often preclude the use of CONWIP or any other pull system and that variants of MRP or MRP II are applicable in such production environments.

The primary objective of an MRP system is to determine how many items exist, how many items are needed, and when items are needed. MRP does this for items to be produced within the plant and for purchased items. Beginning with the end item and for each level in the bill of material (BOM), MRP executes the following activities:

- Netting.
- Lot sizing.
- Time phasing.
- BOM explosion.

This is an iterative process, beginning with the end item and for each successive level of the BOM. The netting process determines the net requirements by subtracting the current inventory and scheduled receipts from gross requirements. The gross requirements for end items come from the master production schedule, while those for successive BOM level items are the result of previous MRP operations. Lot sizing divides the net requirements into the appropriate lot sizes to form jobs. Next, time phasing offsets the due dates of the jobs with fixed lead times to establish start dates. Finally, with the BOM explosion, start dates, and lot sizes, the BOM is used to calculate the gross requirements for subsequent levels. This represents an iterative process for each level of the BOM resulting in the material requirements plan for all inventory, from purchased items through finished goods.

Although commercial production planning and control software producers often suggest their respective approach's are universally appropriate, many industry specific production planning and control needs are not satisfied given that production environments vary greatly with respect to shop floor configuration, product variation, process variation and setup sequence dependency. Researchers including Wisner

(1995) and Bergamaschi et al. (1997) have concluded that there is not one best order review and release mechanism.

## 2.4 Workload Control

As previously noted, operations configured as job shops supply a wide variety of products, ranging from standard products to customized products. In these shops, the arrival rate of customer orders for numerous items represents a stochastic process over time, further confounding day to day operations. Consequently, each order is for a different quantity of items with varying routings and varying processing times. This dynamic and unpredictable production environment makes it inappropriate for organizations to adopt a production strategy such as Kanban, CONWIP, or TOC, as argued by Kingsman and others (refer to Kingsman (2000) and Nicholas (1997)). Such organizations do not have the repetitive manufacturing environments that warrant dedicated facilities to be set up in a simplified shop floor layout (e.g. cellular and group technology layouts).

Stevenson et al. (2005) suggest that the workload control approach is the most applicable production planning and control option for make to order manufacturers with facilities configured as a job shop. Their research also suggested that ERP and TOC (when stationary bottlenecks exist) are viable production planning and control systems in the job shop make to order sector. However Stevenson et al. (2005), consider these systems inferior to workload control since workload control is designed specifically for make to order manufacturers, whose facilities are configured as job shops. Workload control is also considered a lower cost approach to production planning and control, when compared to ERP, as argued by Stevenson et al. (2005).

Kingsman (2000) reported that in make to order industries, orders spend up to 90% of the total production time queuing at work stations and only 10% in actual processing time at work stations. In large job shops, empirical studies indicate that queuing time far exceeds the 90% reported by Kingsman. Thus, the shop floor can be viewed as a network of work centers each with a set of orders queuing and awaiting processing. As the queues grow, so does shop floor congestion.

As a means of managing work center queues and in turn congestion, workload control/order review and release utilize an order entry component, pre-shop pool, and order release mechanism. This three phased approach stabilizes the performance of the shop and helps maintain manageable queue lengths. Several workload control/order review and release methodologies have been developed that address two significant decision levels in job shop environments, the job entry level and the job release level. At the job entry level, customer orders are processed and delivery dates are established (if delivery dates are not pre-determined). At the job release level, the decision to release a job to the shop floor so that processing can be initiated is made.

In the literature, the terms “order review and release” and “workload control” are often used interchangeably. Much of the literature originating in Europe uses the term workload control, however in the literature originating in North America the term order review and release is most often used. Whether termed workload control or order review and release, the objectives are the same, controlling the release of jobs to the shop floor. Workload control does however represent a specific subset of order review and release in that its order release is normally based on a predetermined level of WIP for resource groups, where WIP norms generally exceed resource capacity. Thus, the more general term order review and release will be used throughout the remainder of this work.

The proposed research represents a hybrid approach to production planning and control incorporating elements from the MRP production planning and control methodology and ORR. This hybrid approach will address the specific needs of the job shop production environment where sequence dependent setup and process variability exist.

## 2.5 Role of Order Release in Production Planning and Control

Within a production planning and control system, ORR acts as the interface between the manufacturing planning system and the shop floor. It determines what orders to release to the floor, when they should be released, and which have a good chance of being completed on time and within costs. Order review and release also seeks to ensure that there is a balance between the load released to the shop floor and the capacity available for processing the load.

Bergamaschi et al. (1997) depict the role of the ORR methodology within the general framework of a shop floor control system as presented in Figure 2.1.

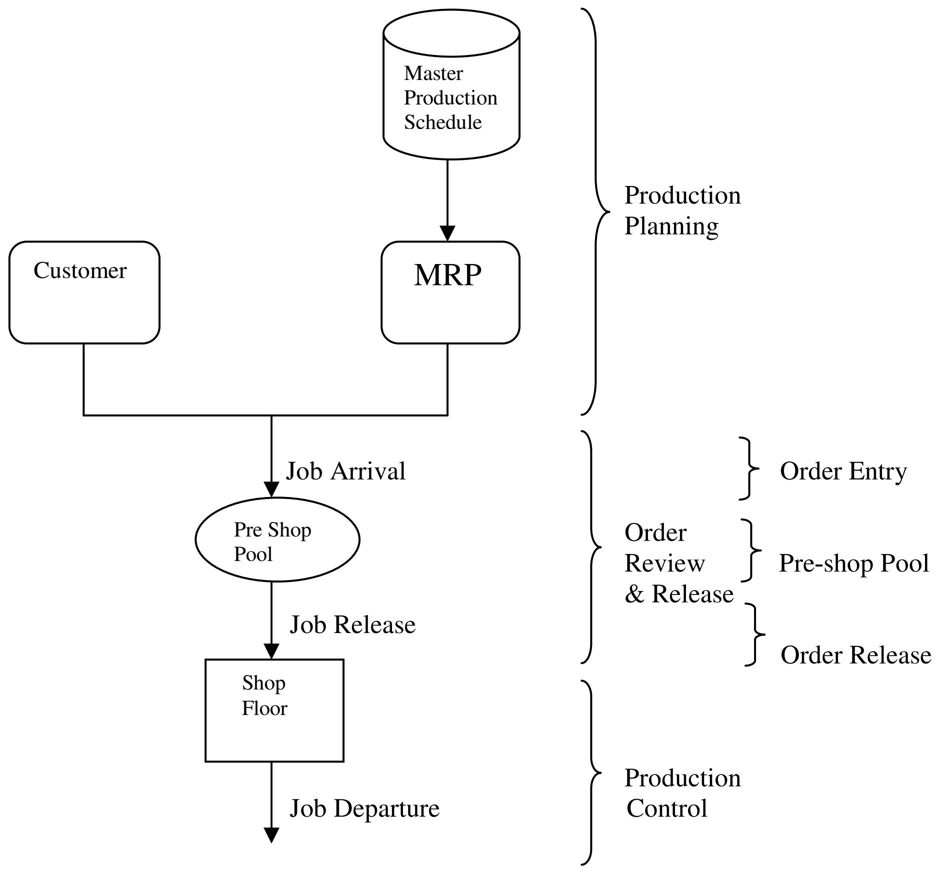


Figure 2.1 Position of ORR within the framework of a shop floor control system.

As illustrated in Figure 2.1, production orders (which are generated from either a requirements planning system or directly from customer orders) arrive continuously to the ORR system over time. The arrival of a production order or customer order to the order review and release system does not automatically initiate the release of a job to the shop floor. On the contrary, orders that are released by the production planning system are stored in a backlog pool, referred to as the pre-shop pool. The pre-shop pool de-couples the planning system from the shop floor. This de-coupling function is executed in order to ensure that excessive orders are not released to the shop floor, thus avoiding shop floor congestion. By controlling the flow of work and ensuring that the shop floor is not overloaded, order review and release helps to generate stable queues and hence stable lead times. By releasing only the jobs that need to be released, the shop is always working on jobs that can be completed in a timely and cost effective manner.

As described above, only a subset of the production orders residing in the pre-shop pool are released each time the order release phase is activated. At this time the ORR system scans all production orders stored in the pre-shop pool and determines which are allowed to be released to the shop floor and at what time.

### *2.5.1 Components of an Order Review and Release System*

As Bergamaschi et al. (1997) suggest, in its most general form a complete ORR system consists of the following subsystems:

- Order entry.
- Pre-shop pool.
- Order release.

#### 2.5.1.1 Order entry Component

The order entry component is the link between the ORR system and the production planning system. This component begins with production order preparation, followed by order release to the pre-shop pool. Activities in the order entry phase include:

- Definition and retrieval of the job routing.
- Required tooling, fixture, and CNC program availability is checked.
- Pick list of all the required materials is developed and checked.

- If due-dates are not set by the production planning and control system, a delivery date is assigned to each production order.

Once the availability of all required resources has been ensured, jobs become eligible for entry into the pre-shop pool.

2.5.1.2 Pre-Shop Pool Component

The pre-shop pool component of the ORR system behaves as a holding area (usually a database), that consists of all production orders already processed by the order entry component, but not yet released to the shop floor. This pool consists of either physical raw materials for orders or just the associated paperwork for the production orders. None of the production orders processed by the order entry phase can reach the shop floor without passing through the pre-shop pool.

Production orders arriving from the order entry component are queued at this gateway in a predefined order. At regular intervals, such as at the beginning of each day, the pool is inspected and a decision is made as to which orders to release, if any. The release decision can be made based on numerous criteria. The set of criteria used to determine which orders to release each time the pool is inspected, is termed the release mechanism (release mechanism is also referred to as triggering mechanism or input control mechanism).

2.5.1.3 Order Release Component

The key to the successful implementation of an ORR strategy is rooted in the design and control of an effective release mechanism. The design element (e.g. time phased or workload based) is concerned with the development of the release mechanism, while the control element is focused on establishing the control parameters of the release mechanism (e.g. WIP levels). Information used to determine which orders to release each time the pool is inspected may include:

- Current pre-shop pool status, how many orders and which orders are currently in the pre-shop pool.
- Current shop status, what orders have already been released to the production system, at which machine center are they currently queuing and what is the current shop capacity.
- Planned shop performances, in terms of manufacturing lead times and delivery timeliness.

By analyzing the characteristics of the orders in the pre-shop pool and the workload on the shop floor as well as its current location, the order release component determines if and at what time the release of each production order can take place. Most ORR research is focused on similar decision criteria.

Several research efforts suggest that as the performance of order release mechanisms increase, the impact of shop floor dispatching diminishes. However, other research efforts have shown that there is significant interaction between the order release function and dispatching, resulting in substantial performance improvement.

## 2.6 Role of Dispatching in Production Planning and Control

Within the production planning and control system, dispatching serves as the mechanism for selecting the next job to be processed from a queue of jobs waiting to be processed at a work station. Dispatching is initiated once orders are released into the shop and processing at the gateway operation is complete. Order release itself can be considered a dispatching mechanism, since it is effectively dispatching at the gateway operation.

The dispatching problem is complex, in that given a queue of n jobs at a work station, there are n! ways to order those jobs for processing. This ordering of jobs is also influenced by the state of other queues on the shop floor and by the sequence dependent setup nature of jobs, further compounding the complexity of the dispatching function. Additionally, shop conditions at other work station can influence the optimal sequence of jobs at the work station of interest. One example of an influencing factor includes jobs that are impacted by sequence dependent setups.

A sequence dependent setup recognizes that the setup time of a job is a function of the preceding job being processed and therefore the overall sequence. Setup includes work to prepare a machine or process for job processing. This includes obtaining tools, positioning material, setting jigs and fixtures, validating settings, material inspection, returning jigs and fixtures, and cleanup. While production concepts such as flexible manufacturing systems and single-minute exchange of dies have reduced the impact of setup time, numerous production environments for which the amount of setup time varies significantly depending on the processing sequence of the jobs still exist. This includes die and fixture changes in metal processing industries, color changes in textile industries, and stamping operations in plastics manufacturing.

Sequence dependent setups impact several job shop performance measures. Both Flynn (1987) and Wortman (1992) emphasized the importance of considering sequence dependent setup times for the effective management of manufacturing capacity. Additionally, setup time has a significant impact on effective capacity and flow time, which directly affects the throughput rate of the job shop and the unit cost of the product produced. Thus, exploiting similarities in setups that exist among parts through the use of dispatching mechanisms that take setup into consideration can be critical to improving shop performance.

As discussed above, while some researchers have concluded that an effective order release mechanism diminishes the importance of dispatching mechanisms, others have concluded that the impact of order release on shop performance is significantly influenced by the type of dispatching rule used on the shop floor. The proposed research incorporates dispatching mechanisms into the proposed production control scheme, in order to cope with the dynamically changing conditions on the shop floor. If the shop floor was deterministic in nature, then an effective order release mechanism and simple dispatching rule would be appropriate. However, since manufacturing environments are stochastic in nature, a dispatching mechanism that utilizes current shop floor information can react to the evolving shop floor conditions. Dependence solely on order release and simple dispatching mechanisms may result in poor performance since job routing decisions would be made based on initial shop floor conditions that change as jobs are released and proceed through the production floor.

# CHAPTER 3

# LITERATURE REVIEW

The literature dealing with ORR is nearly nonexistent prior to 1970. Most production control research was based on the assumption that the rate of arriving orders to the shop floor was controlled by external forces and typically represented as a stochastic process. As a result, shop floor dispatching was the focus of many of the original studies dealing with production planning and control, while ORR did not play a role in these studies.

Section 3.1 presents a review of the ORR literature. This is a comprehensive review of simulation based ORR literature and a survey of descriptive/case studies and analytical/optimization studies in job shop environments. Section 3.2 discusses the renewed interest in scheduling problems involving sequence dependent setup times and presents a comprehensive review of the job shop scheduling literature that explicitly addresses sequence dependent setup.

## 3.1 Order Review and Release

From a researcher's perspective, the lack of attention to the ORR mechanism biases research on the dispatching decision and may overstate the importance of choosing a dispatching rule. The accumulated body of research has however led to opposing opinions on the value of ORR and in turn to what many researchers refer to as the "research paradox". Practitioners recognize the benefits of ORR, Melnyk and Carter

(1987) observed that managers of effective production planning and control systems spent a great deal of resources on ORR activities. They often developed procedures to identify the conditions under which order release was to take place and to smooth the load of work released to the shop.

The literature review is classified into three research segments:

1. Descriptive/case studies.
2. Analytical/optimization studies.
3. Simulation studies.

To date, Kim and Bobrowski (1995) and Missbauer (1996) have published the only known papers that address order release and sequence dependent setups.

*3.1.1 Descriptive/Case Studies*

One of the first researchers in the area of ORR was Harty (1969). Harty's descriptive study emphasized the relationship between ORR and the control of production capacity. He presented seven short term capacity control principles that he believed lead to an effective production planning and control system. These control principles were developed so as to avoid overloading bottleneck work centers and to provide a level flow of work in the shop. Harty summarized his views of production control by stating that control comes from keeping work off the production floor, rather than sorting out work already on it.

The work of Harty was followed by that of Wight (1970). Wight concluded that the flow of work both to the shop and within the shop could be controlled in such a way that the size of the queues at each work center in the shop would remain relatively constant. As a result, the level of WIP is controlled directly, and the lead times at the work centers remain fairly constant. The control of work to the shop was handled by the order release function.

Igel (1981) presented a case study which described a manual scheduling process. This process split jobs into grouped parts that visited the same machines. The grouped parts were scheduled independently through the shop using a backward finite loading technique. Loading sheets were used for each machine and updated weekly. Igel found that the job shops that instituted this technique reduced the average WIP, increased on-time deliveries, and reduced queue lengths.

With a dissenting opinion regarding the value of order release, Kanet (1988) argued against limiting the release of jobs to the shop as a means of reducing WIP and flowtime. Kanet's argument opposing controlled release stemmed from the belief that if arrival rates and process times remained unchanged, then holding jobs in a release queue did not influence mean flowtime. He also argued that controlled release in a multiple machine environment introduced idle time into a schedule, longer mean flowtimes, and greater overall job tardiness.

Bechte (1988) described the implementation of a load limited order release (LOOR) policy in a machine shop that produced appliance fittings. The policy consisted of establishing job priorities and preliminary release dates using backward infinite loading, then releasing jobs in priority order provided the load limits of all work centers on each job's route were not exceeded. The result of implementing this system was reduced inventory and lead-time levels.

Melnyk and Ragatz (1988) presented a general discussion paper regarding order review and release. Their paper included a review of the ORR literature, a discussion of the role of ORR in shop floor control, and the components of the ORR framework. Their literature review included descriptive research by Melnyk and Carter (1987), Nicholson and Pullen (1972), and Sandman and Hays (1980); and experimental research by Bechte (1982) and Ragatz (1985) that are not addressed in this paper.

Milne et al. (1995) reviewed order release mechanisms applicable to various manufacturing environments, including the job shop. Milne et al. refers to these mechanisms as material flow control (MFC) mechanisms. The MFC mechanisms described included: Kanban, CONWIP, workload regulating, starvation avoidance, BORA, maximum load limit, MRP, base stock system, WLC, and production authorization cards. Milne et al. suggested that each of the mechanisms can be improved upon under certain manufacturing conditions and objectives.

Bergamaschi et al. (1987) developed a classification framework for ORR methodologies that is widely referenced throughout the literature (a limited literature review was also included in their research). There are eight dimensions of this framework that describe the fundamental characteristics of an order release procedure:

1. Order release mechanism.
2. Timing convention.
3. Workload measure.
4. Aggregation of workload measure.
5. Workload accounting over time.

6. Workload control.
7. Capacity planning.
8. Schedule visibility.

Order release mechanisms can be classified as either load limited or time phased. Under load limited order release, orders are released to the shop based upon their characteristics and the existing workload in the shop. In contrast, the time phased order release approach is based on computing a release time for each order and then letting orders enter the shop when that predetermined time is reached, regardless of the shop load.

The timing convention determines when an order release can take place. Timing conventions can be classified as either continuous or discrete timing. Under the continuous timing convention a release may occur at any time during the system's operation. By contrast, under the discrete timing convention, an order release may occur only at periodic intervals (e.g. the beginning of each shift, day or week).

In order to evaluate the impact of production order release on shop workload, shop load must be measured. ORR researchers measure workload either in terms of the number of jobs on the shop floor or in terms of the work quantity (work quantity can be expressed in hours or as a percentage of the planned capacity in a given time period)

Related to workload measure is the workload aggregation methodology. The workload can be aggregated at the total shop level (this gives no indication of the way in which the load is distributed among the different work-centers of the shop) or at the work center level. A third alternative approach is to compute and control the workload for selected bottleneck work centers only.

There are three basic methods of accounting for workload over time:

1. A-temporal.
2. Time bucketing.
3. Probabilistic.

With the a-temporal methodology, the total work considered for each machine is determined by summing up the processing times for all jobs in the shop that are to be routed through that machine (there is no differentiation between load in transit and released load from load on hand). This methodology provides no indication of the way in which the load is distributed over time. In the time bucketing methodology, the workload profile is computed at each machine center over time. The time horizon is broken into time periods (e.g. shifts, days, etc.) and the load at a given machine center due to a specific job is summed up in the time bucket according to the time period during which the corresponding operation is scheduled to be completed. Thus, the time bucketing approach considers the load on hand only. Lastly, the probabilistic approach differentiates the released load and load in transit from the load on hand by multiplying the released load and the load in transit by the probability that each order could arrive at the work center considered within the current planning period.

There are several approaches to the workload control dimension. One approach to workload control is to allow the release of an order to the shop only if it does not exceed an upper bound (load limit). In practice the load limit is set by management, according to the chosen aggregation of workload measure. This approach controls the level of work in process inventory. An additional lower workload bound can be used to provide a range for the workload which may be loaded to the shop. In this case the job release mechanism usually operates so that jobs are released only if the shop load remains within its limits. The role of the lower workload bound is to ensure that each work center is provided with an appropriate buffer of work. Lastly, the workload balancing approach relaxes rigid work center bounds in an attempt to maximize overall shop performance.

There are two approaches to capacity planning: active and passive. With active capacity planning the ORR model adjusts the machine capacity during the system's operation, either by assigning overtime or by reallocating operators to machine centers. When capacity planning is considered passive, capacity is assumed as given and outside the control of the ORR strategy.

The last of Bergamaschi's eight dimensions is schedule visibility, which can be characterized as either limited or extended. In the limited schedule visibility case, the release of jobs from the pre-shop pool to the shop floor can be directed to controlling the workload level in the shop during the next closest planning period. Schedule visibility is considered limited in this context, since jobs are selected from the pre-shop pool in order to achieve good shop performance for the present or the next planning periods only. Thus, with limited schedule visibility, workload is smoothed over time, but only in order to optimize the next period. With extended schedule visibility, the order release mechanism seeks to optimize the shop performances along a time horizon greater than a single period. This result is achieved by releasing jobs from the pre-shop pool so as to maintain a balanced workload among the machine centers and over time.

In 2002, *Production Planning and Control* dedicated an issue to the WLC methodology. This issue contained three discussion papers and four simulation based papers applicable to the job shop environment (refer to section 6.1.3.7 for a discussion of the simulation based studies). In the first discussion paper by Gaalman and Perona (2002), they provided an overview of the WLC methodology and suggestions for future research efforts. Additionally, they discussed scheduling system trends in ERP software, including deterministic scheduling tools. In the second discussion paper, Breithaupt et al. (2002) provided a review of the strengths and weaknesses of the LOOR WLC methodology. Additionally, theoretical remedies for the documented weaknesses were developed. In the last of the discussion papers, Missbauer (2002) described the relationship between WLC and lot sizing. A flow time oriented lot sizing model was developed for the single stage problem. Missbauer contends that the single stage lot sizing models are relevant for multi-stage systems; however there are significant limitations especially in the high capacity utilization case.

Henrich et al. (2002) developed a framework to explore the applicability of WLC in make to order companies. They concluded that the applicability of WLC increases with increased variability, as evident by increasing arrival rate fluctuations, due date differences, processing time variability, routing sequence and routing length variability. However, it was noted that assembly operations and sequence dependent setup times may cause problems when using the WLC approach.

Stevenson et al. (2005) reviewed and assessed the applicability of several approaches to production planning and control applicable to make to order manufacturing environments. The systems discussed included: Kanban, CONWIP, Theory of Constraints, MRP II, WLC, POLCA, and web or e-based supply chain management solutions. They concluded that the WLC methodology was the most effective job shop solution and that there are several alternatives depending on individual company characteristics and objectives for other shop configurations.

Stevenson and Hendry (2006) presented a review and re-classification of the WLC methodology developed at the Lancaster University Management School (WLC-L). This WLC methodology serves as more than an order review and release mechanism. The WLC-L approach has the capability of establishing due dates at the customer enquiry stage, providing scheduling at the job entry stage, and assisting in job release decisions. Their work included an analysis of significant research involving the measurement of indirect load and workload bounding. Changes to the WLC-L methodology are detailed and a side by side comparison to the original WLC-L methodology is presented using the classification scheme developed by Bergamaschi et al. (1997).

Additional descriptive studies include the works of Tatsiopoulos (1988), Hendry and Kingsman (1991a), Hendry and Kingsman (1991b), Wiendahl et al. (1992), Land and Gaalman (1996), Tatsiopoulos (1997), Perona and Portioli (1998), Kingsman (2000), Haskose et al. (2002), and Henrich et al. (2004).

*3.1.2 Analytical/Optimization Studies*

Several researchers have utilized analytical or optimization techniques that include delayed release to determine optimal or near optimal job schedules. Several of these articles demonstrated how ORR could be used to enhance performance. For example, Nicholson and Pullen (1971) developed an iterative search technique to find the job schedule minimizing total delay cost. The delay cost function was transformed into a function of release time, then release times were substituted into the function until no further improvement in delay cost could be obtained. In similar research by Faaland and Schmitt (1987), a two phased iterative search technique with the objective of minimizing earliness and lateness costs was developed. Jobs were released immediately to the shop floor in order to obtain an initial feasible schedule. Next, jobs were selectively delayed until no further improvements in cost could be found. The results of the heuristic were compared with a finite loading solution and mixed integer programming solution. The heuristic outperformed the finite loading approach, however yielded inferior results compared to the mixed integer programming solution.

Haskose et al. (2004) modeled the WLC methodology as a queuing network with limited buffer capacities in front of each workstation. An approximation algorithm was developed to address multiple workstations and to allow the flow of work between workstations. They concluded that the resultant model produces valuable estimates of planning norms for use in new shop floor situations once the desired performance objectives have been set. Experimental results suggest that as the shop layout increases in complexity, measures of performance tend to decline.

Onur and Fabrycky (1987) developed an iterative heuristic optimizing algorithm incorporating mixed integer programming. Statistics were collected for mean tardiness, shop utilization, work in process, flow time, overtime usage, second shift usage, and average cost. The heuristic was compared to a finite loading mechanism and outperformed it for all performance measures excluding shop utilization. Similarly, Zozom et al. (2003) developed two heuristic algorithms that used a detailed shop floor model to determine the release times of new jobs, with the objective of minimizing WIP. Experimental results indicated that both heuristics were effective at reducing WIP, yielding solutions close to the computed lower bound.

Raman (1995) modeled the order release decision as a dual objective problem of minimizing total job tardiness and maximizing the sum of job release times in a lexicographic manner. He developed a solution method that decomposed the problem into a bi-criteria problem for critical jobs and a maximum release time problem for non-critical jobs. An iterative procedure was used to solve these problems until no further improvement takes place for the set of critical jobs. This approach yielded significant improvements in job release times, compared to an approach that had the sole objective of minimizing total tardiness.

As a final example of optimization based techniques, Irastoza and Deane (1974) employed a mixed integer programming approach to select jobs to be released from the pre-shop pool. The objective of the release mechanism was to balance the work load across the machine centers while also meeting job due dates. This mechanism resulted in improved control over WIP with equivalent order lateness in comparison to a system employing immediate release.

A common weakness among the analytical and optimization techniques is that order arrivals and shop conditions are typically dynamic processes (especially in job shops), thus rendering the analytical techniques ineffective in practice.

*3.1.3 Simulation Studies*

Simulation studies comprise the majority of the ORR research literature. These studies typically test combinations of release policies and experimental variables such as dispatching rules, due-date tightness levels, and work center utilization levels. Table 3.1. summarizes the characteristics of the simulation-based order release research.

Table 3.1 Simulation Based Job Shop Order Release Research

| Studies | Shop Characteristics | Dispatching Mechanisms Tested | Release Mechanisms Tested |
|---|---|---|---|
| Adam & Surkis (1977) | Hyp/Ran/6,6 | FCFS, SLK | FFL/BFL, BIL, DFL |
| Brown & Davies (1984) | Act/Ran/80 | LOPN, LPN, BLWC, SPT, LPT, HONF,BMCW | BRISCH, LTT |
| Shimoyashiro (1984) | Act/Line/33,80 | FCFS, S/OPN, | IMM, MXL, CAP (3 variants) |
| Ragatz & Mabert (1988) | Hyp/Ran/5,5 | FCFS, SPT, EDD, CR | IMM, BIL, MIL, MNJ, BFL |
| Melnyk & Ragatz (1989) | Hyp/Ran/6,6 | FCFS, SPT, EDD, S/OPN | IMM, AGGWNQ, WCEDD |
| Bobrowski (1989) | Hyp/Line/15,15 | CR | IMM, FFL |
| Scudder & Hoffman (1989) | Hyp/Ran/9,9 | CR, PRF/OPT, VLADRAT, OPCRAT | IMM, BIL |
| Melnyk et al. (1991) | Hyp/Ran/6,6 | FCFS, SPT, MINSLK | IMM, MXL |
| Philipoom & Fry (1992) | Hyp/Line&Ran/5,12 | EDD | MXL (2 variants) |
| Ahmed & Fisher (1992) | Hyp/Ran/5,5 | FCFS, SPT, EDD, CR | IMM, BIL, MIL, FFL |
| Roderick et al. (1992) | Hyp/Line/6-20 | EDD | CONWIP, BOTTLE, INOUT, FIXED |
| Zapfel & Missbauer (1993) | Hypo/Ran/5,5 | FCFS | LOOR, LOOR* |
| Philipoom et al. (1993) | Hyp/Ran/15,15 | SPT, CR | IMM, MIL, PBB |

*Table 3.1 - Continued*

| | | | |
|---|---|---|---|
| *Melnyk et al. (1994)* | *Hyp/Ran/6,6* | *FCFS, SPT, MINSLK, S/OPN, CR* | *IMM, MXL* |
| Hendry & Wong (1994) | Hyp/Ran/6,6 | FRFS | IMM, AGGWNQ, WCEDD, JSSWC |
| Malhotra et al. (1994) | Hyp/Ran/15,15 | EDD, TWOQ, RR, PREE, FP | IMM, MIL PBB |
| Fredendall & Melnyk (1995) | Hyp/Ran/6,12 | FCFS, MODD | IMM, CMS |
| Kim & Bobrowski [1995] | Hyp/Ran/9,9 | JCR,SIMSET,CR,SPT | IMM, MXL, BIL, FFL |
| Park & Salegna (1995) | Hyp/Ran/6,6 | FRFS, SPT, MOD | IMM, MXL |
| Watson et al. (1995) | Hyp/Ran/4,4 | FCFS | BACKSIM, PMRP |
| Tsai et al. (1997) | Hyp/ Ran/5,5 | FCFS,EDD, TSPT | IMM, ORCS, ORCA |
| Cigolini et al. (1998) | Hyp/Ran/11,11 | FCFS | MXL, LOOR, FL* |
| Hendry et al. (1998) | Act/Line/15, | SPT | WLC-L, No Control |
| Land & Gaalman (1998) | Hyp/Ran/6,6 | FCFS,SPT,S/OPN, PST | WLC-L, WLC-I, IMM, SLAR, WCEDD |
| Philipoom & Fry (1999) | Hyp/Ran/8,24 | EDD | MXL (2 variants) |
| Newman & Maffei (1999) | Hyp/Ran/8,8 | FCFS, SPT | IMM, MXL |
| Bragg et al. (1999) | Hyp/Line&Ran/14,14 | EDD | RP, RM |
| Sabuncuoglu & Karapinar (1999) | Hyp/Ran/6,6 | SPT, MOD | IMM, IM, PBB, FFL, MXL (3 variants), INF (2 variants) |
| Oosterman et al. (2000) | Hyp/Ran/6,6 | FCFS | WLC-L, WLC-I |
| Cigolini & Portioli (2002) | Hyp/Ran/11,11 | FCFS | MXL,WB, MXLMNL |
| Kingsman & Hendry (2002) | Act/Line/15 | SPT | WLC-L, No Control |
| Enns & Prongue Costa (2002) | Hyp/Ran/6 | FCFS, BP | MXL (2 Variants) |
| Bertrand & Van Ooijen (2002) | Hyp/Ran/10,10 | FCFS | WLC-E |
| Missbauer (2002) | Hyp/Ran/15 | FCFS | LOOR, LOOR* |
| Rosario-Moreira &Alves (2006) | Hypo/Ran/6,6 | FCFS, EDD | IMM, PIOC, MIL, BIL |

#### 3.1.3.1 Layout and Routing

Shop floor layout and routing characteristics are documented using a three field notation scheme, $\alpha/\beta/\gamma$. The $\alpha$ field documents whether a hypothetical (Hyp) or actual (Act) job shop layout was modeled. The $\beta$ field documents job routings through the shop, random (Ran), line (Line), or a combination of both. Finally, the $\gamma$ field defines the number of work centers and machines simulated. For example, a hypothetical job shop release problem with random job routings, 6 work centers and six machines will be noted as Hyp/Ran/6,6.

The majority of researchers surveyed utilized hypothetical layouts, with random job routings, and six or fewer work centers per facility modeled. 31 researchers modeled hypothetical shops, while only four researchers modeled actual shop layouts. Random job routings were utilized in 28 experimental environments and line routings were used in five. Two researchers used a combination of line and random routings. The complexity and difficulty of modeling large production systems is apparent when considering that 20 researchers modeled shops with six or fewer work centers and only 3 researchers modeled shops with 20 or more work centers.

#### 3.1.3.2 Dispatching Mechanisms

The most common dispatching mechanisms used in the simulation research include:

- Shortest processing time (SPT).
- First come first served (FCFS).
- Earliest due-date (EDD).
- Critical ratio (CR).
- Slack based rules.

With the SPT mechanism, whenever an operation is completed at a machine, the next job processed is the one in the queue that has the shortest processing time for the upcoming operation. Truncated SPT (TSPT) is a variant of the SPT mechanism. TSPT sequences jobs according to the SPT mechanism, except for jobs having waited longer than a pre-determined truncation time. When the truncation time is exceeded, the job is released.

When the FCFS mechanism is utilized, upon completion of a job at a machine, the next job processed is the one that has been waiting in queue the longest at that machine center. This mechanism is also referred to as first in first out (FIFO) and first in first served (FIFS).

With the EDD mechanism, whenever an operation is completed at a machine, the next job processed is the one in the queue that has the earliest due date.

CR is a dynamic due date oriented mechanism. This mechanism determines the priority value of a job as a ratio of the measure of the expected amount of time left until the job's due date.

With the first released first served (FRFS) dispatching mechanism, orders are processed in the same sequence in which they are released to the shop floor. The FRFS mechanism is also referred to as first in system first served (FISFS) mechanism.

Using the MODD mechanism, priority is given to the job with the smaller value of modified operation due date. The modified operation due date is calculated as:

$$\text{MODD} = \text{Maximum}\ (\text{ODD}, \text{Current Time} + \text{OPT}). \qquad (3.1)$$

Where: ODD is the next operation's due date.

OPT is the current operation processing time.

Lastly, there are several slack based dispatching rules, including slack per remaining operation (S/OPN) and minimum slack (MINSLK). These mechanisms determine the priority value of a job as a ratio of some measure of the expected amount of time left until the job's due date. The surveyed researchers employing these dispatching mechanisms did not describe the specific S/OPN methodologies used in their respective works.

Only two sequence dependent setup dispatching rules were discussed in the surveyed simulation based order release literature, job of smallest critical ratio (JCR) and similar setup (SIMSET). The JCR mechanism scans a workstation queue for a job identical to the job that has just finished processing. If there is no identical job, the job with the smallest critical ratio is selected. The SIMSET mechanism considers only the setup time of jobs, selecting the job that requires the shortest setup time.

Other dispatching rules appearing in the order release literature include:

- Lowest operation number first (LOPN).
- Lowest part number first (LPN).
- Batch with least amount of work completed first (BLWC).
- Bottleneck priority (BP), any job in queue that has not passed through the bottleneck resource has priority over other jobs.
- Longest processing time first (LPT).
- Highest operation number first (HONF).
- Batch with most completed work first (BMCW).
- Two Queue (TWOQ), vital priority jobs are released first (sequenced by EDD), followed by normal priority jobs (also sequenced according to EDD).
- Rotating rule (RR), releases the first n jobs (n is a pre-determined parameter, that controls the number of jobs expedited) from either the vital priority or

normal priority queues, then the orders are released by the EDD from the vital priority queue.

- Forced pace (FP), milestone pacing of vital priority jobs.
- Preemption (PREE), sequencing jobs by EDD, unless critical.
- Ratio of total profitability of a job to the work center processing time (PRF/OPT).
- Planned start time (PST) sequences jobs by earliest planned start time.
- Ratio of value added so far to a job to the total value it will have upon completion (VLADRAT).
- Operation critical ratio (OPCRAT), ratio of time remaining until operation due date divided by total operation processing time.

The dispatching mechanisms employed in each of the simulation based studies are listed in Table 3.1, along with the corresponding release mechanism employed.

#### 3.1.3.3 ORR Mechanisms

The benchmark release mechanism employed by most researchers is immediate release (IMM). IMM is often referred to as a naive approach since jobs are released as soon as they are eligible, regardless of the status of the shop floor. In some studies, IMM has resulted in superior performance in terms of lead times, thus contributing to the research paradox. Interval Release (IR) is a periodic variant of the IMM release methodology. The IR mechanism collects jobs in a release pool and then releases them to the shop periodically. The most studied ORR methodologies include:

- Backward infinite (BIL).

- Maximum load (MXL).
- Forward finite loading(FFL).
- Modified infinite loading (MIL).
- Backward finite loading (BFL).
- Path based bottleneck (PBB).
- Constant work in process(CONWIP).
- Starvation avoidance (SA).
- Aggregate work-load trigger, work-in-next queue (AGGWNQ).
- Work-load trigger, earliest due-date (WCEDD).
- Maximum number of jobs (MNJ).
- Workload control – Lancaster (WLC-L).
- Workload control – IFA (WLC-I).
- Load-oriented order release (LOOR).

BIL is a time phased ORR approach that releases jobs to the shop a fixed number of hours per operation ahead of their due date. BIL does not use information regarding the current shop floor workload. If the planned release time is in the middle of a day, the release will occur at the beginning of that day. BIL determines the job release date as follows:

$$RD_i = DD_i - kn_i \tag{3.2}$$

Where: $RD_i$ = release date for job i.

$DD_i$ = due date for job i.

$n_i$ = number of operations in job I.

k = planning factor.

MIL mechanism is also a time phased ORR approach. As with the BIL approach, the MIL approach ignores shop capacity. However, this mechanism allows time spent in the shop to vary with the current shop workload. Jobs are released to the shop floor when the calculated release date is reached. The release date is calculated backward from the jobs due date, using planning factors that provide each job a flow allowance based on the number of operations in the job and the number of jobs waiting in queue along the job's routing. MIL determines the job release date as follows:

$$RD_i = DD_i - k_1 * n_i - k_2 * Q_i \qquad (3.3)$$

Where: $RD_i$ = release date for job i.

$DD_i$ = due date for job i.

$n_i$ = number of operations in job i.

$Q_i$ = number of jobs in queue at machines on job i's routing.

$k_1$, $k_2$ = planning factors.

A variant of the MIL methodology uses a planning factor that accounts for the total processing time of a job and a factor that accounts for the work content of the jobs queuing along the job's path.

MXL release mechanism, is a load limited approach that releases jobs to the shop floor based on first come first served arrival to the pre-shop pool, until the load on the shop floor reaches a predetermined maximum load limit. This methodology directly controls the level of WIP inventory. There are several variants of this methodology. A maximum load limit can be established for the entire shop, only those work centers on an arriving orders routing, or a bottleneck resource only. When the MXL methodology is applied to a bottleneck resource, the current load of the bottleneck work center is checked against the maximum load limit and jobs are released to the shop floor if the bottleneck load does not exceed the maximum limit. Similarly, minimum load limits (MNL) can be established for work centers, where orders are released to the shop floor according to their priority, regardless of the congestion on the shop floor, in order to guarantee at least a workload equal to the lower bound. The MXL and MNL release methodologies have been combined to establish an upper and lower bound methodology (MXLMNL), which is used to provide a range for the workload which may be loaded to the shop.

FFL is a load limited release mechanism in which each operation of each job is loaded using the following equation:

$$\text{Flow time} = k * \text{processing time} \qquad (3.4)$$

Where: k is a planning factor > 1.

The flow-time equation determines at what point in time each job will require capacity at each machine in the job operation sequence. If machine capacity is available for the entire job, then the operation is assigned to the machine in that period and the available capacity is decremented for the period. If capacity is not available in that period, then the job is loaded in the next load period that has sufficient capacity. Loading continues until the last operation of the job is completed at which time the release decision is made. A job is released when the load period for the last operation is in the same load period or the load period following the due date. If a jobs last operation is loaded into a load period that is prior to the load period of the due date, the job is returned to the pre-shop pool.

BFL is a load limited order release mechanism whose planning horizon is broken into time buckets. This mechanism uses workload profiles for each machine in the shop, that indicate the amount of work released for work centers for each time bucket in the planning horizon. Working backward from the job's assigned due date, BFL attempts to fit each operation into available capacity for each machine on the job's routing. If adequate capacity is not available in a time bucket, the operations are backed up to an earlier bucket. Once the operation is loaded, the preceding operation is loaded in the same manner. The work shift into which the first operation in the job's routing is loaded determines the release date for the job. If the mechanism calls for a job to be released in an earlier time bucket, the job will be released in the current period and the operations corresponding to the job will be forwarded loaded from the current time.

The PBB mechanism is a load limited approach that utilizes pre-established maximum loads for all machines in the shop (PBB threshold). The queue of pre-shop pool jobs awaiting entry into the shop are sequenced in increasing order by each job's PBB slack ratio. A machines slack is defined as the difference between its specified threshold and work already committed to it (from jobs on the shop floor). The job that consumes a smaller proportion of slack of machines in its path on average is considered for release into the shop. Starting with the first job in the ordered queue, this job's path through the shop is evaluated. If the current load at each machine along the job's path plus the job's processing time at that machine is below the PBB threshold, the job is released into the shop. The capacity load is evaluated for each operation and if any machine along the job's path has a load greater than the PBB threshold minus the job's processing time at that machine, the job is held in the pre-shop pool. The next job in the pre-shop file, as ordered by slack ratio, is considered for release. Using the same procedure, the ORR system continues to check all jobs in the pre-shop file.

CONWIP is often referred to as a hybrid push/pull system. The objective of this methodology is to maintain constant WIP. Jobs are pulled into the system by the completion of any job and are pushed from one work center to the next. Using production rate versus WIP curves, a WIP level consistent with the desired output is determined. As jobs are completed, new jobs are released in order to maintain the target WIP level.

INOUT is a simplified version of CONWIP that releases an amount of work to the system each day, which is a simple moving average of the previous ten days output. Jobs are then pushed to the subsequent work center as in the CONWIP mechanism.

In the implementation of the SA release mechanism, release is triggered when a pre-determined level of work content destined for the bottleneck is not met. The objective of this mechanism is high bottleneck utilization and low WIP levels. Orders enter the system just in time to avoid bottleneck starvation. If the total work content is insufficient to prevent the bottleneck from starving, a new job is release from the pre-shop pool.

With the FIXED mechanism, the number of jobs released each day is equal to the desired target throughput rate of the system. This methodology attempts to match desired output with required input.

The AGGWNQ rule attempts to ensure that there is enough work in the shop as a whole. Release is trigger when the total workload falls to a predetermined level. The release mechanism selects the work center with the smallest workload queue (measured in hours) and releases an order whose first operation is at that work center. If more than one order can be released, the order with the shortest processing time is chosen. If there are two orders with the same processing time then the first come first served criteria is used to make the selection One order is released at a time until the total shop load increases above the predetermined workload or there are no orders remaining in the pool.

The WCEDD release mechanism is a load limited approach that uses both shop workload information and order delivery dates to trigger order release. Order release is triggered if there is less than a preset amount of work waiting to be processed at any one work center and there are orders in the pre-shop pool. The selection rule chooses the job with the earliest due date among those jobs with their first operation at the work center which triggered the release. If more than one such order exists, then the order with the earliest delivery date is selected. If there is still a tie, the first come first served selection rule is used. Release continues until the pool is empty or until the number of hours of work queuing at each work center is greater than the preset level.

The MNJ mechanism is a load limited technique that releases the highest priority jobs to the shop floor, based on the priority dispatching rule for the shop. Jobs are released at the start of each day, one at a time, until either all jobs are released or the number of jobs in the shop has reached a predetermined maximum, m (where m is a pre-determined planning factor).

The JSSWC mechanism is a load limited release methodology based on order urgency. Order urgency represents the difference between the current date and the latest release date, which an order could be released if it is to be delivered on time. This latest release date is the delivery date minus the required processing time including the expected wait time. The difference between the latest release date and the current date is the slack priority. Orders are considered for release based on their resultant slack priority. As each order is considered for release, its effect on the shop workload (workloads are measured in terms of the released backlog length) is examined. Released backlog lengths are calculated for the shop as a whole and for each work center, with the objective of maintaining each released backlog length between predetermined minimum and maximum limits. Orders which would cause the released backlog length to exceed the maximum are not released. If an order has negative slack, capacity can be adjusted to rectify the problem. Orders are considered for release until either there are no more orders in the pool or all remaining orders have a positive slack or the user becomes satisfied with the released backlog values. Unlike most release strategies, delivery dates are chosen and capacity is planned so that the workload can be controlled over time.

The workload released to a work center can be divided into two segments, the direct load (workload from jobs queuing at a work center) and indirect load (jobs queuing at an upstream work center). WLC concepts attempt to keep the direct load at a low and stable level. This however, is complicated by the fact that job release cannot completely control the direct load of a work center, since jobs arrive continuously from upstream operations (contributing to the direct load at a work center). Two WLC approaches (with numerous variations) have been proposed in the literature, both aimed at controlling the combined inputs to the direct load. Both approaches make the release decision periodically, focusing control on the work remaining at the end of the next release period. The remaining work at a workstation at the end of the release period in addition to the output during the current period are subjected to a norm value. At the beginning of the period, jobs are released to the shop such that the workload at the end of the release period will be within the norms.

The WLC concept developed at the IFA in Hannover estimates the input from jobs upstream to the direct load of a station using a methodology known as load conversion. The values of the workload norms are used to estimate the probability that upstream work proceeds to the next work center.

The WLC concept developed in Lancaster avoids estimating the input to the direct loads. This methodology aggregates the direct and indirect workload of a station by summing them and comparing this aggregate workload to a norm. In order to minimize the feedback requirements from the shop floor, variations of the Lancaster concept extend the aggregate workload by including work already completed at the station, but still downstream on the shop floor. Thus, the required feedback from the shop floor is restricted to completed jobs, instead of completed operations.

LOOR has been implemented in several standard software packages including Copics by IBM, RM-PPS by SAP, and INTEPS by Brankamp. LOOR is controlled by two parameters:

1. Load limit.
2. Time limit.

The LOOR release procedure determines which shop orders should be released for the next planning period. Jobs residing in a pre-shop pool are ordered by their planned release date (determined by backward scheduling from due dates). Jobs whose estimated starting dates are within the time limit (measured in planning periods) are candidates for release. The methodology establishes urgent orders, selecting from the pre-shop pool, only those shop orders whose estimated starting dates are within the time limit (measured in planning periods). After accounting for all jobs released but not finished in the earlier planning period, the urgent orders are examined. Urgent shop orders are released if their operations do not require at least one work center where the load limit is exceeded. The load limit defines the target level of WIP at each work center. Rejected orders are considered for release in the next planning period.

Other release methods presented in the literature include:

- Dynamic forward loading (DFL), similar to other forward loading techniques, however the shop is viewed as a dynamic environment and the loading of work centers includes an estimate for congestion. Congestion (delay time) is calculated for each work center for a specified number of release periods.

- Proposed input-output control (PIOC), releases jobs when the latest release date of a job is reached or when the workload of any work center goes below a defined lower limit. Short term capacity can be adjusted if the computed workload is above the established upper workload limit of the shop.
- Order release control shop (ORCS) is based on the MXL release methodology, where load limits are established for the entire shop, individual work centers, and the first work center in an order's routing (release decisions are made based on satisfying these three pre-established workload limits). Flow times are estimated for each order.
- Order release control adjusted (ORCA) is similar to the ORCS release methodology, however flow time data from completed orders are used to predict flow times for orders awaiting release. A backward checking scheduling algorithm is used to determine whether or not to release the order.
- BACKSIM utilizes a simulation model of the shop floor to capture capacity constraints and operational rules to obtain theoretically feasible order release plans.
- PMRP uses fixed component lead times that are predicted by running a forward simulation model of orders awaiting release, establishing standard lead time values for order release (infinite capacity is assumed).

- Release proportion (RP) is a release mechanism that permits partial order release where orders in the release list are processed according to the earliest due date rule.
- Reservation method (RM) is a mechanism for reserving components for production orders when material is not available at the initial scheduled release date.
- Workload balancing (WB) permits the release of orders to the shop floor when a negligible overload or under-load occurs at one or more work centers, seeking to optimize the balance of the shop floor as a whole.
- RAN is similar to PMRP in that simulation runs are used to predict lead times, however orders are released to the shop in decreasing order of their predicted throughput times.
- Brown and Davies (1984) state that the BRISCH system generally releases orders to the shop in the order that their manufacturing routing cards become available.
- Bottleneck (BOTTLE) release mechanism calculates the amount of work at the final bottleneck on the shop floor every five minutes and releases an order if the total work content is insufficient to prevent the bottleneck from starving.
- Superfluous load avoidance release (SLAR) selects a new job for release in two situations. If the direct load of a workstation is zero, then the job with the earliest planned start time and its first operation at an idle workstation is

released. Secondly, if all the jobs in the queue of a workstation are non-urgent, then an urgent job is selected from the pre-shop pool for release whose first operation is at that workstation. If neither condition exists, then jobs are not released from the pre-shop pool.

- CAP is similar to the MXL release methodology in that work is released to the shop until the load rate reaches a pre-determined capacity level for the entire shop. However, workloads are balanced by increasing the capacity of some overloaded work centers, jobs are then released according to the slack per operation or first come first served methodologies.
- Critical machine selection (CMS) is a release mechanism similar to MIL, with the exceptions that planning factor $k_1$ is multiplied by the processing time of the order (versus the number of operations required by the order) and the order is released only if the queue of the first work center in the job's routing is empty and an operator is available.

Descriptions of due date setting methodologies and job shop models developed by researchers are presented below. An understanding of these research parameters is necessary due to the interaction of each of these parameters with various ORR mechanisms.

3.1.3.4 Due Date Setting

The most common due date setting approach used by researchers is the total work content approach. Researchers employing this approach include Melnyk et al. (1989), Philipoom and Fry (1994), Hendry and Wong (1994), Malhotra et al. (1994), Newman and Maffei (1999), Cigolini and Portioli (2002), and Rosario-Moreira and Alves (2006). With total work content due date setting, each job is assigned a due date upon arrival to the pre-shop pool. Due dates are calculated by applying a work flow allowance to each job consisting of a lead time estimate multiplied by an integer. The due date is equal to the arrival time plus the work flow allowance for that job:

$$\text{Due date}_j = \text{Arrival Time} + (K*TWK_j) \qquad (3.5)$$

Where: K is the multiplier and $TWK_j$ is the total operation time for order j.

Tight due dates are set by using a small integer multiplier, while loose due dates are set by using a large integer multiplier. Fredendall and Melnyk (1995) and Ragatz and Mabert (1988) employed a variant of the total work content approach where total number of operations replaces total operation time for due date calculations.

Another common approach is to set due dates external to the decisions made in the pre-shop stage of the scheduling process. Thus, due dates are essentially given, as far as the scheduling process is concerned. Similarly, researchers have established fixed lead times (derived via simulation) to establish due dates. Researchers employing these methods include Philipoom and Fry (1992), Bobrowski (1989), Roderick et al. (1992), Bragg et al. (1999), and Watson et al. (1995).

The most extensive ORR research involving due dates was conducted by Ahmed and Fisher (1992) and Tsai et al. (1995). Ahmed and Fisher hypothesized that a three way interaction existed between the due date assignment, release, and dispatching procedures employed in a job shop. To test their hypothesis, they employed four due date setting procedures that incorporated job processing times, number of jobs queuing at work centers, and number of jobs in the system. Similarly, Tsai et al. tested three due date setting procedures that were based on flow time estimates.

Nearly all surveyed researchers used pilot simulation runs to calculate the constants used in their due date models.

#### 3.1.3.5 Shop Floor Modeling

The most commonly utilized models in ORR simulation research are based on the job shop model developed by Ragatz and Mabert (1988). Their model is based on the following parameters and assumptions:

- Jobs arrive to the shop according to a Poisson distribution.
- Processing times are exponentially distributed.
- Setup times are not sequence dependent and are included in processing time.
- Five work centers, each containing one machine.
- Jobs are routed randomly.
- One week planning horizons.
- Arriving jobs are accumulated for one week and placed in the pre-shop file.
- At the end of the week, the jobs in the pre-shop file are assigned delivery dates.
- Release mechanisms are employed at the start of each shift.
- All pre-shop activities are assumed to be completed.

While most researchers have employed minor variations of the model described above, researchers such as Bobrowski (1989), Park et al. (1995), and Roderick et al. (1992) constructed models that they believed might help resolve the "research paradox".

The uniqueness of Bobrowski's model is that it considers alternate job routings and alternate loading prior to jobs reaching the shop floor. While the job shop simulation model created by Park and Salegna included a mechanism for load smoothing of the bottleneck work center.

The simulation models developed by Roderick, Phillips, and Hogg contain several parameters and assumptions not previously considered by researchers. Unique characteristics of their models include:

- Presence of multiple bottlenecks.
- Variable shop sizes (containing as few as three processes per job and as many as 20 processes per job).
- Processing times derived from normal, exponential, and beta distributions.
- Machine failures (exponentially distributed).

Limited research has been conducted with respect to actual job shops operating in industry. Researchers who have modeled actual job shops include Shimoyashiro et al. (1984), Brown and Davies (1984), Hendry et al. (1998), and Kingsman and Hendry (2002).

3.1.3.6 Performance Measurement

The performance measurements utilized by ORR researchers can be classified as either cost or non-cost measures. The research contains over 15 different cost related measures, the most common include WIP cost, inventory holding cost, and late delivery (tardy) cost. The research also contains over 40 different non-cost related measures. Non-cost measures address metrics related to lateness, tardiness, flow time, queuing, lead time, utilization, labor efficiency, and WIP. The most common non-cost performance measures include mean tardiness, root mean square of tardiness, proportion tardy, mean lateness, mean queue time, utilization, mean flow time, and WIP.

There was no clear consensus among researchers with respect to performance cost metrics. However, researchers addressing total cost utilized the same fundamental approach when calculating the average total cost per time period, where total cost consists of late delivery cost and holding cost for both WIP and finished goods inventory. Holding costs are assumed to be proportional to the amount of work completed on a job. There is no cost associated with a job held in the pre-shop file. Late delivery charges are assessed per hour of work content in the job, per time period late. The ratio of late delivery penalty to inventory carrying charge was set at 20:1 by most researchers.

All surveyed researchers incorporated non-cost performance measures in their studies. However, as was the case for cost performance measures, there was no clear consensus with respect non-cost performance metrics. Based on this comprehensive review of simulation based ORR research, it is clear that there is very little agreement with respect to both cost and non-cost performance metrics. This lack of agreement may result in skewed results and hinder the ability to compare results amongst researchers.

3.1.3.7 Results and Comparisons

Adam and Surkis (1977) examined three order release mechanisms in a job shop environment: finite capacity; infinite capacity; and dynamic forward loading. They did not specify whether forward or backward loading was utilized with the finite loading mechanism. Irrespective of this, their results indicated that the dynamic mechanism resulted in the most favorable measures of lateness and of the number of jobs completed. However, this mechanism resulted in the poorest results relative to earliness measures, the infinite loading technique resulted in the most favorable earliness measures.

Brown and Davies (1984) compared releasing orders to the shop floor using Brisch code order and by decreasing order of throughput time. Their results indicated that the controlled release mechanism based on decreasing throughput time improved delivery performance and was insensitive to the priority dispatching mechanism tested.

Shimoyashiro et al. (1984) examined the impact of load balancing and work load limiting in the simulation of an actual production facility. They tested IMM, MXL, and three variants of the CAP ORR methodology. Their results indicated that the CAP release mechanisms (controlled load balance and the amount of work released to the shop) significantly improved lateness, mean flow time, and utilization metrics. Experimental results were independent of the dispatching mechanism employed. Shimoyashiro et al. reported that this concept (SCOPE2) was implemented in an industrial machine shop.

Ragatz and Mabert (1988) investigated the interactive effects of dispatching and order release by evaluating five release mechanisms and four dispatching mechanisms.

Other experimental variables included due date tightness and utilization. They uncovered two important relationships in their examination of cost related performance measures. First, they determined that the ranking of the dispatching rules studied are the same regardless of the due date tightness or releasing mechanism employed. That is CR performed the best, followed by EDD, FCFS, and SPT. Second, controlled release always resulted in equivalent or lower total costs than immediate release, with the MIL release mechanism producing the best total cost results. For the non-cost measures, results indicated that all controlled release mechanisms resulted in reduced shop lead time and congestion. The sensitivity analysis performed by Ragatz and Mabert did result in some unexpected results. When utilization was decreased, the advantages of controlled release became more pronounced, suggesting that capacity is critical to the load limited release methodologies. Also, when the due dates were set to loose and utilization was increased, the IMM release strategy resulted in the lowest total cost. For the experimental conditions tested, the impact of controlled release on shop performance was influenced by the type of dispatching rule used and by the tightness of the jobs due dates.

Melnyk and Ragatz (1989) examined the impact of order release on shop floor performance. Experimental factors included three release mechanisms, four dispatching mechanisms, and four levels of due date tightness. When testing the WCEDD and AGGWNQ release mechanisms, Melnyk and Ragatz concluded that these mechanisms resulted in poorer delivery performance (for mean tardiness and proportion tardy measures) as compared to IMM. These results are attributed to the increased time jobs spend waiting in the pre-shop pool, since under controlled release queuing on the shop floor is replaced by time waiting in the pre-shop pool. However, the use of either WCEDD or AGGWNQ resulted in better performance when evaluated using the WIP and workload balance measures. The overall ranking of the dispatching rules differed in this study compared to that obtained by Ragatz and Mabert (1998). In this study the best overall dispatching mechanism was SPT, followed by EDD, S/OPN and FCFS. The differing dispatching results between researchers may be attributed to the interaction between dispatching and release mechanisms. The most significant finding resulting from this study is that ORR may best be utilized as part of a closed loop system. In a closed loop system, ORR can monitor capacity conditions on the shop floor, feeding back information to the planning system. The planning system can then respond by adjusting the quantity of jobs released for the period.

Bobrowski (1989) developed release mechanisms that take order routing and machine loading into consideration. Experimental factors evaluated include shop flexibility (includes alternate machines and routings), and due date tightness. Bobrowski's proposed release mechanism simultaneously evaluated alternate machines (ALTMACH release mechanism) and alternate routings (ALTSEQ release mechanism). Bobrowski's experiment also incorporated a loading exchange heuristic for jobs scheduled for current release. These jobs proceeded to a loading exchange heuristic, seeking schedule improvements by altering the routing or loading that previously were unavailable due to the sequential nature of the initial process. Bobrowski's benchmark mechanism was FFL, with no flexibility and no exchange heuristics. Using ALTSEQ (without the heuristic), the introduction of a low level of shop flexibility improved the overall shop performance from the benchmark shop. When the loading exchange heuristic was employed in the low flexibility shop, the number of tardy jobs decreased. The number of tardy jobs continued to decrease as the shop flexibility was increased. In all but two of the twelve cases (six for each routing strategy tested using the ALTSEQ mechanism), shop performance with the exchange heuristic showed a smaller tardiness per job. The exchange heuristic improved shop performance by allowing the WIP cost to increase, but it offset this increase in a majority of cases by reducing the penalty cost far in excess to the WIP increase. Implementation of the ALTMACH routing methodology with the exchange heuristic, did not statistically show an improvement over the benchmark case. The exchange heuristic with ALTMACH was not needed. Shop flexibility was sufficient to improve shop performance and the number of cases that required the loading heuristic did not warrant its inclusion.

Scudder and Hoffman (1989) simulated four order release/dispatching mechanisms in an open shop at four levels of utilization. This study is included in the job shop literature review as a result of its applicability to job shop environments and the proposed research. The study tested two cost based order release/dispatching mechanisms (PRF/OPT and VLADRAT) and two time based order release/dispatching mechanisms (CRRAT and OPCRAT). All mechanisms utilized a two queue model, consisting of an active queue and an inactive queue. The active queue contains jobs whose earliest operation start date has been reached (the proposed order release/dispatching mechanisms are applied to only those jobs residing in this queue) and an inactive queue whose earliest operation start date has not been reached. The results of the simulation study indicated that the application of the two queue system was effective in reducing finished goods inventory, while causing a slight increase in work in process. The time based release mechanism (CRRAT and OPCRAT) outperformed the cost based release mechanisms in nearly all performance measures.

Melnyk et al. (1991) examined the impact of load smoothing via demand variance smoothing and controlled order release. They tested two ORR mechanisms, three dispatching rules, and seven work load smoothing techniques. The results of their study indicated that planning system smoothing results in significant improvement to job flow time, while the MXL release mechanism significantly reduces WIP. They concluded that planning system smoothing and order release act as complementary tools for reducing system variance. Additionally, they concluded that load smoothing and ORR negate the need for complex dispatching rules such as MinSlk, making simple rules such as FCFS a viable option.

Philipoom and Fry (1992) examined the impact of rejecting shop orders in times of high shop congestion using two variants of the MXL ORR methodology (shop load order review and path load order review). Unlike other ORR mechanisms, the proposed mechanisms determine whether to accept or reject an order (in effect smoothing the demand variance), not whether to release or delay an order. With the shop load order review mechanism, orders are accepted if the total workload in the shop plus the workload of the incoming order is less than a predetermined shop limit, otherwise orders are rejected. With the path load order review mechanism, orders are accepted if the workload at any machine along the orders routing (including the incoming order) exceeds a predetermined work center limit, otherwise the order is rejected. Philipoom and Fry's results indicated that rejecting a small percentage of arriving orders results in significant improvement to flow time, tardy, and utilization metrics. Additionally, they concluded that the path based release methodology produced superior results in comparison to the shop load release mechanism.

The research of Ahmed and Fisher (1992) investigated the interactions of order release, dispatching, and due date assignment. Each experimental variable was tested at four utilization levels. Their work resulted in a number of discrepancies relative to the work of previous researchers. Most importantly, there was no clear distinction between controlled release and immediate release for the majority of performance measures. Specifically, MIL did not perform well relative to the total cost performance measure, contrasting the results of Ragatz and Mabert (1988). In fact IMM produced the best results in four of the eight experimental performance measures. In agreement with previous research, IMM did perform worst overall with respect to due date and shop congestion metrics. Additionally, as Ragatz and Mabert (1988) concluded, the interaction between the release mechanism, dispatching mechanism, and due dates was significant, suggesting that a single policy combination cannot be identified which is superior to others at all utilization levels.

Roderick et al. (1992) tested four order release methodologies (CONWIP, INPUT, BOTTLE, and FIXED), three processing time distributions, similar and dissimilar routings, and two shop sizes. For the total mean throughput criteria, the

CONWIP strategy was statistically the best performer overall. CONWIP was outperformed in throughput under the following experimental conditions: large shop; similar routing; and normally distributed processing times, for which the INOUT release strategy provided the best results. For percent tardy jobs, the INOUT strategy was the worst performer. Under no conditions did the CONWIP strategy have a statistically larger percentage of tardy jobs. For the performance criteria of percent tardy jobs, both the CONWIP and BOTTLE strategies yielded the most favorable results (the difference between their results was insignificant).

Zapfel and Missbauer (1993) examined the impact of parameter setting on a load-oriented order release mechanism. They tested the LOOR mechanism and two alternate versions, in conjunction with three capacity load levels (underutilization, full utilization, and temporary overload). Their preliminary experiments indicated that the effectiveness of the LOOR mechanism is dependent on parameter setting, which in turn is influenced by capacity demand. Additionally, they concluded in the case of time varying demand, preset standard parameters are ineffective. Consequently, Zapfel and Missbauer developed and tested two linear programming models for rough-cut capacity planning that dynamically adjust the model parameters based on capacity demand. The experimental results indicated that the alternate versions of LOOR yielded superior flow-time and WIP results compared to the LOOR methodology based on standard parameter setting.

Philipoom et al. (1993) developed a capacity sensitive order release mechanism (PBB) and compared it to two other release mechanisms (IMM and MIL).

Experimental factors evaluated included two dispatching mechanisms, three levels of due date tightness, and two levels of utilization. The SPT dispatching mechanism was the best scheduling rule to use at all capacity levels tested, with the exception of the loose due date case (were CR was preferred), irrespective of the ORR method used. This result is in conflict with that of Ragatz and Mabert (1988), who also tested IMM and MIL. However, in agreement with the research of Philipoom et al., Ragatz and Mabert found that irrespective of the utilization level, MIL is the best ORR rule under loose and medium due date tightness conditions. Also, when MIL is used with the CR dispatching rule, CR produces the best overall performance for loose due dates (this is also consistent with the work of Ragatz and Mabert). For tight due dates PBB produced the best results, outperforming IMM. Lastly, they concluded that the selection of an ORR mechanism depended only on the tightness of the due dates and not on the dispatching mechanism employed.

The research of Melnyk et al. (1994), focused on the impact of variance control when using the MXL release mechanism. Experimental variables included two levels of planning, two order release mechanisms (IMM and MXL), five dispatching mechanisms, and two levels of processing time distribution. Their results indicate that when variances on the shop floor are significant, ORR is overwhelmed. It cannot adequately respond to the large changes in shop load as jobs having either large or small processing times are completed. Conversely, low variance on the shop floor simplifies ORR's task of releasing the right level of work from the pre-shop pool to the floor. These findings suggest that order release mechanisms may be more effective when operating within a specified range of variance. It was also concluded that the SPT dispatching mechanism was most effective when there was no variance control. The presence of variance control adversely affects the performance of SPT to the point that it is the worst of the various dispatching rules examined. The reason for this unexpected finding lies in the interaction between SPT and variance control. When system variance is high, SPT uses the high variance on the shop floor to improve system performance by giving the jobs with the shortest processing times priority over those with the longest. Processing those jobs first contributes to system variance, in effect offsetting the effects of variance control. As variance is increased, system performance deteriorates. The benefits gained from the use of sophisticated dispatching rules such as CRR, MinSlk and S/OPN were minimal relative to a simple rule (FCFS) when variance control was present. Sophisticated rules are designed to manage the flow of jobs in a setting where variance (especially on the shop floor) is present, thus controlling the variance diluted the advantages offered by these rules. With adequate variance control, job completion times became more predictable which simplified shop floor dispatching. These findings demonstrate the interaction among dispatching, order release, and variance control. The results of this study were consistent with those of Melnyk et al. (1991).

Hendry and Wong (1994) developed a release mechanism that allows capacity to be adjusted as jobs enter the system and as they are released to the shop floor. Experimental variables included four release mechanisms (four versions of the JSSWCD mechanism were tested), five dispatching mechanisms, and four levels of due date tightness. In testing the AGGWNQ and WCEDD release mechanisms, Hendry and Wong's findings were consistent with those of Melnyk and Ragatz (1989). That is, both mechanisms lead to less congestion in the shop, lower WIP, and unfortunately poor delivery performance as compared to the IMM methodology. An important finding in this study was that JSSWCD version 4 methodology resulted in better delivery performance when compared to IMM. Hendry and Wong attribute the improved delivery performance to the rules sophistication. This research supports that of Melnyk and Ragatz (1989), who concluded that releasing rules that are part of a hierarchical planning system and which allow capacity to be adjusted can improve delivery performance when compared to release rules that do not have these capabilities. Each of the experimental factors had a significant effect on the experimental results and the SPT rule yielded the best overall performance for almost all of the releasing rules.

Malhotra et al. (1994) examined the use of order release (IMM, MIL, and PBB) and dispatching mechanisms to manage vital customer orders. The objective of the research was to provide near perfect delivery performance for vital customer orders while maintaining an acceptable delivery performance level for normal priority customers. They concluded that capacity based (finite) order release mechanisms and dispatching mechanisms that balance the priority of normal and vital jobs yield the best overall performance results. Specifically, Malhotra et al. suggest that the combination of the PBB order release mechanism and the FP dispatching mechanism (uses milestones to pace vital priority jobs through the shop) was desirable for enhancing the overall performance of the job shop studied. The success of the PBB order release mechanism is consistent with the findings of Philipoom et al. (1993).

The impact of demand variance smoothing and shop floor control in a dual resource constrained job shop was studied by Fredendall and Melnyk (1995). Experimental variables included planning system, order release mechanisms (IMM and CMS), dispatching mechanisms, and labor assignment rules. The results of their analysis indicated that reducing demand variance, by generating and releasing smoothed schedules accounts for the largest gain in performance compared to ORR and dispatching mechanisms. They also concluded that the use of ORR mechanisms can further reduce mean tardiness and that complex dispatching rules result in no material improvements in performance, suggesting that simple dispatching rules such as FCFS be used. These findings are consistent with those of Melnyk et al. (1989), Melnyk et al. (1994) and Fredendall and Melnyk (1995), who concluded that reducing variance at the planning and shop floor levels enhances the effectiveness of ORR mechanisms.

The interaction of order release mechanisms (IMM, MXL, BIL, and FFL) and dispatching rules in a sequence dependent setup environment was studied by Kim and Bobrowski (1995). This is the only known study that examines multiple order release and dispatching mechanisms in the presence of sequence dependent setups (Missbauer (1997) examined the relationship between WIP and total setup time for a single server). They concluded that order release mechanisms were effective when used in conjunction with ordinary dispatching rules (CR and SPT); however, ineffective when used in conjunction with setup oriented dispatching mechanisms (JCR and SIMSET). The setup oriented dispatching rules performed well, regardless of the order release mechanism employed. Kim and Bobrowski recognized that the order release mechanisms studied were not sufficiently effective to account for sequence dependent setup time and their use of average setup times in the application of release rules may have biased their results, resulting in the over estimation of expected flow times.

Park and Salenga (1995) tested two simple order release mechanisms (IMM and MXL), four load smoothing mechanisms, three sequencing mechanisms, and two feedback mechanisms. Among the variables tested in their study, the feedback variable appeared to have the greatest impact on shop performance. This is the result of pulling jobs forward from the planning file when there are no jobs in the backlog file and the bottleneck resource is under utilized. The load smoothing approach FLOOR, that pulls jobs forward to maintain the minimum shop load level during the planning period, outperformed the other smoothing rules in flow time and tardiness measures. Conversely, the load smoothing mechanisms that pushed jobs back to maintain the maximum load did not perform better than no smoothing in terms of flow time and tardiness criteria. Also, load smoothing to maintain the shop load between the minimum and maximum load did not perform better than no smoothing. With respect to the tested order release mechanisms, IMM performed better than MXL overall, regardless of the load smoothing and dispatching mechanisms employed. Additionally, as was the case for Melnyk and Ragatz (1989), the SPT dispatching rule out performed all tested dispatching mechanisms for flow time related measures.

Watson et al. (1995) compared the BACKSIM release methodology to the PMRP release methodology. Experimental variables included bill of material complexity, type of shop flow, master production schedule stability, shop load, and shop variability. The PMRP methodology was studied since it simulates the release logic employed by MRP systems. The experimental results indicated that the BACKSIM approach resulted in superior performance compared to the PMRP methodology. As the product structure increased in complexity and as the master production schedule became increasingly unstable the advantages of BACKSIM over PMRP increased. Watson et al. contend that this superior performance is due to BACKSIM's continuous calculation of lead times, versus PMRP's use of fixed lead times.

Tsai et al. (1997) examined the interaction of order release mechanisms (IMM, ORCS, and ORCA) and due date assignment rules and their impact on due date performance and inter-operation time estimation. Experimental variables included three order release mechanisms, three due date assignment rules, and three dispatching mechanisms. The results of their study indicated that integrating order release with due date assignment rules has a significant influence on improving due date performance and average flow-time estimation.

Russell and Fry (1997) evaluated the use of order release mechanisms as the rope in a drum-buffer-rope (DBR) planning and control system. The production environment modeled was a pliers manufacturing facility consisting of 12 work centers and a total of 49 machines. Experimental variables tested included three order release mechanisms (BIL, BFL, and RT), process/transfer batch size, and capacity balance. RT is a continuous release mechanism that releases work to the gateway work center based on the production rate of the bottleneck resource. FCFS dispatching was used in all simulation experiments. Although the simulated production environment does not represent a job shop environment (thus the study is not included in Figure 2.), it is included in the literature review due to its applicability to the proposed research, with respect to lot splitting, actual demand streams, and simulation of an existing manufacturing environment. Experimental results demonstrated that the real time release mechanism resulted in the lowest WIP when used as the rope in the DBR system under all shop conditions. Additionally, the experiments demonstrated that process batch splitting results in significant performance improvement for tardiness and flow time measures, irrespective of capacity balance.

Cigolini et al. (1998) investigated the impact and robustness of ORR timing conventions in a dynamic and uncertain production environment. Experimental variables included system workload, mix imbalance, machine availability, and processing time variability. Three release mechanisms were tested, however the only differentiating factor amongst them was the timing convention employed (time bucketing, a-temporal, or probabilistic). The experimental results indicated that the probabilistic timing convention resulted in the best overall performance results and was the most robust. These results can be attributed to the fact that the current shop load information is used in the decision release process, thus permitting adjustment to a dynamic and unpredictable production environment. However, under the lowest uncertainty level, time bucketing yielded the best overall performance results. Cigolini et al. concluded that the time bucketing approach is most suitable for environments with minimal uncertainty, while probabilistic techniques are better suited for shop environments with a high degree of uncertainty.

Hendry et al. (1998) examined the job entry component of the WLC concept developed at Lancaster University and compared performance results to a system exhibiting no control. Experimental factors included planning horizon length, manufacturing lead time for small orders, and job priority assignment (due date assignment). Experimental results indicated that planning horizon length and the length of the manufacturing lead time for small orders had a significant affect on manufacturing lead time and workload performance measures. These results suggest that the planning horizon and lead time for small orders should be selected carefully (during the order entry phase) in order to achieve the desired lead times for all orders when the WLC-L methodology is utilized. Additionally, the performance of the WLC-L method was not significantly affected by the due date setting methodology.

Land and Gaalman (1998) presented a WLC methodology that did not subject the shop workload to norms. Experimental factors included machine utilization and planning factors for the superfluous load avoidance release (SLAR) methodology. Initial experiments tested the WLC-L and WLC-I methodologies. Simulation results demonstrated unfavorable results with respect to lead time and due date performance. Land and Gaalman suggest that workloads should not be subjected to rigid norms and that the release of a job which prevents a workstation from starvation should not be dictated by the workload norms of downstream work centers. The SLAR methodology resulted in favorable due date and lead time performance, independent of the shop load (as measured by the shop utilization). This is due to the methodologies ability to deal with various utilization levels, without the requirement of having to adjust norms, thus establishing minimal workloads in a self regulating way.

Philipoom and Fry (1999) examined the impact of ORR methodologies on "cherry picking" by production workers. Cherry picking is the practice of ignoring formal scheduling priorities in lieu of orders where the difference between actual processing time and standard processing time is smallest (resulting in greater production efficiency). The study utilized the shop load order review and path load order review methodologies examined by Philipoom and Fry (1992), with the exception that orders were not accepted or rejected; orders were either released or delayed. The results of their study indicated that the proposed ORR mechanisms resulted in situational improvements with respect to performance criteria when cherry picking was not present. When cherry picking was present, ORR significantly reduced the deterioration in shop performance due to cherry picking.

Newman and Maffei (1999) investigated whether or not a competitive advantage could be gained by incorporating routing flexibility, order release, or dispatching techniques in a job shop environment. Three levels of routing flexibility were examined: low, medium, and high. The results of their study indicated that as flexibility increased, lateness decreased, the percent of tardy jobs decreased, and time in system decreased. Newman and Maffei concluded that the value of order release mechanisms decrease as flexibility increases and that under conditions of high shop flexibility, order release mechanisms may be rendered ineffective. These results are consistent with the findings of Bobrowski (1989) and Melnyk and Ragatz (1989). However, Newman and Maffei do recognize that although flexibility is very powerful, it can also be very expensive, increasing capital budgets and operating expenses.

The effects of partial order release and component reservation in the order review and release process were examined for an MRP environment by Bragg et al. (1999). Although the ORR literature recognizes the issue of material shortages, this is the only known research that provides an assessment of its influence on shop performance and a release methodology addressing this specific situation. Results of this study showed that partial order release yielded superior results compared to the component reservation strategy. Bragg et al. suggest that the benefits resulting from partial order release are that available material and capacity resources are utilized. However, they recognize that this may have a negative impact on unit cost due to increased setups and setup nervousness (due to the re-planning of production orders).

Sabuncuoglu and Karapinar (1999) performed the most comprehensive study of order release mechanisms to date, testing nine release mechanisms, in combination with two dispatching mechanisms, two system load levels, and two levels of due date tightness. This included three versions of the MXL methodology (continuous aggregate loading, periodic aggregate loading, and work center information based loading), and two versions of the infinite loading methodology (continuous infinite loading and periodic infinite loading). The primary objective of this study was to demonstrate that the potential benefits of ORR can be achieved in research environments if congestion is properly modeled. The experimental results indicated that continuous release rules (continuous aggregate loading and interval release) yielded superior mean flow time and tardiness performance results, compared to their periodic release counterparts (periodic aggregate loading and immediate release), whereas the PBB and periodic aggregate loading mechanisms yielded better performance results for the mean absolute deviation (MAD) from due date metric. Their results also indicated that significant interaction between release mechanisms and dispatching rules existed for the MAD metric only. Sabuncuoglu and Karapinar concluded that current shop load and due date information is extremely important for successful implementation of release mechanisms.

Oosterman et al. (2000) investigated the influences of shop floor configuration (pure job shop, general flow shop, restricted job shop, and pure flow shop) on the effectiveness of five WLC methodologies. The WLC methodologies included WLC-I, WLC-L, and three variants of the WLC-L methodology. The first variant of the WLC-L methodology extends the aggregate workload to the shop load. The second variant methodology accounts for work center position within the shop. Lastly, the third variant accounts for the expected influences related to routing length. As postulated by Oosterman et al., the effectiveness of WLC methodologies were strongly influenced by shop floor configuration. In the pure job shop, the WLC-I methodology outperformed all other methods and in the restricted job shop, variant two of the WLC-L methodology outperformed all other methods. In the general flow shop and pure flow shop the WLC-L methodology outperformed all other methods. Thus, they concluded that as flows are completely undirected it is more important to estimate the impact of order release on the direct load of each station and as the flow becomes more directed, aggregate workloads appear to be an important variable to control.

Cigolini and Portioli-Staudacher (2002) examined the performance of three workload limiting order release mechanisms in conjunction with the following experimental variables: system workload; mix imbalance; machine availability; and processing time variability. Their results indicated that no single release mechanism performed best under all tested conditions, however the upper bound only release mechanism performed best overall and the upper and lower bound method was worst overall. Additionally, the workload balancing mechanism was most robust to changes in workload, mix imbalance, machine availability and processing time variability, however not all performance results were statistically significant. Cigolini and Portioli-Stadacher suggest that the workload balancing mechanism shows potential and is worthy of further examination.

The relative contribution of input control versus output control was studied by Kingsman and Hendry (2002). They examined the use of input control alone and the joint application of input control and output control using the WLC-L methodology. The comparison of the performance of the WLC-L method to a system that exhibited no control was also examined. The output control methodology employed by the WLC-L methodology dynamically plans extra capacity at the bottleneck processes as the need arises. This is especially important in the job shop environment where wandering bottlenecks may exist (bottleneck scheduling methods such as OPT address fixed bottlenecks). The results of their experiment indicated that the introduction of input control alone, results in reduced lead time, reduced WIP, and reduced queuing, at the expense of workload accomplished. Their results also demonstrated that the combination of both input and output control leads to reductions in lead time, WIP, and queuing with an insignificant reduction in workload. Thus, Kingsman and Hendry concluded that input and output control should be considered together to ensure that the desired workload is maintained (versus the use of input control alone, which terminates order release when the preset level of WIP is reached).

Enns and Prongue-Costa (2002) compared a release mechanism based on aggregate shop load and a bottleneck release mechanism that releases work to the shop floor when the bottleneck WIP is below an established workload threshold. Additionally, a dispatching rule (bottleneck priority) that gives priority to jobs still having to visit the bottleneck machine was tested. Experimental variables included shop configuration, shop load balance, dispatching mechanism, and workflow pattern. Experimental results suggest that the aggregate shop load release mechanism yields favorable results in a shop environment with balanced loads and simple flow patterns. This is consistent with the work of Oosterman et al. (2000). In the job shop, the bottleneck release mechanism performed as well as the aggregate release mechanism when there was no bottleneck and much better when a bottleneck was present. Additionally, the experimental results indicated that the bottleneck priority dispatching mechanism improved performance under both release mechanisms. Notably, the effectiveness of the dispatching rule increased with the severity of the bottleneck and as the flow of the shop became more random.

Bertrand and Van Ooijen (2002) compared the throughput for the WLC-I methodology to the immediate release mechanism at three different workload levels and 11 levels of workload dependent processing times. They contend that there is an inverse U-shaped relationship between workload in a job shop and the production performance of the operator. Thus, the effective output of a job shop may decrease if the shop deviates from its optimal workload. As a consequence, they developed a model of the relationship between workload and effective processing times and incorporated this into their WLC-I simulation model. The application of their WLC-I methodology stabilized the shop and mitigated the impact of demand variations on system throughput time and shop output. Experimental results indicated that WLC is a necessary function for shops operating at a high level of capacity, operating under a varying demand pattern, and for which effective processing times are a function of workload level.

Missbauer (2002) developed a decision model for the optimization of aggregate order release, addressing the inherent limitations in the case of varying capacity demand under WLC. Linear programming was used to determine the optimal release load by period. Missbauer compared simulations results based on this release mechanism to the LOOR methodology. Simulation results indicated that the optimization model successfully addressed varying demand levels, without requiring additional load balancing and variation of parameters as dictated by the LOOR methodology.

However, Missbauer recognized that the proposed model has limitations resulting in earliness and lateness of a small number of orders in the under utilization and constant high utilization cases, suggesting that the dynamic behavior of the shop floor should be modeled more closely in future research.

Rosairo-Moreira and Alves (2006) analyzed the activities of order acceptance/rejection, due date setting, order release, and dispatching. The objective of their proposed release methodology was to simultaneously control the release of jobs to the shop floor and control output via shop capacity adjustments. Experimental factors included two order acceptance/rejection methods, four levels of due date tightness, four order release rules, and two dispatching mechanisms. They concluded that considering all experimental factors simultaneously results in significant improvements to delivery and workload related performance measures. Additionally, they concluded that the four experimental variables are not independent of one another. The best overall performance results (excluding the mean wait time in pre-shop pool metric) were achieved using the EDD dispatching mechanism, the MIL release logic, and the actual and future work (AFW) order acceptance/rejection rule (orders are accepted if they will not cause the workload limit to be exceeded, otherwise they are rejected).

Wisner's (1995) review of order release policy research contained 10 additional simulation based job shop order release studies not discussed above. Figure 3. summarizes the characteristics of the models discussed by Wisner (NA indicates that dispatching mechanisms utilized in the simulation studies were not specified). Wisner's review of order release research also identified several descriptive research papers not discussed in Section 6.1.1, including Plossl and Wight (1973), Ragatz (1988), and Hendry and Kingsman (1991).

Table 3.2 Job Shop Order Release Simulation Research Reported in Wisner (1995)

| Studies | Shop Characteristics | Dispatching Mechanisms Tested | Release Mechanisms Tested |
|---|---|---|---|
| Ragatz & Mabert (1984) | Hyp/Ran/5 | FCFS, SOPT, EDD, CR | IMM, BFL, BIL, FFL |
| Scudder et al. (1990) | Hyp/Ran/9 | CR, Others (NA) | IMM, BIL |
| Bobrowski & Park (1989) | Hyp/Ran/10 | MODD, CR | IMM, BIL, FFL |
| Bertrand (1983) | Hyp/Ran/5 | NA | IMM, FFL |
| LeGrande (1963) | Act/Ran/115 | NA | FFL |
| Ackerman (1963) | Hyp/Ran/5 | NA | IMM, BIL |
| Deane & Moodie (1972) | Hyp/Ran/4 | NA | IMM, FFL |
| O'Grady & Azoza (1987) | Hyp/Ran/9 | FCFS, SPT | FFL |
| Morton et al. (1988) | Hyp/Ran/1-5 | NA | IMM, FFL |
| Scudder et al. (1990) | Hyp/Ran/9 | CR, Others (NA) | IMM, BIL |

Lastly, Bergamaschi et al. (1997) describes the LIMITE model proposed by Portioli (1991). This model is based on the work of Bechte, with the exception that rigid limitations on workload are relaxed, allowing single work centers to become overloaded if the overall workload balance on all the shops work centers is improved. Portioli's model is considered load limited and probabilistic.

Within the surveyed simulation research, multiple approaches to the order release problem were investigated. Most of the research took a load limited approach and compared their results to the immediate release methodology, while utilizing both cost and non-cost performance measures. The surveyed research identified numerous shop conditions where benefits were realized by controlling the entry of jobs to the shop floor (via the order release mechanism). Other environments were identified that benefited from immediate job release. Additionally, multiple approaches to dispatching were incorporated into the simulation research. Once again, as was the case with the order release mechanisms, the effectiveness of dispatching rules and their relative performance ranking varied significantly amongst researchers. A third area of inconsistency of results amongst researchers deals with the interaction of experimental variables (e.g. due date tightness, shop utilization, dispatching mechanism, and shop environment). Effects of interaction among experimental variables varied greatly within the simulation research. These inconsistencies may be attributed to simulation modeling differences, shop environment differences, interaction among experimental variables, or interpretation of experimental results

The order release research to date has been deficient with respect to shop floor simulation modeling and sequence dependent setup. Of the 45 simulation models identified in Tables 3.1 and 3.2, only five represented actual production environments. Additionally, of the 45 models documented, only one addressed sequence dependent setups in the presence of an order release mechanism. As discussed below, sequence dependent setup research is important to researchers and remains a fertile area for research with respect to job shop scheduling. Clearly, additional research in these areas is warranted considering the potential benefits that could be reaped by practitioners.

## 3.2 Sequence Dependent Setup Dispatching

In Allahverdi et al.'s (1999) comprehensive survey of scheduling problems with sequence dependent setup times, they identified approximately 190 papers that were published over a period of time that exceeded 25 years. Only 11 of these papers examined the job shop environment. Allahverdi et al.'s (2006) comprehensive study of scheduling problems addressing setup literature published between 1999 and 2006 showed a dramatic increase in the total number of papers published. Over this seven year period, approximately 280 papers on scheduling with setup times were published, however only 15 of these papers addressed the job shop environment. Allahverdi contends that this increase in publications is the result of the fact that there are tremendous opportunities for savings when setup times are explicitly incorporated into scheduling decisions in real world industrial environments.

The literature review addressing sequence dependent setup scheduling in a job shop environment is classified into three research segments:

1. Mathematical programming.
2. Neighborhood search studies.
3. Dispatching/simulation studies.

*3.2.1 Mathematical Programming Studies*

Mathematical programming has been applied extensively to job shop scheduling problems in recent years, with problems formulated using integer programming (solution techniques include branch and bound and Lagrangian relaxation), mixed-integer programming and dynamic programming techniques. Until recently, the use of these approaches has been limited due to a lack of solution techniques and limited computational power. Although these techniques have received much attention in recent years, difficulties in the formulation of material flow constraints as mathematical inequalities has limited the use of these approaches. A comprehensive review of mathematical programming methodologies presented in the literature for job shops with sequence dependency is presented below.

A branch and bound algorithm was proposed by Gupta (1982) for minimizing total setup cost for the static job shop scheduling problem. This algorithm was limited to solving small size problems, no comparisons were made to other methods. Brucker and Thiele (1996) also developed a branch and bound technique, with the objective of minimizing make-span.

Ballicu et al. (2002) developed a mixed-integer linear program that can be applied to general job shop scheduling problems. Multiple performance objectives were studied. Comparison of results to the software Lekin and heuristics were mixed. Choi and Choi (2002) also developed a mixed-integer programming model for the same problem and a local search scheme. Their objective was to minimize make-span. The results of this work showed that the scheme significantly enhances the performance of several greedy-based dispatching rules. Choi and Korkmaz (1997) developed a mixed integer programming formulation that outperformed the approach developed by Zhou and Egbelu (1989), utilizing a polynomial heuristic. Their procedure was based on sequentially identifying a pair of operations that provide a minimum lower bound on the make-span two-job/m-machine problem with release times. Zhou et al. (2006) utilized a mixed integer program model and a scheduling algorithm based on a biologic immunity mechanism to minimize make-span in a job shop environment. Results showed that the proposed methodology can greatly improve the effectiveness of dealing with complex job shop scheduling problems. Luh et al. (1998) developed a mixed integer problem and a solution methodology based on a combined Lagrangian relaxation technique and heuristics. Although the facility studied is essentially a flow-shop, it is considered in this review, since it behaved as a job shop from a scheduling perspective. The objective of the study was to obtain near optimal solutions for minimizing total weighted earliness and tardiness.

Low et al. (2005) investigated job shop scheduling problems with re-entrant operations with setup times and the objectives of minimizing total job flow time, minimizing total job tardiness and minimizing machine idle time. They first developed an integer programming model to optimize individual objectives and an acceptable tradeoff schedule was obtained by evaluating three objectives simultaneously. Chen et al. (2003) studied an actual job shop whose manufacturing is characterized by the need to simultaneously consider machines and operators, setup times, operators of different capabilities, and lots divisible into transfer lots. The objective of the study was to maximize on time delivery, reduce inventory, and reduce setups. The problem was formulated as an integer optimization problem and decomposed into smaller sub-problems that are solved using a novel dynamic programming procedure. A heuristic was then used to obtain a feasible schedule based on sub-problem solutions.

Using Markov decision processes, Taner et al. (2003) developed state dependent scheduling rules for the single machine problem. The results were generalized, to establish a generalized scheduling policy for the job shop problem. The policy was combined with a forecasting mechanism for local dispatching decisions, with the objective of minimizing maximum lateness. Results of the study showed significant improvement over existing methods.

Artigues, Lopez and Ayache (2005) obtained upper bounds by a priority rule-based multi-pass heuristic. Artigues et al. (2004) developed a branch and bound procedure that improved upon the results of the branch and bound procedure developed by Focacci et al. (2000).

Allahverdi et al. (2006) documented the results of numerous scheduling problems involving setup times or cost. Their survey included the results of the research presented below. Sun and Yee (2003) addressed the job shop scheduling problem with the additional characteristic of re-entrant work flows. They developed disjunctive graph representations of the problem and proposed heuristics. Balas et al. (2005) formulated a traveling salesman problem which can be solved by a dynamic programming algorithm whose complexity is linear in the number of operations. The objective of this study was to minimize make-span. The sequence dependent setup problem, with the objective of maximizing lateness was solved by Artigues and Roubellat (2002) utilizing a polynomial insertion algorithm. A Lagrangian relaxation based approach was used by Sun and Noble (1999) to solve a series of single machine scheduling problems within a shifting bottleneck framework. The objective of this study was to minimize total weighted tardiness.

*3.2.2 Neighborhood Search Studies*

Neighborhood search methods provide reasonable solutions to scheduling problems and can be enhanced when combined with heuristics. These techniques continue to add small changes and evaluate schedules until there are no more improvements to the objective function. Neighborhood search techniques include Tabu search, simulated annealing, and genetic algorithms.

Cheung and Zhou (2002) developed a genetic algorithm and heuristic rules, with the objective of minimizing make-span for the job shop problem. The genetic algorithm determines the first operation for each machine and the remaining operations on each machine are scheduled using heuristic rules. Through computational analysis they showed that their hybrid algorithm is superior to the methods proposed by Choi and Korkmaz (1997) for the same problem. Candido et al. (1998) also developed a genetic algorithm and heuristic rules, with the objective of minimizing mean completion time and make-span. Comparative results were not provided. Monch et al. (2007) compared dispatching sub-problem solution procedures to a more sophisticated sub-problem solution procedure based on genetic algorithms. The objective of the study was to minimize total weighted tardiness for parallel machine scheduling. Results of the study indicated that using near to optimal sub-problem solution procedures often leads to improved results compared to dispatching based sub-problem solution procedures.

Zoghby et al. (2005) studied the feasibility conditions for meta-heuristic searches when incorporating setups and re-entries in the disjunctive graph model of a job shop. An ejection chain algorithm was developed to remove infeasible solutions from traditional search methods and a simple algorithm for obtaining initial feasible solutions was developed.

Zozom et al. (2003) developed two heuristics with the objective of meeting due dates while minimizing WIP. Their approach first computes a lower bound for WIP and repeatedly simulates the jobs to be scheduled while simultaneously updating job sequences based on the results of the previous simulation run. Both heuristics were effective at reducing WIP (providing solutions close to the computed lower bound) while satisfying due dates over a broad range of problem scenarios.

The scheduling survey of Allahverdi et al. (2006) also documented the following neighborhood search studies. Artigues and Buscaylet (2003) proposed a Tabu search heuristic, with the objective of minimizing make-span. A synthesis of the methods proposed by Artigues and Buscaylet (2003), Artigues et al. (2004), and Artigues, Lopez, and Ayache (2005) was presented by Artigues, Buscaylet and Feillet (2005). The synthesis integrated tabu search with multi pass sampling heuristics. Tahar et al. (2005) proposed an ant colony algorithm to solve the job shop scheduling problem where precedence constraints exist between jobs. The algorithm outperformed a genetic algorithm for the minimizing maximum tardiness performance objective. Artigues and Roubellat (2001) developed a Petri net approach for on-line and off-line scheduling with the objective of maximizing the lateness objective.

*3.2.3 Simulation Studies*

Dispatching rules have been extensively applied to the scheduling problem in job shop environments. In practice they are computationally efficient and easy to implement. Dispatching rules are designed to provide effective solutions to complex problems in real-time.

For the dynamic scheduling problem, Wilbrecht and Prescott (1969), Flynn (1987), Jacobs and Bragg (1988), Kim and Bobrowski (1994), and Low (1995) all used simulation to study the effect of sequence dependent setups in a job shop.

Wilbrecht and Prescott (1969) tested seven priority rules, including SIMSET (job with the shortest actual setup time has priority). They concluded that setup times play a critical role in shop performance and the SIMSET mechanism resulted in the best overall performance of the mechanisms tested.

Flynn (1987) examined three sequencing mechanisms including repetitive lots (queues are searched for transfer lots that are identical to the transfer lot just processed by a machine) and truncated repetitive lots (follows the repetitive lots procedure until there are no identical lots in the queue, or until a predetermined number of transfer lots have been combined into a production lot, whichever occurs first). Both mechanisms outperformed the mechanism that did not take sequence dependent setup into consideration. Jacobs and Bragg also examined the repetitive lots methodology and tested two additional dispatching mechanisms that did not take sequence setup dependency into consideration. Six different performance measures were analyzed. Their findings were consistent with those of Flynn.

Kim and Bobrowski (1994) extended the research of Wilbrecht and Prescott by testing four dispatching rules including JCR. The JCR mechanism searches a work center queue for an identical job to the one that has just finished processing, if no such job exists than the job with the smallest critical ratio is sequenced next. They concluded that explicit consideration must be given to setups in sequence dependent setup environments and that due date information should be included in the sequencing decision in order to improve due date performance. Kim and Bobrowski (1997) also examined the impact of setup time variation on sequencing decisions. They tested four dispatching methods (two rules addressed setup dependency and the other two did not) and concluded that setup time variation has a negative impact on shop performance, but does not diminish the importance of dispatching rules that take setup sequence dependency into consideration.

The findings of Low (1995) also support the findings of Wilbrecht and Prescott. Low tested seven mechanisms in a static job shop and concluded that mechanisms which incorporate setup dependency yield superior results, when compared to methods that do not incorporate setup sequence dependency information. Lastly, O'Grady and Harrison (1988) developed a search sequencing rule that prioritized jobs using a linear combination of due dates, processing times, and setup times. Their rule outperformed the benchmark rules tested.

In Patterson's (1993) analysis of setup time at constraint resources, he concluded that MRP based software packages fail to recognize that the setup procedure for a particular inventory item could be the same for more than one inventory item. He suggests that establishing a setup procedure code with a work center number will create a unique field, which can be used for re-sequencing queued orders, resulting in efficient scheduling decisions. Allahverdi et al. (1999) stated that Patterson's conclusion is consistent with the findings of Hershauer. Hershauer (1970) developed a linear additive priority function that considered the sequence dependency of setup times for a printing shop that had machines with sequence dependent setup times and cost. The function gave high priority to the jobs that would reduce setup time.

White and Wilson (1977) developed a heuristic method for sequencing jobs to minimize the total setup time that would be appropriate for use in job shops. This methodology is based on a nearest neighbor rule. Work center queues are examined for orders with the least estimated setup time relative to the part currently being processed on a machine.

Using real time shop floor information, Ovacik and Uzsoy (1994) developed a heuristic algorithm for minimizing maximum lateness. The algorithm used global information on the state of the shop floor to make dispatching decisions.

Yeh (2005) developed a color coding and priority system to identify production jobs that are to be processed at work centers which have a work sequence preference. Using a realistic production schedule, a three-phase sequencing method was developed to create a feasible shop schedule, with the objective of minimizing setup. Zhou and Egbelu (1989) also developed an interactive graphical approach to minimize make-span. The heuristic allows interactions with a human expert via a computer graphic interface.

# CHAPTER 4

## RESEARCH METHODOLOGY AND QUESTIONS

Although some researchers have concluded that an effective order release mechanism diminishes the importance of dispatching mechanisms, others have concluded that the impact of order release on shop performance is significantly influenced by the type of dispatching rule used on the shop floor. This dissertation incorporates dispatching mechanisms into a production control scheme, in order to cope with the dynamically changing conditions on the shop floor. If the shop floor was deterministic in nature, then an effective order release mechanism and simple dispatching rule might be appropriate. However, since manufacturing environments are stochastic in nature, order release and dispatching mechanisms that utilize current shop floor information can make sequencing decisions to cope with the ever changing shop floor conditions. Dependence solely on order release and simple dispatching mechanisms may result in poor performance since job routing decisions would be made based on initial shop floor conditions that change as jobs are released and proceed through the production floor.

The examination of the order release and sequence dependent setup dispatching mechanisms developed by researchers and their results provided the basis for establishing a new material flow control strategy aimed at reducing unit cost, improving delivery performance, and reducing shop floor congestion. Based on the research performed to date, it is evident there is not one best combination of order release rule and dispatching mechanism that can be used in all job shop environments. Although the surveyed literature yielded some results that can be considered inconsistent, other experimental results contained common findings that warranted further investigation. These results include the following conclusions:

- Due date information is important.
- Current work-load information is important.
- If workloads are more undirected, work center workloads can be effectively used in release mechanisms and if work flows are more directed, aggregate workloads can be effectively used in release mechanisms.
- Stringent parameter setting for release mechanisms degrades system performance.
- Load smoothing and reducing system nervousness in general improves overall system performance.
- Pulling jobs forward results in better performance than delaying release.
- Two queue systems for normal and high priority jobs are effective for improving system performance.
- Where bottlenecks exist, ensure starvation avoidance.

These documented results were used as a guide for the development of the work flow control methodology presented in this dissertation.

The work flow control strategy presented in this dissertation represents a hybrid approach to material flow control, in that the production control methodology incorporates MRP generated release dates and lot sizes, where the lot sizes can be modified by the order release and dispatching mechanisms, to gain efficiencies. Effectively, order release is executed via an independent order release mechanism (independent of the MRP system), while the dispatching mechanism controls workflow within the shop, once order release is initiated. A flow diagram of this material flow control strategy is presented in Figure 4.1.

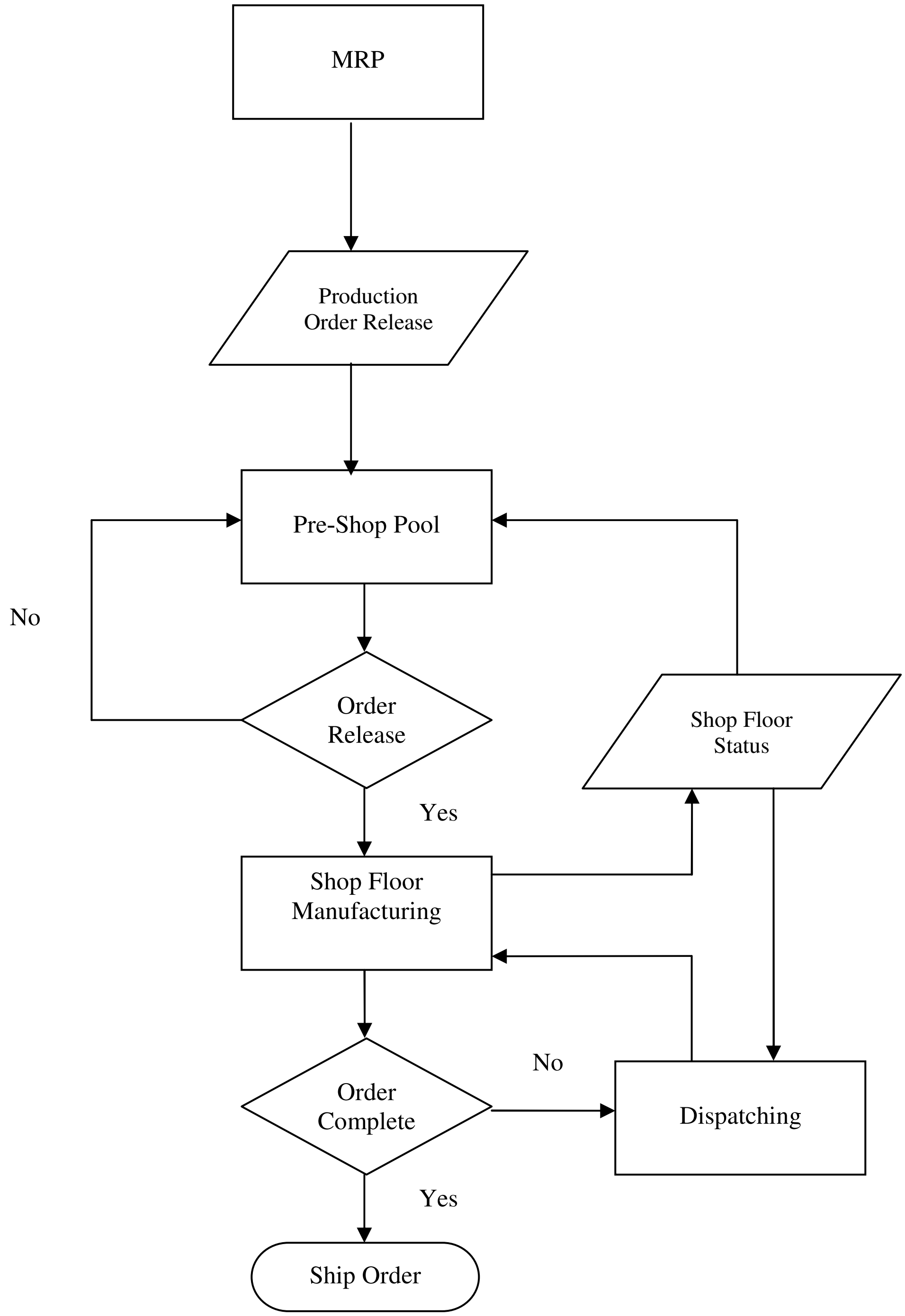


Figure 4.1  Flow diagram of the proposed material flow control strategy.

As illustrated in Figure 4.1, production orders released by MRP are sent directly to the pre-shop pool. The characteristics of the order and the status of the shop floor (including information regarding WIP, job urgency, queue lengths, and part families in work) are evaluated by the proposed release mechanism. Based on this evaluation, a release decision is made. If the release mechanism elects not to release the job, then the order remains in the pre-shop pool. If the release criteria is satisfied, the order is released to the shop floor. As orders queue on the shop floor, dispatching decisions are made based on the characteristics of the order and characteristics of the work queuing at the various work centers. The dispatching mechanisms give priority to orders with sequence dependent setups and due date urgency.

Although this order release and dispatching research addresses only the job shop facility layout, it incorporates some of the principles of the group technology production philosophy related to the establishment of part families. This overall production control approach was selected since its implementation cost and disruption to production lines would be minimal. Additionally, this approach yields intuitive solutions that both planners and operators can easily understand and apply to daily operations.

The material flow control strategy in this dissertation is consistent with the views of Hopp and Spearman (1996), who suggest that a variety of scheduling systems (including MRP) can be used in conjunction with a WIP cap (a method of order release that limits the amount of WIP on the shop floor). Additionally, they state that the benefits of capping WIP in an MRP system were addressed by Wight (1970), but mechanisms for achieving this have been rare in practice.

Testing of the new and existing order release and dispatching mechanisms that serve as the basis for the material flow control methodology described above were conducted via simulation, in two phases. Simulation modeling was conducted using Witness 2006, Manufacturing Performance Edition, Release 1.0.

# CHAPTER 5

# PHASE ONE SIMULATION MODELING

Phase one of the simulation process is based on the model developed by Ragatz and Mabert (1988). This model represents the benchmark model employed by most ORR researchers. Modifications were made to the Ragatz and Mabert model to account for setup sequence dependency. These modifications are consistent with the work of Kim and Bobrowski (1995). The phase two model is based on data obtained from an operating job shop in the metal fabrication and cutting tool industry.

Phase one modeling consists of four distinct simulation activities:

1. Planning factor and statistical characteristics development.
2. Control strategy investigation.
3. Main experiments.
4. Sensitivity experiments.

Phase two modeling consists of two distinct simulation activities:

1. Planning factor and statistical characteristics development.
2. Experimentation.

## 5.1 Model Development, Planning Factors, and Statistical Characteristics

The phase one model consists of a six machine dynamic job shop. The job shop operates seven days a week, eight hours per day. During each eight hour shift all necessary labor and machines are available, machine breakdowns and maintenance are not considered. The model does not contain any assembly operations, all orders consist of sequential operations. Capacity is assumed to be passive in all experiments and outside the control of the order release strategy.

*5.1.1 Job Arrivals*

Jobs arrive at the pre-shop pool prior to the start of each eight hour shift. The jobs arrive according to a Poisson process at a mean rate of 1.0526 (used in the main and sensitivity experiments, for the low utilization treatments) and 1.1760 (used only in the sensitivity experiment, for the high utilization treatments) jobs per hour, resulting in utilization rates of 87.5% and 95.0% respectively, for the benchmark order release and dispatching mechanisms. All jobs entering the pre-shop pool are populated with attributes defining the job's setup type, setup time, run time, and due date. Once job attributes are defined, the jobs are ordered in the pre-shop pool queue according to the first come first served (FCFS) sequencing rule. The order release mechanism determines which jobs and when order release to the shop should take place.

*5.1.2 Job Routings*

Job routings are random, with a minimum of one operation per job and a maximum of six operations per job. Each machine has an equal probability of being the first in the sequence of operations and subsequently there is an equal probability that the job is routed to one of the other five machines or the job is completed. Return visits to any machine is prohibited. This routing methodology results in a system that does not have a stationary bottleneck.

*5.1.3 Job Run Time*

Run processing times follow an exponential distribution with a mean of 90 minutes per operation. Processing times were truncated at 30 and 210 minutes, simulating low variability in the experimental process. Processing times were also truncated at 15 and 315 minutes, simulating high variability in the experimental process.

*5.1.4 Job Setup Time*

The job shop processes six types of jobs, representing six different setups (setup types are randomly assigned to each job prior to the job entering the pre-shop pool). The same type of jobs can be processed with the same machine setting as any other member of its job type, regardless of the number of operations in the job, processing time of the job, or job routing. Thus, the setup time of any two jobs of the same job type processed in succession would result in a setup time of zero for the second job. The setup time for jobs following others of a different type are taken from a predefined setup matrix, based on White and Wilson's (1977) research. The setup matrix defines the setup time for any combination of job types. The average setup time in the matrix is approximately 20 minutes.

Setup times were estimated as approximately 20% of the total job run time, which is consistent with the work of Kim and Bobrowski (1995). The 20% setup factor was developed by Flynn (1984), who conducted research at an operating job shop (EDI shop). Thus, the 20% setup factor represents a realistic setup time and provides operating characteristics that will differentiate the performance of the dispatching rules without providing an undue advantage to setup oriented rules.

*5.1.5 Job Due Date Setting*

The due date for each job is based on the total work content (TWK) methodology. The TWK methodology has been employed by numerous researchers, including Melnyk and Ragatz (1989), Hendry and Wong (1994), and Cigolini and Portioli-Staudacher (2002). The TWK methodology is based on the average setup time of a job, the total estimated processing time of a job and a planning factor allowance that accounts for queue delays. For each new order *i*, the due date was calculated as follows:

$$DD_i = AT_i + TWKP_i * K_i + TWKSU_i * K_i * NOP_I \quad (5.1)$$

Where: $DD_i$ = due date for order *i*.

$AT_i$ = arrival time for order *i*.

$TWKP_i$ = total run time for order *i*.

$K_i$ = planning factor used for all jobs.

$TWKSU_i$ = average setup time for all jobs.

$NOP_i$ = number of operations for order *i*.

The planning factor ($K_i$) was developed using pilot simulation runs. The planning factor was set such that the use of the workload control (WLC) order release mechanism, along with the first come first served (FCFS) dispatching mechanism would result in 40% of the jobs being tardy. This methodology is consistent with the work of Kim and Bobrowski (1995). The pilot simulation runs were conducted under low variability and low utilization conditions.

## 5.2 Control Strategy Investigation

Using the benchmark simulation model described in paragraph 5.1, preliminary experiments were conducted to assess the common findings among non-sequence dependent setup researchers. The objective of this assessment was to determine which findings and which order release and dispatching mechanisms warranted further examination.

### *5.2.1 Due Date Information*

The use of due dates was investigated from two perspectives. First due dates were investigated from a dispatching perspective and secondly from a queuing perspective.

With respect to dispatching mechanisms, due dates were used to determine which jobs to delay, when jobs were ahead of schedule and which jobs to expedite when jobs were delinquent. Several delay strategies were investigated including strategies that examined the total number of operations remaining and number of hours ahead of schedule. Numerous combinations of number of operations remaining and hours of operations remaining were studied. None of these strategies proved effective in reducing tardiness or WIP performance measures. The delaying of jobs resulted in increased system nervousness, thus degrading overall system performance. Delaying jobs resulted inefficiencies with respect to setup changeovers and hence shop utilization. Similar results were observed with respect to jobs that were expedited based on their due dates, with the exception of the test case where expediting was executed for jobs that were over seven days late. This case was examined in the main experiments and is referred to as SIMSET2.

When due date information was examined from a queuing perspective, it was observed that the critical ratio sequencing rule outperformed first come first served, shortest processing time, and earliest due date sequencing rules for each of the preliminary dispatching and order release mechanisms tested. The critical ratio rule is defined as:

$$CR_i = (DD_i - AT_i) / TWKP_i \quad (5.2)$$

Where: $CR_i$ = critical ratio for order *i*.

$DD_i$ = due date for order *i*.

$AT_i$ = arrival time for order *i*.

$TWKP_i$ = total run time for order *i*.

Thus, the critical ratio rule was used to sequence all queues in both the main and sensitivity experiments.

*5.2.2 Workload Information*

In the control strategy simulation experiments, the use of work load information was compared to the immediate release methodology which does not make use of work load information.

The immediate release methodology is the simplest of the order release mechanisms utilized by researchers. This methodology results in the release of all jobs from the pre-shop pool at the beginning of each day. The immediate release methodology does not consider any shop or job information when releasing orders to the shop floor, thus emulating the behavior of many MRP systems.

Initial experiments utilizing the immediate release methodology demonstrated that this methodology was incapable of yielding acceptable performance levels, as has been often demonstrated in the non-sequence dependent setup literature. When the FCFS dispatching methodology was used in conjunction with the immediate release methodology, WIP increased exponentially and over 90% of the jobs were tardy. System performance degraded further as experiments were repeated under high variability conditions. The failure to combine similar type jobs via a sequence sensitive dispatching mechanism resulted in the inefficient use of resources and hence excessive queue lengths.

When setup oriented dispatching rules were used with the immediate release methodology performance improved significantly, however as process variability increased there was a dramatic decrease in system performance. As process variability increased, delivery performance plummeted over 25% and WIP increased approximately 40%. Although delivery performance improved, excessive queues still formed and long runs of similar part types caused jobs of other types to be delayed.

The performance of the release mechanisms that included work load information grossly outperformed the immediate release methodology. These mechanisms used workload load information at two different levels. The first mechanism considers the job's processing time and the aggregate shop load (the total amount of work in hours on the shop floor), while the second mechanism considers the job's processing time and the shop load of individual work centers.

Based on the initial experiments it was concluded that no further consideration should be given to the immediate release methodology and hence immediate release was excluded from the main experiments and the sensitivity experiments. It was observed that the use of work loads resulted in smoothed loadings and reduced system nervousness, which in turn improved overall system performance.

*5.2.3 Undirected Workload Management*

As discussed in paragraph 5.2.2 work load information significantly enhances system performance when included in the order release criteria. The use of work load information was investigated at two distinct levels of control:

1. Total shop load.
2. Work center load.

At the aggregate shop load level, simulation experiments were conducted to identify a "near optimal" level of work to be released to the shop floor. Similarly, simulation experiments were conducted to determine the "near optimal" level of work to be released to each work center. Preliminary experiments were then conducted utilizing these "near optimal" workloads.

The release methodology that incorporated information at the work center level yielded superior results in contrast to the methodology that released orders based on aggregate shop loads. The work center based released methodology helped to smooth the work load across work centers and in turn resulted in reduced system nervousness, when compared to the aggregate release methodology. The difference in performance was not significant enough to exclude the aggregate shop load release mechanism from the main experiments and the sensitivity experiments. Thus, both methodologies underwent detailed analysis.

*5.2.4 Parameter Setting*

The effects of setting stringent parameters for the two workload control mechanisms described above was examined in the control strategy simulation experiments. The experiments illustrated that stringent parameter setting is detrimental to system performance in the presence of work load control release mechanisms. From these experiments it was concluded that individual jobs should be allowed entry into the shop for both the work center based released methodology and the aggregate shop load release methodology when the job causes the threshold to be exceeded. However, additional jobs cannot enter the shop until the workload reseeds to a level below the pre-established release threshold.

*5.2.5 Expediting and Delaying Jobs*

The impact of pulling jobs forward versus delaying jobs was investigated with respect to both order release and dispatching mechanisms. Due dates were examined to determine which jobs to delay, when jobs were ahead of schedule, for both order release and dispatching mechanisms. As discussed in paragraph 5.2.1, several delay strategies were investigated including strategies that examined the total number of operations remaining and number of hours ahead of schedule. Numerous combinations of number of operations remaining and hours of operations remaining were studied. None of these strategies proved effective in reducing tardiness or WIP performance measures. The delaying of jobs resulted in increased system nervousness, thus degrading overall system performance. Delaying jobs resulted inefficiencies with respect to setup changeovers and hence shop utilization. In contrast, pulling jobs forward via dispatching mechanisms resulted in improved system performance. These improvements are attributed to the efficiencies gained by eliminating or reducing setup requirements by combing jobs without consideration to due dates.

*5.2.6 Two Queue Systems*

The effectiveness of two queue systems was examined in the control strategy investigation simulations. Although two queue systems have proven to be effective in the non-sequence dependent order release literature, this analysis proved that the two queue system is ineffective and severely degrades system performance when sequence dependent setups are present. This degradation in system performance is due to the interruption of sequenced setups of the same type, thus significantly increasing the number of required setups during production. The disruption caused by two queue systems resulted in extreme system nervousness and consequently degradation to all performance variables (tardiness, WIP, and cost).

*5.2.7 Bottleneck Starvation Avoidance*

As was expected, bottleneck starvation avoidance in the presence of sequence dependent setups is critical to achieving acceptable levels of performance, as is the case for non-sequence dependent setup systems. This was validated in the control strategy investigation simulations, where it became necessary to increase the workload release threshold as system demand increased.

Of the common findings among non-sequence dependent setup researchers described in paragraphs 5.2.1 through 5.2.7, only the effectiveness of two queue systems resulted in differences between sequence dependent and non-sequence dependent systems.

## 5.3 Main Experiments

The baseline model used in the main experiments is described in paragraph 5.1. The model planning factors and statistical characteristics are unchanged. Additionally, the due date setting methodology is unchanged. The one difference between the model described in paragraph 5.1 and the main experiments model is queue sequencing. In the main experiments and sensitivity experiments all queues are ordered by critical ratio.

The main experiments and sensitivity experiments focused efforts with respect to the findings documented during the control strategy investigation phase of this dissertation. As most models in the literature, the main experiments model does not represent any specific existing operational system. Although it includes a number of assumptions which may or may not be true for a given operational system, results of previous research efforts suggest that the differences between hypothetical and operational job shops do not have a significant impact on the performance of different operating policies in the job shop. Moore and Wilson (1967) found that work flow pattern and size of the shop do not have a significant impact on the performance of dispatching procedures.

*5.3.1 Order Release Mechanisms*

Two order release mechanisms were used in the simulation experiments, Workload Control Shop (WLC) and Workload Control Machine Center (WLCMC). With both mechanisms, orders arrive to the production system over time. However, the orders are not released to the shop floor immediately, rather they are prioritized in the pre-shop pool according to the critical ratio sequencing rule. Throughout the operating hours of the shop (representing a continuous timing convention), beginning with the highest priority job in the pre-shop pool, the release decision about the currently considered job is taken. In the case of releasing orders, the shop's workload is updated accordingly. Otherwise the order is retained in the pre-shop pool and the next order in the queue is considered for release. Both mechanisms are considered load limited approaches to order release, in that workload information is used in the release decision process. However, the level at which the workload is controlled differs between the mechanisms.

The WLC mechanism considers the job's processing time and the aggregate shop load (the total amount of work in hours on the shop floor). This represents an a-temporal methodology, since the total work considered for each machine is determined by summing up the processing times for all jobs in the shop that are to be routed through that machine (there is no differentiation between load in transit and released load from load on hand). Effectively, order release to the shop floor occurs if the aggregate shop load plus the job's estimated processing time is below the pre-established shop load limit. This mechanism releases orders to the shop floor one at a time, searching the pre-shop pool queue from the highest priority job on until either all jobs have been released from the pre-shop pool or the shop load reaches its predetermined maximum load limit. The expected setup time was not included in the calculation of the shop load. At the aggregate shop load level, simulation experiments were conducted to determine a "near optimal" level of work to be released to the shop floor. Thus, the experiments resulted in the establishment of an aggregate shop load limit of 16,500 hours.

The WLCMC mechanism considers the job's processing time and the individual loads at each work center. As is the case in for the WLC methodology, this represents an a-temporal approach to workload control. Thus, order release to the shop floor occurs if the load at each work center plus the job's estimated processing time at each work center is below the pre-established work center shop loads. The WLCMC mechanism releases orders to the shop floor one at a time, searching the pre-shop pool queue from the highest priority job on until either all jobs have been released from the pre-shop pool or the load at any single work center reaches its predetermined maximum load limit. The expected setup time was not included in the calculation of the shop load. Simulation experiments were conducted to determine a "near optimal" level of work to be released to each work center on the shop floor. Thus, the experiments resulted in the establishment of work center load limits of 1,200 hours per work center.

*5.3.2 Dispatching Mechanisms*

Three dispatching mechanisms were tested in the simulation experiments. Two of the mechanisms take setup into to consideration, while the third mechanism represents an ordinary dispatching mechanism. The three rules are:

1. Similar setup (SIMSET1).
2. Similar setup expedite (SIMSET2).
3. First come first served (FCFS).

The SIMSET mechanism selects a job from a queue that will minimize the setup time for the next operation to be processed. Queues are first searched for a job whose setup requirements are identical to the job that has just completed processing. If a job with identical setup requirements is not found, then the job with the most similar setup is selected for processing next. The queues from which the jobs are selected are ordered by their critical ratio. The preliminary experimental process, demonstrated that critical ratio ordering of queues was most effective. This represents a departure from the literature which most often orders queues by queue entry time. As described in paragraph 5.1.4, the setup times are selected from a setup matrix (defines the setup time for any combination of job types) within the simulation model.

The SIMSET2 dispatching mechanism utilizes the same logic as the SIMSET mechanism, with one exception. If any job in a machine center's queue is greater than seven days delinquent, the job will be expedited, regardless of its setup requirement. If there are no jobs in the machine center's queue greater than seven days late, than the dispatching mechanism operates identical to the SIMSET1 methodology. The seven day threshold for expediting was derived during the control strategy investigation phase of this dissertation. The ordering of the queues by critical ratio is also utilized in the SIMSET2 methodology.

The third dispatching mechanism examined is the FCFS ordinary dispatching rule, which does not take setup into consideration. This mechanism is commonly employed in non-sequence dependent setup research. The mechanism simply selects the job from a work center queue that has been in the queue the longest.

*5.3.3 Process Variability*

As In the preliminary experiments, two levels of process variability were studied. Utilizing a mean processing time of 90 minutes for both levels, variability was addressed by truncating the tails of the Poisson distribution. For the low variability case, processing times were truncated at 30 and 210 minutes. To simulate high variability the processing times were truncated at 15 and 315 minutes. Effectively, the high variability case extended the distribution tails by 50%, thus permitting more extreme values with respect to processing time.

*5.3.4 Performance Measurement*

Three performance measures were collected in the simulation experiments. These measures include the percentage of jobs completed on time, WIP , and total cost.

The percentage of jobs on time is calculated by dividing the total number of jobs completed on time by the total number of jobs completed for the 500 day simulation period. An order is defined as on time when:

$$DD_I > CD_I \qquad (5.3)$$

Where: $CD_i$ = completion date for order i (hours).

$DD_i$ = due date for order i (hours).

The WIP performance measure (hours of work) is simply calculated by summing the average WIP accumulated at each work center over the 500 day simulation period.

Most researchers, including Kim and Bobrowski (1995) measure cost as the sum of inventory holding and late penalty cost. Where inventory holding cost is calculated by summing both WIP and finished goods inventory (for orders that complete prior to their due date) and late penalty cost calculated as the amount of finished work (measured in hours) times the number of days late. The ratio of inventory holding cost to late penalty cost is set at 1:20. Other researchers such as Cigolini and Portiolini-Staudacher (2002) have elected not to include cost performance measurements in their work due to the difficulty in estimating both inventory holding and late penalty costs.

Since this research addresses the production issue of sequence dependent setups, production cost must be included in the measure of total cost in order to capture the cost savings associated with setup sharing. Thus, the total cost performance measure is calculated by summing the average unit production cost, the average inventory cost, and the average unit late penalty costs. The average unit production cost and inventory cost are calculated using standard practices used within the U.S. Department of Defense (no standard practices exist for calculating late penalty cost). The late penalty cost is calculated as a function of the inventory holding cost (a 1:20 inventory holding cost to late penalty cost ratio was utilized, as documented in the literature).

The unit production cost was calculated by multiplying the machine utilization by the total hours of production by the production cost per hour, divided by the total number of units produced during the simulation period. This is expressed as:

$$\text{Unit Production Cost} = \sum_{i=1}^{n} [u_i * APH_i] * [\$310.00] / TUP \qquad (5.4)$$

Where: n = number of machines.

$u_i$ = average utilization of machine i.

$APH_i$ = available production hours for machine i.

TUP = total units produced.

The $310.00 production rate was derived by averaging the total hourly cost of production (including overhead) for the two manufacturing facilities that served as the motivation for this dissertation.

The average inventory cost was calculated by summing the average WIP cost and the average inventory holding cost. The average WIP cost and average inventory cost are calculated as follows:

$$\text{Unit WIP Cost} = [[ TUP * AQ] * [COM/365] * [AUC/2]] / TUP \qquad (5.5)$$

Where: TUP = total units produced.

AQ = average time spent queuing.

COM = cost of money factor, current Federal Treasury rate.

AUC = average unit production cost.

Unit Early Cost = [[UPE * AE] * [COM/365] * AUC] / TUP (5.6)

Where: UPE = total units produced early.

AE = average time early.

COM = cost of money factor, Federal Treasury rate.

AUC = average unit production cost.

TUP = total units produced.

As discussed above, the average tardy cost per day is equivalent to 20 times the average inventory holding cost per day, as described by Kim and Bobrowski (1995). The average tardy cost is calculated as follows:

Unit Tardy cost = [AIHC * 20 * ANDT] * UPT / TUP (5.7)

Where: AIHC = average inventory holding cost per day.

ANDT = average number of days tardy.

UPT = total units produced tardy.

TUP = total units produced.

Thus, the total unit cost measure is expressed as:

Unit Cost = Unit Production Cost + Unit WIP Cost + Unit Early Cost + Unit Tardy Cost.

### *5.3.5 Experimental Design and Null Hypothesis Testing*

A full factorial 2 x 3 x 2 experiment (resulting in a total of 12 treatments) was conducted in order to evaluate all main effects and two-way interactions. The independent variables consisted of two order release mechanisms, three dispatching mechanisms, and two levels of process variability.

The objective of the simulation experiments were to identify the most effective experimental treatments, evaluate the significance of each experimental variable and the potential interactive effects of experimental variables. The following null hypothesis were tested for each of the three performance measurements:

H1: Choice of order release mechanism has no significant impact on the dependent performance variables.

H2: Choice of dispatching mechanism has no significant impact on the dependent performance variables.

H3: Interactive effect between order release mechanism and dispatching mechanism has no significant impact on the dependent performance variables.

H4: Interactive effect between order release mechanism and processing time variability has no significant impact on the dependent performance variables.

H5: Interactive effect between dispatching mechanism and processing time variability has no significant impact on the dependent performance variables.

*5.3.6 Data Collection*

During the control strategy investigation process, data was collected with reference to the steady state of the system. Several simulation runs were made in order to determine the effects of job shop start-up. Performance criteria and utilization levels reached steady state after approximately 300 working (simulated) days. Thus, to be cautious, for each simulation run all statistics were reset to zero and restarted after a warm-up period of 500 days. Statistics were then collected for an additional 500 days of operation.

The experiments were performed using 10 replications of each treatment. The sample size of 10 was determined by controlling the risks of making Type I and II errors. The values of $\alpha = 0.10$ and $\beta = 0.10$ were used. Each of the 10 replications used different random number seeds for job arrival rate, job processing time, and job routing, in order to prevent correlation between observations.

*5.3.7 Results*

A summary of the performance results is presented in table 5.1 (the last two characters in the treatment column indicate whether the treatment was based on a low variability or high variability level). Paragraphs 5.3.7.1 through 5.3.7.3 contain the detailed analysis of results for each of the three system performance measures. The detailed analysis (for each performance measure) included Analysis of Variance

(ANOVA) and Tukey's Paired Comparison Procedure (TPCP). ANOVA was performed in order to test the null hypotheses defined in paragraph 5.3.5, while TPCP (set for 95% confidence) was used to determine statistically significant differences in performance measures between experimental treatments. ANOVA was conducted utilizing Statistica (1995). Cells shaded in the TPCP tables indicate that the difference between treatments is not statistically significant.

Table 5.1 Main Experiment Performance Results Summary

| | **% On Time** | | **WIP** | | **Unit Cost 20:1** | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean** | **Variance** | **Mean** | **Variance** | **Mean** | **Variance** |
| WLCFCFSLV | 0.5975 | 0.00049 | 39.88 | 0.15 | 1,842.89 | 105.95 |
| WLCFCFSHV | 0.5486 | 0.00018 | 39.49 | 0.22 | 1,838.09 | 225.37 |
| WLCSIMSET1LV | 0.7129 | 0.00135 | 37.47 | 3.06 | 1,716.89 | 444.71 |
| WLCSIMSET1HV | 0.6588 | 0.00023 | 37.83 | 0.16 | 1,745.12 | 197.01 |
| WLCSIMSET2LV | 0.7637 | 0.00057 | 37.01 | 3.01 | 1,699.21 | 339.20 |
| WLCSIMSET2HV | 0.7249 | 0.00004 | 37.14 | 0.64 | 1,730.60 | 106.18 |
| WLCMCFCFSLV | 0.7675 | 0.00023 | 21.51 | 0.61 | 1,756.22 | 321.79 |
| WLCMCFCFSHV | 0.7241 | 0.00053 | 20.94 | 1.01 | 1,768.75 | 81.81 |
| WLCMCSIMSET1LV | 0.8600 | 0.00006 | 19.47 | 0.53 | 1,682.43 | 82.51 |
| WLCMCSIMSET1HV | 0.7910 | 0.00090 | 19.15 | 0.65 | 1,691.69 | 156.47 |
| WLCMCSIMSET2LV | 0.8560 | 0.00008 | 19.34 | 0.53 | 1,687.41 | 91.05 |
| WLCMCSIMSET2HV | 0.7739 | 0.00071 | 19.01 | 0.62 | 1,695.92 | 140.67 |

5.3.7.1 On Time Orders

The three-way ANOVA test (Table 5.2), demonstrates that the main effect of the order release mechanism is significant with respect the percentage of jobs completing on time. This result contradicts the work of Kim and Bobrowski (1995) who concluded that the order release mechanism was insignificant at the 0.05 level. These findings are however consistent with the results of several non-sequence setup dependent researchers such as Ragatz and Mabert (1988) and Bobrowski and Park (1989). The ANOVA also indicates that main effects for dispatching and variability are also significant at the .05 level. The results regarding dispatching significance are consistent with the work of Kim and Bobrowski (1995). Table 5. also indicates that a significant interaction exists between the order release and dispatching mechanism factors and the order release and variability factors. These results demonstrate that the on time performance of orders is affected by the combination of order releasing and dispatching mechanisms. Additionally, process variability has a significant affect on time performance.

Table 5.2 Main Experiment Three Factor ANOVA Results for Orders On Time

| *Variation Source* | *SS* | *df* | *MS* | *F** | *P-Value* |
|---|---|---|---|---|---|
| Between Treatments | 0.7771 | 11 | 0.0706 | | |
| Factor 1 (Release) | 0.4893 | 1 | 0.4893 | 1094.72 | 0.00000 |
| Factor 2 (Dispatching) | 0.1619 | 2 | 0.0810 | 362.28 | 0.00000 |
| Factor 3 (Variability) | 0.0942 | 1 | 0.0942 | 210.75 | 0.00000 |
| 12 Interactions | 0.0272 | 2 | 0.0136 | 60.77 | 0.00000 |
| 13 Interactions | 0.0023 | 1 | 0.0023 | 5.18 | 0.02489 |
| 23 Interactions | 0.0007 | 2 | 0.0004 | 1.65 | 0.19686 |
| 123 Interactions | 0.0015 | 2 | 0.0007 | 3.35 | 0.03867 |
| Error | 0.0483 | 108 | 0.0004 | | |
| Total | 0.8254 | 119 | | | |

An examination of Table 5.1 reveals that at low variability, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments yield the most favorable results with respect to orders completed on time. The results of the TPCP at a .05 level (Table 5.3), indicate that that both treatments yield statistically significant differences when compared to the other four treatments. However, an overall best treatment could not be selected between WLCMCSIMSET1 and WLCMCSIMSET2 since the TPCP results indicated that there was no statistically significant difference between these treatments.

Table 5.3 Main Experiment TPCP for Orders On Time at Low Variability

| | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | -0.1154 | -0.1663 | -0.1701 | -0.2625 | -0.2585 |
| WLCSIMSET1 | -0.1154 | | 0.0509 | 0.0547 | 0.1471 | 0.1431 |
| WLCSIMSET2 | -0.1663 | 0.0509 | | -0.0038 | -0.0962 | -0.0923 |
| WLCMCFCFS | -0.1701 | 0.0547 | -0.0038 | | -0.0924 | -0.0885 |
| WLCMCSIMSET1 | -0.2625 | 0.1471 | -0.0962 | -0.0924 | | 0.0040 |
| WLCMCSIMSET2 | -0.2585 | 0.1431 | -0.0923 | -0.0885 | 0.0040 | |

As in the low variability case, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments yield the most favorable results with respect to orders completed on time under high variability conditions. Again, the results of the TPCP at a .05 level (Table 5.4), indicated that that both treatments yield statistically significant differences when compared to the other four treatments. However, an overall best treatment could not be selected between WLCMCSIMSET1 and WLCMCSIMSET2 since the TPCP results indicated that there was no statistically significant difference between these treatments.

Table 5.4 Main Experiment TPCP for Orders On Time at High Variability

| | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | -0.1102 | -0.1763 | -0.1756 | -0.2424 | -0.2253 |
| WLCSIMSET1 | -0.1102 | | -0.0661 | -0.0653 | -0.1322 | -0.1151 |
| WLCSIMSET2 | -0.1763 | -0.0661 | | 0.0008 | -0.0661 | -0.0490 |
| WLCMCFCFS | -0.1756 | -0.0653 | 0.0008 | | -0.0669 | -0.0498 |
| WLCMCSIMSET1 | -0.2424 | -0.1322 | -0.0661 | -0.0669 | | 0.0171 |
| WLCMCSIMSET2 | -0.2253 | -0.1151 | -0.0490 | -0.0498 | 0.0171 | |

Thus, under both low and high variability conditions the WLCMC order release mechanism yielded superior results in comparison to the WLC order release mechanism. The superior results of the WLCMC mechanism may be attributed to its refined approach (limiting work center queues) to workload control, which results in more stable and equitable workloads among the individual work centers.

The dispatching mechanism (FCFS) that ignored setup sequence dependency produced the most unfavorable results, due to FCFS's inability to consistently spread setup cost across multiple orders. The difference between the SIMSET1 and SIMSET2 dispatching mechanisms proved statistically insignificant. The use of these mechanisms caused different orders to complete on time, however their overall performance was indistinguishable. Both mechanisms also yielded similar variances.

5.3.7.2 WIP

The three-way ANOVA test (Table 5.5), demonstrated that the main effect of the order release mechanism is significant with respect the WIP. This was expected since the order release mechanism effectively sets the WIP level, via the establishment of a WIP cap. This result also contradicts the work of Kim and Bobrowski (1995) who concluded that the order release mechanism was insignificant at the 0.05 level. The ANOVA also indicates that main effects for dispatching are also significant at the .05 level. The results regarding dispatching significance are consistent with the work of Kim and Bobrowski (1995). No two-way interactions were significant. As was the case for the number of jobs completing on time, the main experiments demonstrated that the WIP performance of the shop can be improved by the selection of an appropriate order releasing mechanism.

Table 5.5 Main Experiment Three Factor ANOVA Results for WIP

| *Variation Source* | *SS* | *df* | *MS* | *F** | *P-Value* |
|---|---|---|---|---|---|
| Between Treatments | 10041.64 | 11 | 912.8766 | | |
| Factor 1 (Release) | 9974.36 | 1 | 9974.3623 | 10702.40 | 0.00000 |
| Factor 2 (Dispatching) | 63.14 | 2 | 31.5723 | 67.75 | 0.00000 |
| Factor 3 (Variability) | 1.01 | 1 | 1.0083 | 1.08 | 0.30059 |
| 12 Interactions | 0.87 | 2 | 0.4352 | 0.93 | 0.39613 |
| 13 Interactions | 1.44 | 1 | 1.4388 | 1.54 | 0.21674 |
| 23 Interactions | 0.67 | 2 | 0.3334 | 0.72 | 0.49131 |
| 123 Interactions | 0.15 | 2 | 0.0758 | 0.16 | 0.85017 |
| Error | 100.65 | 108 | 0.9320 | | |
| Total | 10142.30 | 119 | | | |

Also, as was the case for the orders completed on time performance measurement, at low variability, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments yielded the most favorable results with respect to WIP (Table 5.1). The results of the TPCP at a .05 level (Table 5.6), indicate that both treatments yield statistically significant differences when compared to the other four treatments. However, an overall best treatment could not be selected between WLCMCSIMSET1 and WLCMCSIMSET2 since the TPCP results indicated that there was no statistically significant difference between these treatments. As addressed above, the favorable results for the WLCMC mechanism, with respect to WIP were expected since this mechanism caps WIP at approximately 7,200 hours (1,200 hours per work center) contrasting the WLC mechanism that capped WIP at 16,500 hours for the entire shop.

Table 5.6 Main Experiment TPCP for WIP at Low Variability

| | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | 2.406 | 2.871 | 18.370 | 20.410 | 20.542 |
| WLCSIMSET1 | 2.406 | | -0.465 | -15.964 | -18.004 | -18.136 |
| WLCSIMSET2 | 2.871 | -0.465 | | 15.499 | 17.539 | 17.671 |
| WLCMCFCFS | 18.370 | -15.964 | 15.499 | | 2.040 | 2.172 |
| WLCMCSIMSET1 | 20.410 | -18.004 | 17.539 | 2.040 | | 0.132 |
| WLCMCSIMSET2 | 20.542 | -18.136 | 17.671 | 2.172 | 0.132 | |

As in the low variability case, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments yield the most favorable results with respect to WIP under high variability conditions. Again, the results of the TPCP at a .05 level (Table 5.7), indicated that that both treatments yield statistically significant differences when compared to the other four treatments. However, an overall best treatment could not be selected between WLCMCSIMSET1 and WLCMCSIMSET2 since the TPCP results indicated that there was no statistically significant difference between these treatments.

Table 5.7 Main Experiment TPCP for WIP at High Variability

| | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | 1.6670 | 2.3540 | 18.5520 | 20.3440 | 20.4840 |
| WLCSIMSET1 | 1.6670 | | 0.6870 | 16.8850 | 18.6770 | 18.8170 |
| WLCSIMSET2 | 2.3540 | 0.6870 | | 16.1980 | 17.9900 | 18.1300 |
| WLCMCFCFS | 18.5520 | 16.8850 | 16.1980 | | 1.7920 | 1.9320 |
| WLCMCSIMSET1 | 20.3440 | 18.6770 | 17.9900 | 1.7920 | | 0.1400 |
| WLCMCSIMSET2 | 20.4840 | 18.8170 | 18.1300 | 1.9320 | 0.1400 | |

Under both low and high variability conditions the WLCMC order release mechanism yielded superior results in comparison to the WLC order release mechanism. The significant reduction of WIP experienced under the WLCMC order release mechanism is attributed to the WIP caps established for the two mechanisms. With the WLCMC mechanism, the WIP cap is set at 1,200 per machine center resulting in a total of 7,200 for the entire shop, when each work center is fully loaded. Under the WLC scheme, the WIP cap is set at 16,500. Thus, these differences naturally lead to different levels of average WIP in the shop. Again, the superior results of the WLCMC mechanism is attributed to its refined approach (limiting work center queues) of workload control, which results in more stable and equitable workloads among the individual work centers.

Again, the dispatching mechanism (FCFS) that ignored setup sequence dependency produced the most unfavorable results, due to FCFS's inability to combine orders, thus allowing excessive queues to form. Again, the difference between the SIMSET1 and SIMSET2 dispatching mechanisms proved statistically insignificant. Both mechanisms also yielded similar variances.

5.3.7.3 Cost 1:20

Figure 5.1 presents the unit cost breakdown for the main experiments, under low variability conditions and Figure 5.2 presents the unit cost breakdown for the main experiment under high variability conditions. There are four cost components that comprise the total unit cost:

1. Production cost.
2. Late cost.
3. WIP cost.
4. Early cost.

In the main experiments (at both levels of variability tested), production cost accounted for approximately 96% of the total cost , while tardy costs accounted for 3% of the total cost, and WIP and early cost accounted for less than 1% of the total cost. This study represents the first sequence dependent setup research to consider production cost. Production costs must be considered when evaluating cost since setup dependency is a significant production cost driver and clearly represents a dispatching mechanism's effectiveness with respect to unit cost.

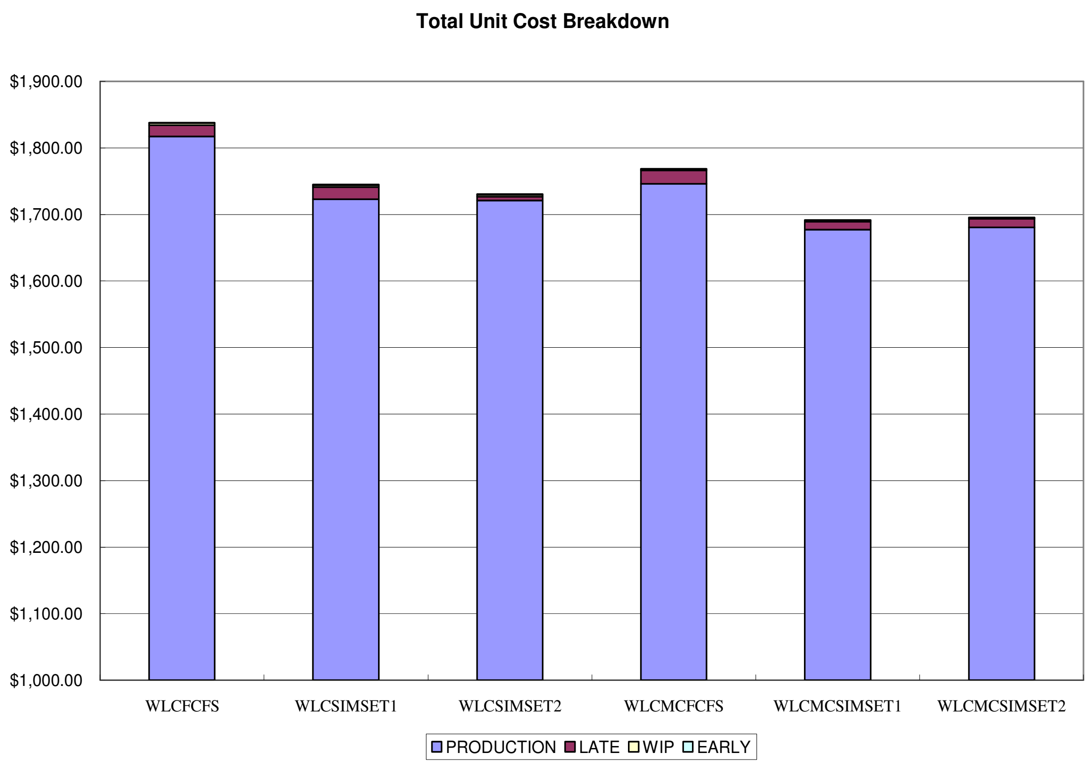


Figure 5.1 Components of total unit cost, main experiment, low variability.

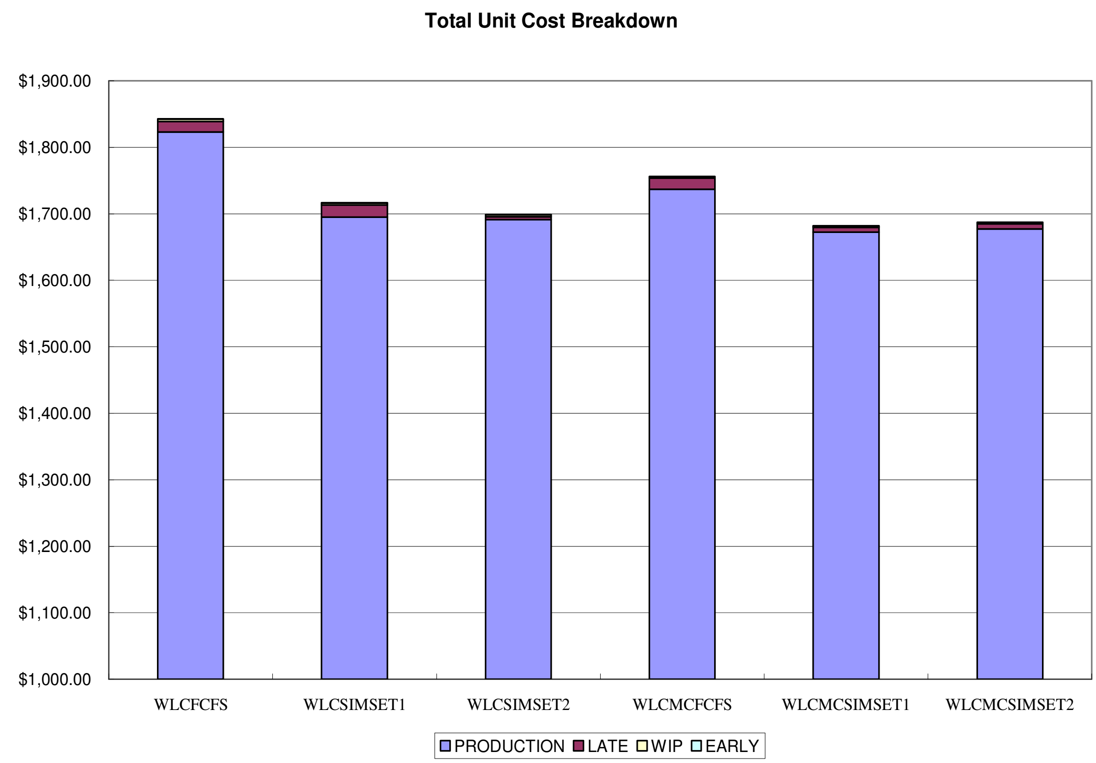


Figure 5.2 Components of total unit cost, main experiment, high variability.

The three-way ANOVA test (Table 5.8), demonstrates that each of the three main effects (order release mechanism, dispatching mechanism, and variability) are significant with respect to the cost performance variable. The dispatching mechanism effect accounts for a substantial amount of the total sum of squares, which is consistent with the work of Kim and Bobrowski (1995). Table 5.8 also indicates that a significant interaction exists between the order release and dispatching mechanism factors. This demonstrates that the cost performance of orders can be greatly improved by the selection of an appropriate dispatching mechanism and that release mechanisms play a significant role with respect to cost performance. Additionally, process variability and the interactive effects of order release and dispatching mechanisms impact cost performance to a lesser extent.

Table 5.8 Main Experiment Three Factor ANOVA Results for Cost, Low Variability

| *Variation Source* | *SS* | *df* | *MS* | *F** | *P-Value* |
|---|---|---|---|---|---|
| Between Treatments | 164200.58 | 11 | 14927.3253 | | |
| Factor 1 (Release) | 18300.03 | 1 | 18300.0273 | 37.77 | 0.00000 |
| Factor 2 (Dispatching) | 131665.47 | 2 | 65832.7344 | 271.77 | 0.00000 |
| Factor 3 (Variability) | 3828.28 | 1 | 3828.2783 | 7.90 | 0.00587 |
| 12 Interactions | 7760.65 | 2 | 3880.3247 | 16.02 | 0.00000 |
| 13 Interactions | 486.48 | 1 | 486.4831 | 1.00 | 0.31855 |
| 23 Interactions | 966.89 | 2 | 483.4445 | 2.00 | 0.14089 |
| 123 Interactions | 1192.78 | 2 | 596.3909 | 2.46 | 0.09004 |
| Error | 52322.89 | 108 | 484.4712 | | |
| Total | 216523.46 | 119 | | | |

The WLCSIMSET2, WLCMCSIMSET1, and WLCMCSIMSET2 treatments yielded the most favorable results with respect to cost (Table 5.1) for the low variability condition. The results of the TPCP at a .05 level (Table 5.9), indicated that that there was not a statistically significant difference among these treatments. The performance of the WLCSIMSET2 treatment was unexpected. Examination of the components of total cost revealed that although production cost for the WLCSIMSET2 treatment was higher than that of the WLCMCSIMSET1 and WLCMCSIMSET2 treatments, its tardy cost component was significantly less. The average tardiness of jobs for the WLCSIMSET2 treatment was approximately 50% less than the average tardiness for the WLCMCSIMSET1 and WLCMCSIMSET2 treatments respectively. Analysis of all queues in the production system revealed that although work center queues were smaller for the WLCMCSIMSET1 and WLCMCSIMSET2 treatments, compared to the

WLCSIMSET2 treatment, the time spent waiting in the pre-shop for the WLCMCSIMSET1 and WLCMCSIMSET2 treatments was approximately 60% greater than the WLCSIMSET2 treatment. This is the result of the difference in WIP caps between the WLC and WLCMC mechanisms. As noted above, WIP is capped at approximately 7,200 hours (1,200 hours per work center) for the WLCMC mechanism and 16,500 hours for the WLC mechanism, thus pre-shop pool queues for the WLC mechanism will be significantly smaller.

Table 5.9 Main Experiment TPCP for Cost, Low Variability

| | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | 126.000 | 143.680 | 86.670 | 160.460 | 155.480 |
| WLCSIMSET1 | 126.000 | | -17.680 | 39.330 | -34.460 | -29.480 |
| WLCSIMSET2 | 143.680 | -17.680 | | -57.010 | 16.780 | 11.800 |
| WLCMCFCFS | 86.670 | 39.330 | -57.010 | | 73.790 | 68.810 |
| WLCMCSIMSET1 | 160.460 | -34.460 | 16.780 | 73.790 | | -4.980 |
| WLCMCSIMSET2 | 155.480 | -29.480 | 11.800 | 68.810 | -4.980 | |

The WLCMCSIMSET1 and WLCMCSIMSET2 treatments yielded the most favorable results with respect to cost (Table 5.1) for the high variability condition. The results of the TPCP at a .05 level (Table 5.10), indicate that that there was not a statistically significant difference between these treatments. The performance of the WLCSIMSET2 treatment deteriorated slightly under the high variability condition, resulting in a significant increase in production cost, with respect to the WLCMCSIMSET1 and WLCMCSIMSET2 treatments. This increase in production cost resulted from the WLC methodology's sensitivity to system nervousness. The system nervousness is the result of the extreme values for processing time experienced under high variability conditions, which resulted in a degradation to throughput. However, the average tardy costs of the WLCSIMSET2 treatment remained materially less than that of the WLCMCSIMSET1 and WLCMCSIMSET2 treatments, but not enough to offset the increased production cost.

Table 5.10 Main Experiment TPCP for Cost, High Variability

| | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | 92.970 | 107.490 | 69.340 | 146.400 | 142.170 |
| WLCSIMSET1 | 92.9700 | | 14.520 | -23.630 | 53.430 | 49.200 |
| WLCSIMSET2 | 107.4900 | 14.520 | | -38.150 | 38.910 | 34.680 |
| WLCMCFCFS | 69.3400 | -23.630 | -38.150 | | 77.060 | 72.830 |
| WLCMCSIMSET1 | 146.4000 | 53.430 | 38.910 | 77.060 | | -4.230 |
| WLCMCSIMSET2 | 142.1700 | 49.200 | 34.680 | 72.830 | -4.230 | |

## 5.4 Sensitivity Experiments

Experiments were conducted to assess the impact of increased utilization on the effectiveness of the order release and dispatching mechanisms examined in the main experiments. Additionally, sensitivity to cost structure was analyzed. The sensitivity experiments were identical to the main experiments with respect to the model characteristics and processes listed below:

- Model planning factors.
- Statistical characteristics.
- Order release mechanisms.
- Dispatching mechanisms.
- Due date assignment.
- Performance measures.
- Data collection.

The sensitivity experiments differed from the main experiments with respect to utilization (two levels tested), process variability (one level tested, low variability), ratio of late penalty cost to inventory holding cost, and null hypothesis testing objectives.

*5.4.1 Utilization*

In order to examine the order release and dispatching mechanisms sensitivity to a higher level of utilization, the arrival rate of orders to the pre-shop pool was examined at two levels. Moderate utilization was based on jobs arriving according to a Poisson process at a mean rate of 1.0526, while the high utilization case was based on jobs arriving according to a Poisson process at a mean rate of 1.1760 jobs per hour, resulting in utilization rates of 87.5% and 95.0% respectively.

*5.4.2 Ratio of Late Penalty Cost to Inventory Holding Cost*

The ratio of late penalty cost to inventory holding cost was examined at two ratios, 20 to 1 and 10 to 1. This analysis was conducted to assess the impact of significantly different estimating parameters for the late penalty cost estimator. These costs were assessed at the low variability level and the low and high utilization levels.

*5.4.3 Null Hypothesis Testing*

The simulation experiments demonstrate the significance of each experimental variable and the potential interactive effects of experimental variables. The following null hypothesis were tested:

H1: Choice of order release mechanism has no significant impact on the dependent performance variables.

H2: Choice of dispatching mechanism has no significant impact on the dependent performance variables.

H3: Interactive effect between order release mechanism and dispatching mechanism has no significant impact on the dependent performance variables.

H4: Interactive effect between order release mechanism and shop utilization has no significant impact on the dependent performance variables.

H5: Interactive effect between dispatching mechanism and shop utilization has no significant impact on the dependent performance variables.

*5.4.4 Results*

A summary of the sensitivity experiments performance results is presented in Table 5.11. Paragraphs 5.4.4.1 through 5.4.4.3 contain the detailed analysis of results for each of the three system performance measures. As in the main experiments, the detailed analysis (for each performance measure) included Analysis of Variance and Tukey's Paired Comparison Procedure. ANOVA was performed in order to test the null hypotheses defined in paragraph 5.4.3, while TPCP (set for 95% confidence) was used to determine statistically significant differences in performance measures between experimental treatments. ANOVA was conducted utilizing Statistica (1995). Shaded cells in the TPCP tables indicate that the difference between treatments is not statistically significant.

Table 5.11 Sensitivity Experiment Performance Results Summary

| | **% On Time** | | **WIP** | | **Unit cost 20:1** | |
|---|---|---|---|---|---|---|
| **Treatment** | **Mean** | **Variance** | **Mean** | **Variance** | **Mean** | **Variance** |
| WLCFCFSHU | 0.5497 | 0.00032 | 41.34 | 2.06 | $ 1,785.28 | 162.73 |
| WLCFCFSLU | 0.5975 | 0.00049 | 39.88 | 0.15 | $ 1,842.89 | 105.95 |
| WLCSIMSET1HU | 0.6617 | 0.00003 | 38.78 | 0.70 | $ 1,678.89 | 152.95 |
| WLCSIMSET1LU | 0.7129 | 0.00135 | 37.47 | 3.06 | $ 1,716.89 | 444.71 |
| WLCSIMSET2HU | 0.7288 | 0.00004 | 39.62 | 0.13 | $ 1,667.92 | 77.10 |
| WLCSIMSET2LU | 0.7638 | 0.00057 | 37.01 | 3.01 | $ 1,699.21 | 339.20 |
| WLCMCFCFSHU | 0.7038 | 0.00619 | 24.07 | 0.20 | $ 1,706.18 | 118.76 |
| WLCMCFCFSLU | 0.7676 | 0.00023 | 21.51 | 0.61 | $ 1,756.22 | 321.79 |
| WLCMCSIMSET1HU | 0.7826 | 0.00006 | 22.06 | 0.31 | $ 1,623.43 | 60.09 |
| WLCMCSIMSET1LU | 0.8600 | 0.00006 | 19.47 | 0.53 | $ 1,682.43 | 82.51 |
| WLCMCSIMSET2HU | 0.7444 | 0.00024 | 22.74 | 0.22 | $ 1,624.20 | 81.02 |
| WLCMCSIMSET2LU | 0.8560 | 0.00008 | 19.34 | 0.53 | $ 1,687.41 | 91.05 |

5.3.7.3 On Time orders

The three-way ANOVA test (Table 5.12), demonstrates that the main effect of the order release mechanism is significant with respect to the percentage of jobs completing on time. Again, these result contradict the work of Kim and Bobrowski (1995) who concluded that the order release mechanism was insignificant at the 0.05 level. The ANOVA also indicates that main effects for dispatching and utilization are also significant at the .05 level. The results regarding dispatching significance are consistent with the work of Kim and Bobrowski (1995). Additionally, Table 5.12 indicates that a significant interaction exists between the order release and dispatching mechanism factors and the order release and utilization factors. Thus, changes in utilization may significantly impact the performance of order release mechanisms. This demonstrates that the on time performance of orders can be improved by the selection of an appropriate order releasing mechanism, when utilization is high.

Table 5.12 Sensitivity Experiment Three Factor ANOVA Results On Time Orders

| *Variation Source* | *SS* | *df* | *MS* | *F** | *P-Value* |
|---|---|---|---|---|---|
| Between Treatments | 0.7421 | 11 | 0.067466 | | |
| Factor 1 (Release) | 0.4084 | 1 | 0.40838 | 471.49 | 0.00000 |
| Factor 2 (Dispatching) | 0.1624 | 2 | 0.081208 | 187.51 | 0.00000 |
| Factor 3 (Utilization) | 0.1246 | 1 | 0.12465 | 143.91 | 0.00000 |
| 12 Interactions | 0.0315 | 2 | 0.015747 | 36.36 | 0.00000 |
| 13 Interactions | 0.0118 | 1 | 0.011778 | 13.60 | 0.00036 |
| 23 Interactions | 0.0008 | 2 | 0.000384 | 0.89 | 0.41488 |
| 123 Interactions | 0.0026 | 2 | 0.001322 | 3.05 | 0.05137 |
| Error | 0.0935 | 108 | 0.0009 | | |
| Total | 0.8357 | 119 | | | |

The TPCP is not presented for the low utilization treatment, since the results of this treatment are presented in Table 5.3. As described in paragraph 5.3.7.1, at low utilization and low variability, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments yield the most favorable results with respect to orders completed on time and the results of the TPCP at a .05 level (Table 5.3), indicate that that both treatments yield statistically significant differences when compared to the other four treatments. However, an overall best treatment could not be selected between WLCMCSIMSET1 and WLCMCSIMSET2 since the TPCP results indicated that there was no statistically significant difference between these treatments.

Under high utilization conditions, the WLCMCSIMSET1 treatment yielded the most favorable mean with respect to jobs completed on time. However, based on the TPCP results presented in Table 5.13, there was not a statistically significant difference between the WLCMCSIMSET1 and WLCMCSIMSET2 treatments, even though the mean percentage of on time orders for the WLCMCSIMSET1 treatment was nearly 4% greater than that of the WLCMCSIMSET2 treatment. Although the performance difference is not statistically significant, the mean performance difference may be attributed to the increased system nervousness caused by the SIMSET2 dispatching mechanism. At high utilization, the production system is operating nearly at its limit, thus any disruptions (such as expediting) will cause system performance to degrade. Examination of the pre-shop pool indicated that jobs were queuing longer in the WLCMCSIMSET2 pool, in comparison to the jobs queuing in the WLCMCSIMSET1 pre-shop pool. This indicates that shop flow times increased under the SIMSET2 dispatching mechanism, as the result of an increased number of setups resulting from disruption caused by expediting.

Table 5.13 Sensitivity Experiment TPCP for On Time Orders at High Utilization

| **OTHU** | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | -0.1120 | -0.1791 | -0.1541 | -0.2329 | -0.1947 |
| WLCSIMSET1 | -0.1120 | | 0.0671 | 0.0421 | 0.1209 | 0.0827 |
| WLCSIMSET2 | -0.1791 | 0.0671 | | 0.0250 | -0.0538 | -0.0156 |
| WLCMCFCFS | -0.1541 | 0.0421 | 0.0250 | | -0.0789 | -0.0406 |
| WLCMCSIMSET1 | -0.2329 | 0.1209 | -0.0538 | -0.0789 | | 0.0383 |
| WLCMCSIMSET2 | -0.1947 | 0.0827 | -0.0156 | -0.0406 | 0.0383 | |

5.3.7.3 WIP

Similar to the ANOVA for the on time delivery performance metric, the three-way ANOVA test (Table 5.14), demonstrates that the main effect of the order release mechanism is significant with respect to the average WIP in the shop. Again, these results contradict the work of Kim and Bobrowski (1995) who concluded that the order release mechanism was insignificant at the 0.05 level. The ANOVA also indicates that main effects for dispatching and utilization are also significant at the .05 level. The results regarding dispatching significance are consistent with the work of Kim and Bobrowski (1995). Additionally, Table 5.14 indicates that a significant interaction exists between the order release and utilization factors. Thus, changes in utilization may significantly impact the performance of order release mechanisms. This demonstrates that the WIP performance can be improved by the selection of an appropriate order releasing mechanism.

Table 5.14  Sensitivity Experiment Three Factor ANOVA Results for WIP

| *Variation Source* | *SS* | *df* | *MS* | *F** | *P-Value* |
|---|---|---|---|---|---|
| Between Treatments | 9408.51 | 11 | 855.32 | | |
| Factor 1 (Release) | 9172.11 | 1 | 9172.11 | 6995.83 | 0.00000 |
| Factor 2 (Dispatching) | 61.42 | 2 | 30.71 | 46.85 | 0.00000 |
| Factor 3 (Utilization) | 162.03 | 1 | 162.03 | 123.58 | 0.00000 |
| 12 Interactions | 0.87 | 2 | 0.43 | 0.66 | 0.51768 |
| 13 Interactions | 8.42 | 1 | 8.42 | 6.42 | 0.01272 |
| 23 Interactions | 3.52 | 2 | 1.76 | 2.69 | 0.07267 |
| 123 Interactions | 0.15 | 2 | 0.07 | 0.11 | 0.89304 |
| Error | 141.60 | 108 | 1.31 | | |
| Total | 9550.11 | 119 | | | |

The TPCP is not presented for the low utilization treatment, since the results of this treatment are presented in Table 5.6. As described in paragraph 5.3.7.2, at low utilization and low variability, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments yield the most favorable results with respect to WIP and the results of the TPCP at a .05 level (Table 5.6), indicate that that both treatments yield statistically significant differences when compared to the other four treatments. However, an overall best treatment could not be selected between WLCMCSIMSET1 and WLCMCSIMSET2 since the TPCP results indicated that there was no statistically significant difference between these treatments.

Similarly, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments yield the most favorable results with respect to WIP under high utilization conditions. The results of the TPCP at a .05 level (Table 5.15), indicated that that both treatments yield statistically significant differences when compared to the other four treatments. However, an overall best treatment could not be selected between WLCMCSIMSET1 and WLCMCSIMSET2 since the TPCP results indicated that there was no statistically significant difference between these treatments. Since the WLCMC mechanism caps WIP at the work center level, no significant differences were expected between the WLCMCSIMSET1 and WLCMCSIMSET2 treatments with respect to WIP.

Table 5.15 Sensitivity Experiment TPCP for WIP at High Utilization

| | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | 2.5560 | 1.7240 | 17.2730 | 19.2780 | 18.5960 |
| WLCSIMSET1 | 2.5560 | | 0.8320 | -14.7170 | -16.7220 | -16.0400 |
| WLCSIMSET2 | 1.7240 | 0.8320 | | 15.5490 | 17.5540 | 16.8720 |
| WLCMCFCFS | 17.2730 | -14.7170 | 15.5490 | | 2.0050 | 1.3230 |
| WLCMCSIMSET1 | 19.2780 | -16.7220 | 17.5540 | 2.0050 | | -0.6820 |
| WLCMCSIMSET2 | 18.5960 | -16.0400 | 16.8720 | 1.3230 | -0.6820 | |

5.3.7.3 Cost 1:20

The three-way ANOVA test (Table 5.16), demonstrates that each of the three main effects (order release mechanism, dispatching mechanism, and variability) are significant with respect to the cost performance variable. As was the case in the main experiments, the dispatching mechanism effect accounts for a substantial amount of the total sum of squares, which is consistent with the work of Kim and Bobrowski (1995). Table 5.16. also indicates that significant interactions also exist between the order release and dispatching mechanism factors and the order release and utilization factors. This suggests that the cost performance of orders are impacted by utilization and can be greatly improved by the selection of an appropriate dispatching and order release mechanism.

Table 5.16 Sensitivity Experiment Three Factor ANOVA Results for Cost

| *Variation Source* | *SS* | *df* | *MS* | *F** | *P-Value* |
|---|---|---|---|---|---|
| Between Treatments | 392856.40 | 11 | 35714.22 | | |
| Factor 1 (Release) | 37057.08 | 1 | 37057.08 | 74.14 | 0.00000 |
| Factor 2 (Dispatching) | 136726.44 | 2 | 68363.22 | 273.54 | 0.00000 |
| Factor 3 (Utilization) | 204004.02 | 1 | 204004.02 | 408.14 | 0.00000 |
| 12 Interactions | 6348.41 | 2 | 3174.21 | 12.70 | 0.00001 |
| 13 Interactions | 6285.47 | 1 | 6285.47 | 12.57 | 0.00058 |
| 23 Interactions | 886.67 | 2 | 443.34 | 1.77 | 0.17458 |
| 123 Interactions | 1548.32 | 2 | 774.16 | 3.10 | 0.04919 |
| Error | 53983.04 | 108 | 499.84 | | |
| Total | 446839.44 | 119 | | | |

As in the main experiments, the WLCSIMSET2, WLCMCSIMSET1, and WLCMCSIMSET2 treatments yielded the most favorable results with respect to cost (Table 5.11) for the low utilization condition. The results of the TPCP at a .05 level (Table 5.9), indicate that that there was not a statistically significant difference among these treatments. As previously discussed, the performance of the WLCSIMSET2 treatment was unexpected. Examination of the components of total cost revealed that although production cost for the WLCSIMSET2 treatment was higher than that of the WLCMCSIMSET1 and WLCMCSIMSET2 treatments, its tardy cost component was significantly less. The average tardiness of jobs for the WLCSIMSET2 treatment was approximately 50% less than the average tardiness for the WLCMCSIMSET1 and

WLCMCSIMSET2 treatments respectively. Analysis of all queues in the production system revealed that although work center queues were smaller for the WLCMCSIMSET1 and WLCMCSIMSET2 treatments, compared to the WLCSIMSET2 treatment, the time spent waiting in the pre-shop for the WLCMCSIMSET1 and WLCMCSIMSET2 treatments was approximately 50% greater than the WLCSIMSET2 treatment. This is the result of the difference in WIP caps between the WLC and WLCMC mechanisms. As previously discussed, WIP is capped at approximately 7,200 hours (1,200 hours per work center) for the WLCMC mechanism and 16,500 hours for the WLC mechanism, thus pre-shop pool queues for the WLC mechanism will be significantly smaller.

The WLCMCSIMSET1 and WLCMCSIMSET2 treatments yielded the most favorable results with respect to cost (Table 4.) for the high utilization condition. The results of the TPCP at a .05 level (Table 5.17), indicate that that there was not a statistically significant difference between these treatments. The performance of the WLCSIMSET2 treatment deteriorated slightly under the high variability condition, resulting in a significant increase in production cost, with respect to the WLCMCSIMSET1 and WLCMCSIMSET2 treatments. This increase in production cost resulted from the WLC methodology's sensitivity to system nervousness. The system nervousness is the result of the high utilization condition, which resulted in throughput degradation. However, the average tardy costs for the WLCSIMSET2 treatment remained significantly less than that of the WLCMCSIMSET1 and WLCMCSIMSET2 treatments, but not enough to offset the increased production cost.

Table 5.17 Sensitivity Experiment TPCP for Cost at High Utilization

| | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | 106.39 | 117.36 | 79.10 | 161.85 | 161.08 |
| WLCSIMSET1 | 106.39 | | -10.97 | 27.29 | -55.46 | -54.69 |
| WLCSIMSET2 | 117.36 | -10.97 | | -38.26 | 44.49 | 43.72 |
| WLCMCFCFS | 79.10 | 27.29 | -38.26 | | 82.75 | 81.98 |
| WLCMCSIMSET1 | 161.85 | -55.46 | 44.49 | 82.75 | | -0.77 |
| WLCMCSIMSET2 | 161.08 | -54.69 | 43.72 | 81.98 | -0.77 | |

5.3.7.3 Cost 1:10

In the sensitivity analysis of cost the impact of a 1:10 ratio of inventory holding to late penalty cost was examined. Researchers including Kim and Bobrowski (1995) and Ragatz and Mabert (1988) examined both the 1:10 and a:20 ratios. Table 5.18 summarizes the resultant cost when the ratio of inventory holding to late penalty cost is set at a 1:10 ratio.

Table 5.18. Sensitivity Experiment, 1:10 Inventory Holding to Late Penalty Cost

| | Low Utilization | High Utilization |
|---|---|---|
| WLCFCFS | $ 1,834.83 | $ 1,776.69 |
| WLCSIMSET1 | $ 1,707.83 | $ 1,670.86 |
| WLCSIMSET2 | $ 1,696.98 | $ 1,665.41 |
| WLCMCFCFS | $ 1,747.73 | $ 1,689.27 |
| WLCMCSIMSET1 | $ 1,678.58 | $ 1,616.36 |
| WLCMCSIMSET2 | $ 1,683.54 | $ 1,617.06 |

At low utilization and a 1:10 ratio of inventory holding to late penalty cost, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments outperformed all other treatments. This contrasts the results where the 1:20 ratio of inventory holding to late penalty cost was used. At the 1:20 ratio the WLCSIMSET2 treatment was statistically indifferent from the WLCMCSIMSET1 and WLCMCSIMSET2 treatments. As discussed in paragraph 5.3.7.3., although production cost for the WLCSIMSET2 treatment was higher than that of the WLCMCSIMSET1 and WLCMCSIMSET2 treatments, its tardy cost component was significantly less. The average tardiness of jobs for the WLCSIMSET2 treatment was approximately 50% less than the average tardiness for the WLCMCSIMSET1 and WLCMCSIMSET2 treatments respectively. Thus, as the ratio of inventory holding to late penalty cost increases beyond 1:20, the cost performance of the WLCSIMSET2 treatment approaches and surpasses that of the WLCMCSIMSET1 and WLCMCSIMSET2 treatments.

Table 5.19 Sensitivity Experiment TPCP for Cost at Low Utilization

| SELU 10:1 | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | 93.7400 | 101.8500 | 70.9700 | 143.8800 | 140.1500 |
| WLCSIMSET1 | 93.7400 | | 8.1100 | -22.7700 | 50.1400 | 46.4100 |
| WLCSIMSET2 | 101.8500 | 8.1100 | | -30.8800 | 42.0300 | 38.3000 |
| WLCMCFCFS | 70.9700 | -22.7700 | -30.8800 | | 72.9100 | 69.1800 |
| WLCMCSIMSET1 | 143.8800 | 50.1400 | 42.0300 | 72.9100 | | -3.7300 |
| WLCMCSIMSET2 | 140.1500 | 46.4100 | 38.3000 | 69.1800 | -3.7300 | |

At high utilization and a 1:10 ratio of inventory holding to late penalty cost, the WLCMCSIMSET1 and WLCMCSIMSET2 treatments outperformed all other treatments. These results are consistent with the results where the 1:20 ratio of inventory holding to late penalty cost was used. The increase in utilization degrades the performance of the WLCSIMSET2 treatment, since system nervousness increases significantly under these shop conditions, resulting in significant erosion with respect to the effectiveness of the WLCSIMSET2 treatment. This degradation in performance is similar to that experienced in the main experiments when variability was increased, which in turn increased system nervousness and consequently resulted in performance deterioration of the WLCSIMSET2 treatment.

Table 5.20 Sensitivity Experiment TPCP for Cost at High Utilization

| SEHU 10:1 | WLCFCFS | WLCSIMSET1 | WLCSIMSET2 | WLCMCFCFS | WLCMCSIMSET1 | WLCMCSIMSET2 |
|---|---|---|---|---|---|---|
| WLCFCFS | | 105.8300 | 111.2800 | 87.4200 | 160.3300 | 159.6300 |
| WLCSIMSET1 | 105.8300 | | -5.4500 | 18.4100 | -54.5000 | -53.8000 |
| WLCSIMSET2 | 111.2800 | -5.4500 | | -23.860 | 49.0500 | 48.3500 |
| WLCMCFCFS | 87.4200 | 18.4100 | -23.8600 | | 72.9100 | 72.2100 |
| WLCMCSIMSET1 | 160.3300 | -54.5000 | 49.0500 | 72.9100 | | -0.7000 |
| WLCMCSIMSET2 | 159.6300 | -53.8000 | 48.3500 | 72.2100 | -0.7000 | |

# CHAPTER 6

# PHASE TWO SIMULATION MODELING

Phase two of the simulation process is based on an operational plant layout in the metal processing industry. The phase two simulation model represents a significant departure from most simulation based research efforts in that capacities of work centers are not necessarily balanced, and job routings are not random with equal probability for each work center to be visited in each operation of a production order. Phase two modeling consists of two distinct simulation activities:

1. Planning factor and statistical characteristics development.
2. Experimentation.

The objective of this simulation phase is to compare the material flow strategy identified as best performing (in the phase one simulation effort), to the material flow control strategy utilized in practice in the machine shop modeled here and from which the operational data originated.

## 6.1 Model Development, Planning Factors, and Statistical Characteristics

The phase two model consists of nine machine centers and an inspection station. Two of the ten machine centers contain two machines and one of the machine centers contains three machines. Heat treat and inspection are required for the processing of all parts. The heat treat process is modeled as a batch machine and the inspection process is modeled as a single machine in the simulation model. The machine centers process 21 different part numbers.

The job shop operates five days a week, eight hours per day. During each eight hour shift all necessary labor and machines are available, machine breakdowns and maintenance are not considered. The model does not contain any assembly operations, all orders consist of sequential operations. Capacity is assumed to be passive in all experiments and outside the control of the order release strategy.

*6.1.1 Job Arrivals*

Jobs arrivals are based on the monthly demand stream for the 21 part numbers modeled in the study. Jobs are modeled as arriving according to a Poisson process at a mean rate of approximately 21 batches per month. All jobs are populated with attributes defining the jobs' setup type, setup time, run time, and due date. As orders arrive to the pre-shop, they queue according to the CR sequencing rule. In the pre-shop pool, the order release mechanism determines which jobs and when order release to the shop should take place.

*6.1.2 Job Routings*

Job routings are fixed, with a minimum of nine operations per job and a maximum of sixteen operations per job. There is a dominant flow in the shop. Most part numbers are processed in the following sequence: CNC lathe, gear hobber, spindle deburr, heat treat, interior grind, exterior grinder, speed lathe, kapp gear grinder, spindle deburr, gear hone, and inspection. There are return visits to some machine centers. These routings and the order arrival rates result in a system that does not have a stationary bottleneck. In practice the bottleneck wonders between the kapp gear grinder, interior grinder, and exterior grinder.

*6.1.3 Job Run and Setup Times*

Run and setup times are constant for each of the 21 parts simulated in the phase two model. The setup and run times were obtained from simulation data utilized by the machine shop under study. An analysis of part number routings resulted in the establishment of 16 different setup families, where four families have two members each and one family has three members. The model setup logic results in zero hours setup when members of the same family are processed consecutively. The setup time for jobs following others of a different family are taken from a predefined setup matrix. The setup matrix defines the setup time for every combination of job types.

*6.1.4 Job Due Date Setting*

As in the phase one simulation effort, the due date for each job is based on the TWK methodology. The TWK methodology is based on the expected setup time of a job, the total estimated processing time of a job, and a planning factor allowance that accounts for queue delays.

The planning factor allowance was calculated so that approximately 40% of orders would be tardy when immediate release and FCFS dispatching were utilized. This resulted in a planning factor of 15.

## 6.2 Main Experiments

The basic model used in the main experiments is described in paragraph 6.1. The model planning factors, statistical characteristics, and due date setting methodology are unchanged. The objective of the main experiment is to compare the performance of the best performing material control strategy identified in the phase one experimentation process with the control strategy utilized in the machine shop under study.

### *6.2.1 Material Flow Control Strategies*

Two order release mechanisms were used in the simulation experiments, immediate release and WLCMC. With both mechanisms, orders arrive to the production system over time. With the immediate release mechanism, orders are released immediately to the shop floor without any consideration to the status of the shop. However, with the WLCMC release mechanism orders are not released to the shop floor immediately, rather they are prioritized in the pre-shop pool according to the critical ratio sequencing rule. Throughout the operating hours of the shop, beginning with the highest priority job in the pre-shop pool, the release decision about the currently considered job is considered. In the case of releasing orders, the shop's workload is updated accordingly. Otherwise the order is retained in the pre-shop pool and the next order in the queue is considered for release. As in the phase one simulation model, the WLCMC mechanism considers the job's processing time and the individual loads at each work center. Order release to the shop floor occurs if the load at each work center requiring input control plus the job's estimated processing time at each of these work centers is below the pre-established work center shop loads. The WLCMC mechanism releases orders to the shop floor one at a time, searching the pre-shop pool queue from the highest priority job on until either all jobs have been released from the pre-shop pool or the load at any single work center reaches its predetermined maximum load limit. The expected setup time was not included in the calculation of the shop load. Simulation experiments were conducted to determine a "near optimal" level of work to be released to each of the potential bottleneck work centers. These experiments resulted in the establishment of work center load limits of 350 hours per work center for the kapp gear grinder, interior grinder and exterior grinder.

As discussed above, the FCFS dispatching rule was used in conjunction with the immediate release mechanism, in order to replicate the material flow control strategy employed in the machine shop under study. The FCFS mechanism simply selects the job from a work center queue that has been in the queue the longest.

The SIMSET1 mechanism was used in conjunction with the WLCMC release mechanism. As was the case in the phase one simulation model, the SIMSET1 mechanism first searches for a job whose setup requirements are identical to the job that has just completed processing. If a job with identical setup requirements is not found, then the job with the highest CR priority is selected for processing next (the queues from which the jobs are selected are order by their critical ratio). As described in paragraph 6.1.3, the setup times are selected from a setup matrix (defines the setup time for any combination of job types) within the simulation model.

### *6.2.2 Performance Measurement*

Three performance measures were collected in the simulation experiments. Measures include the percentage of jobs completed on time, WIP , and total cost. All performance measures represent averages of the 21 part numbers simulated (no attempt was made to analyze performance at the part number level).

As in the phase one experiments, the percentage of orders on time is calculated by dividing the total number of orders completed on time by the total number of jobs completed for the 500 day simulation period and the WIP performance measure (hours of work) is calculated by summing the average WIP accumulated at each work center over the 500 day simulation period.

The total cost performance measure is calculated by summing the average unit production cost, the average inventory cost, and the average unit late penalty costs. The average unit production cost, the average inventory cost, and the average unit late penalty costs where calculated as in the phase one experiments. However, a $128 per hour production rate was utilized in all calculations to replicate the hourly cost of production (including overhead) associated with the facility under study.

### *6.2.3 Null Hypothesis Testing*

Since the objective of the phase two simulation experiments was to compare the existing shop material flow control strategy with the best performing control strategy identified in phase one modeling, the following null hypothesis were tested:

H1: Mean on time percentage of the immediate release and FCFS dispatching mechanism is the same as the mean cost of the WLCMC release and SIMSET1 dispatching mechanism.

H2: Mean WIP of the immediate release and FCFS dispatching mechanism is the same as the mean cost of the WLCMC release and SIMSET1 dispatching mechanism.

H3: Mean cost of the immediate release and FCFS dispatching mechanism is the same as the mean cost of the WLCMC release and SIMSET1 dispatching mechanism.

*6.2.4 Data Collection*

During the planning factor and statistical characteristics development process, data was collected with reference to the steady state of the system. Several simulation runs were made in order to determine the effects of job shop start-up. Performance criteria and utilization levels reached steady state after approximately 150 working (simulated) days. Thus, to be cautious, for each simulation run all statistics were reset to zero and restarted after a warm-up period of 250 days. Statistics were then collected for an additional 500 days of operation.

The experiments were performed using 10 replications of each treatment. Each of the 10 replications used different random number seeds for job arrival rate.

*6.2.5 Results*

A summary of the performance results are presented in Table 6.1. Detailed analyses (for each performance measure) included T-tests to compare group means. T-tests were conducted since the variables are approximately normally distributed. A sample size of 10 observations and an alpha value of .05 was used in all tests. T-tests were conducted utilizing Microsoft Office Excel 2003.

Table 6.1 Main Experiment Performance Results Summary

| **Treatment** | **On Time Mean** | **WIP Mean** | **Cost Mean** |
|---|---|---|---|
| IMMFCFS | 60.8% | 104 Units | $691.61 |
| WLCMCSIMSET1 | 92.2% | 23 Units | $572.91 |

6.2.5.1 On Time Orders

An examination of Table 6.1 reveals that the WLCMCSIMSET1 treatment results in a 34% improvement in delivery performance as compared to the IMMFCFS treatment. These results were expected, since the control strategy investigation phase one simulation experiments indicated that the IMMFCFS treatment was grossly ineffective in comparison to other treatments tested. The immediate release of orders to the shop floor, with disregard to the workload status of shop results in excessively long queues. As queue lengths grow the probability of an order completing on time decreases significantly. Application of the FCFS dispatching mechanism further degrades system performance by failing to recognize similarities in setup that could potentially increase the effective capacity of work centers and improve system throughput. The FCFS dispatching mechanism disregards setup sequence dependency resulting in unfavorable results, due to FCFS's inability to consistently spread setup cost across multiple orders. In contrast the application of the WLCMCSIMSET1 material flow control strategy, regulates queue lengths of those work centers operating at near capacity and increases the effective capacity of work centers by minimizing setups. Effectively, this strategy controls queue lengths and increases effective capacity, resulting in improved throughput, cycle time reduction, and reduced WIP.

Although the FCFS dispatching rule is often employed in practice, informal dispatching decisions are sometimes made, resulting in shared setups.

6.2.5.2 WIP

As was the case for the orders completed on time performance measurement, the WLCMCSIMSET1 material flow control strategy grossly outperformed the IMMFCFS strategy with respect to WIP (refer to Table 6.1). T-test results indicated that there was a statistically significant differences between the means. On average, the WLCSIMSET1 treatment resulted in 78% less WIP than the IMMFCFS treatment. The favorable results for the WLCMC mechanism, with respect to WIP were expected since this mechanism caps WIP at approximately 350 hours per work center, contrasting the IMM mechanism which does not cap WIP, thus permitting WIP to increase exponentially. The superior results of the WLCMC mechanism are attributed to its refined approach to workload control (limiting work center queues), which results in more stable and equitable workloads among the individual work centers.

6.2.5.3 Cost

As with the on time delivery and WIP performance measures, the WLCSIMSET1 material flow control methodology outperformed the IMMFCFS methodology. T-test results indicated that there was a statistically significant differences between the total cost means. Table 6.2 provides a comparison of the cost components that sum to the total cost. This table demonstrates that each cost component (excluding early cost) for the WLCMCSIMSET1 is less than the respective cost component for the IMMFCFS strategy. The shop modeled in the phase two simulation has a total hourly cost of production (including overhead) of $128.

Table 6.2 Comparison of Total Cost Components

| | IMMFCFS | | WLCMCSIMSET1 | |
|---|---|---|---|---|
| Production Cost | $ | 676.74 | $ | 568.17 |
| Early Cost | $ | 0.29 | $ | 0.82 |
| Late Cost | $ | 3.58 | $ | 1.43 |
| WIP Cost | $ | 11.00 | $ | 2.49 |
| Total Cost | $ | 691.61 | $ | 572.91 |

The average production cost for the WLCMCSIMSET1 strategy is approximately 16% less than the cost of the IMMFCFS strategy. Although significantly less WIP accumulates on the shop floor when the WLCMCSIMSET1 strategy is employed, the methodology leverages setup savings by prioritizing dispatching with respect to job family types. Conversely, although the IMMFCFS strategy results in significantly more WIP on the shop floor (hence more opportunities for setup sharing), setup sharing is merely left to chance since orders are processed at work centers on a

FCFS basis. The results presented in Table 6.2 demonstrate that the production cost component is by far the largest component comprising total cost. Thus, from a cost perspective manufacturers must recognize this fact and reassess the manner in which they address order release and dispatching in a sequence dependent setup environment.

Early cost was the only performance measure where IMMFCFS outperformed WLCMCSIMSET1. This outcome is the result of the WLCMCSIMSET1 methodology producing orders ahead of due dates, since orders are pulled forward (with respect to delivery dates) to take advantage of setup sharing. Additionally, the planning factor for the TWK due date rule was derived using the IMMFCFS methodology, thus placing the WLCSIMSET1 strategy at a disadvantage since the due date methodology does not consider the mechanics of this strategy when establishing due dates.

The WLCMCSIMSET1 strategy outperformed the IMMFCFS strategy with respect to both late cost and WIP cost. This was as expected since WIP cost is directly related to the average WIP maintained on the shop floor and late cost is correlated with the percentage of jobs completing on time.

# CHAPTER 7

# CONCLUSIONS AND FUTURE RESEARCH

Presented below is a summary of conclusions based on the results of the literature review presented in Chapter 3 and based on the analysis of the simulation based studies performed in Chapters 5 and 6. Additionally, future research efforts are proposed.

## 7.1 Conclusions

The literature review revealed that the topic of order release in a sequence dependent setup job shop environment has been nearly non-existent, with the publication of only one known article (Kim and Bobrowski 1995) in the past 30 years. The existing literature is also deficient with respect to modeling actual production environments. Of the 45 simulation models identified in Tables 3.1 and 3.2 only five represented actual production environments.

Within the surveyed simulation research, multiple approaches to the order release problem were investigated. These approaches and their respective research methodologies resulted in three significant inconsistencies within the job shop simulation based order release literature. First, several research efforts identified instances where benefits were realized by controlling the entry of jobs to the shop floor (via the order release mechanism), while other research efforts concluded there were no advantages with respect to order release and that immediate release was most effective. Most order release research incorporated multiple approaches to dispatching and evaluated the effectiveness of these mechanisms. Similar to the order release research efforts, the effectiveness of dispatching rules and their relative performance ranking varied significantly amongst researchers. A third area of inconsistency of results amongst researchers deals with the interaction of experimental variables (e.g. order release mechanisms, shop utilization, dispatching mechanism, and shop environment). Effects of interaction among experimental variables varied greatly within the simulation research, for example some researchers concluded that interaction existed between order release and dispatching mechanisms, while others concluded that such interactions were not present. These inconsistencies may be attributed to simulation modeling differences, shop environment differences, interaction among experimental variables, or interpretation of experimental results

Based on the research performed to date, it is evident there is not one best combination of order release rule and dispatching mechanism that can be used in all sequence independent job shop environments. Although the surveyed literature yielded some results that are considered inconsistent, other experimental results contained common findings that warranted further investigation with respect to the sequence dependent setup job shop environment. All but one of these common findings were determined to be applicable to the sequence dependent job shop environment, as tested in the simulation experiments of Chapters 5 and 6. The eight applicable findings are:

1. Current due date information is extremely important.

2. Current work-load information is extremely important.

3. If work flows are more directed, aggregate workloads can be effectively used in release mechanisms.

4. If workloads are more undirected, work center workloads can be effectively used in release mechanisms.

5. Stringent parameter setting for release mechanisms degrades system performance.

6. Load smoothing and reducing system nervousness in general improves overall system performance.

7. Pulling jobs forward results in better performance than delaying release.

8. Where bottlenecks exist, ensure starvation avoidance.

The only finding from the non-sequence dependent setup literature that was not applicable to the sequence dependent setup environment was the use of two queue systems. In the non-sequence dependent setup environment, two queue systems for normal and high priority jobs were effective at improving system performance. However, in the sequence dependent setup simulation (Chapter 5), the two queue system proved ineffective and degraded system performance. In the sequence dependent setup case, the two queue systems increased system nervousness, thus degrading cost, WIP, and on time performance measures.

Null hypothesis testing was conducted in order to determine the impact of release mechanism and dispatching mechanism main effects with respect to the unit cost, delivery performance and shop floor congestion performance measures. Additionally, the interactive effects between order release mechanism and dispatching mechanism, order release mechanism and processing time variability, order release mechanism and shop utilization, dispatching mechanism and processing time variability, and dispatching mechanism and shop utilization, were examined with respect to the performance measures.

Simulation experiments demonstrated the main effects of order release mechanism and dispatching mechanism were significant with respect to each of the three performance measures examined, at both utilization and process variability levels tested. These results contradict the findings of Kim and Bobrowski 1995, who concluded that the main effects of order release mechanisms were insignificant. This difference may be attributed to several factors. First, the controlled release mechanisms simulated by Kim and Bobrowski may have been ineffective. Thus, their results should not be generalized (that is the order release mechanisms tested were ineffective, not order release mechanisms in general). Secondly, Kim and Bobrowski did not evaluate the WLCMC release mechanism, thus excluding a mechanism that has demonstrated its performance effectiveness. Lastly, Kim and Bobrowski's primary performance measure was total cost, which consisted of late penalty cost and early penalty cost, neither of which had an objective basis. The basis for the costs used were not detailed in their study. Additionally, the preliminary simulation experiments described in Chapter 5 demonstrated the IMM release mechanism is totally ineffective. Experiments demonstrated that when IMM is utilized, an explosion in WIP occurs, thus resulting in excessive cost and tardiness.

The Simulation experiments also demonstrated that the interactive effects between order release mechanisms and dispatching mechanisms were significant with respect to delivery and cost performance measures examined, at both utilization and process variability levels tested. This interaction was however insignificant with respect to the WIP performance measurement. This lack of interaction may be attributed to the fact that the ANOVA results indicated that the majority sum of squares are accounted for by the release mechanism, which is as expected since the release mechanism caps the system WIP.

The interactive effects between order release mechanisms and process variability were not significant with respect to any of the performance variables examined. Additionally, the interactive effects between dispatching mechanisms and process variability and dispatching mechanisms and utilization were insignificant. However, interactive effects were significant between order release mechanisms and utilization, for each of the performance variables. This interaction was expected, since changes in utilization are the result of changes in workload which are influenced by order release mechanisms that are based on WIP control.

Based on the simulation results of Chapter 5 and the null hypothesis testing summarized above, effective order release and dispatching mechanisms are critical to the operation of an efficient sequence dependent job shop. These results were validated by the Chapter 6 simulation results of an operational sequence dependent setup shop, where the WLCMCSIMSET1 material flow control strategy grossly outperformed the immediate release FCFS strategy. The WLCMCSIMSET1 strategy was identified as the best performing treatment in the Chapter 5 simulation studies.

Lastly, the experiments performed in Chapters 5 and 6 demonstrated that the largest contributor to total cost is the production cost component, which is significantly impacted by setup sharing. Other costs often cited in order release studies, such as early penalty cost and late penalty cost have a dramatically smaller influence over the total cost measure. Thus, future research efforts must capture the actual cost of production in their measures of cost performance in order to fully realize the impact of setup sharing and provide an unbiased measure of total cost.

Sequence dependent setup and order release research remain important to researchers and remain fertile areas for research with respect to job shop scheduling. Clearly, additional research in these areas is warranted considering the potential benefits that could be reaped by practitioners.

## 7.2 Future Research

There are five research paths that may pursued as a result of the research efforts presented here.

1. Research should address the incorporation of an output control mechanism into the WLCMCSIMSET1 material flow control strategy. Output control must be considered in practice since order release and no amount of dispatching can make an infeasible schedule released by MRP feasible. The output control research should focus on adjusting capacity (via overtime or

offload) such that those jobs that are projected to be delinquent are processed outside of the normal production window. Isolating these jobs should result in a more effective use of capacity.

2. Future research should consider due date setting in the presence of the WLCMCSIMSET1 material flow control strategy. Within this strategy there are two components comprising the due date. First there is the pre-shop pool queue time and secondly the order flow time, once the order has been released from the pre-shop pool. Real-time analysis of shop flow times should be examined for establishing the basis of estimating the due date component associated with shop flow times. The sequencing of orders and projected release times should be examined for the estimation of the due date component associated with pre-shop pool queuing.
3. Consideration should be given to the establishment of a "latest release date" from the pre-shop pool. Such a mechanism may be useful in reducing tardy jobs by allowing jobs to be released to the shop floor, regardless of the WIP caps that have been established at the various work centers.
4. The development of a mechanism that can be integrated into the SIMSET1 dispatching rule that overrides SIMSET1 when production runs of a specific part family tie up a machine for an excessive duration should be considered. When SIMSET1 dispatching is implemented, lengthy runs of a part family are permitted, thus causing orders belonging to other part families to be delayed (potentially resulting in tardiness). Thus, an analysis of batch sizes

should be performed in order to examine the most effective manner of minimizing setups, while minimizing the number of tardy orders.

5. Lastly, the relationship between WIP, utilization, and throughput should be examined so that WIP setting in a workload control environment can be accomplished without the use of simulation.

# APPENDIX A

# PHASE ONE SIMULATION EXPERIMENTS OUTPUT DATA

Table A.1 Main Experiments, WLCFCFSLV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 59.2% | 60.8% | 62.5% | 54.4% | 60.7% |
| PSP Buffer Avg. Size | 525 | 526 | 533 | 598 | 520 |
| Buffer Machine 1 Avg. Size | 8.5 | 5.77 | 7.25 | 7.5 | 5.15 |
| Buffer Machine 2 Avg. Size | 7.35 | 8.25 | 6.22 | 5.21 | 9.42 |
| Buffer Machine 3 Avg. Size | 6.11 | 6.84 | 7.93 | 4.89 | 4.42 |
| Buffer Machine 4 Avg. Size | 7.34 | 6.89 | 5.6 | 9.13 | 5.66 |
| Buffer Machine 5 Avg. Size | 6.15 | 4.85 | 5.4 | 8.22 | 9.08 |
| Buffer Machine 6 Avg. Size | 4.94 | 7.44 | 6.9 | 5.42 | 5.76 |
| WIP Avg. Size | 40 | 40 | 39 | 40 | 39 |
| Machine 1 % Setup | 15.93 | 16.02 | 16.03 | 15.62 | 15.65 |
| Machine 2 % Setup | 15.91 | 16.32 | 16.05 | 16.05 | 15.88 |
| Machine 3 % Setup | 16.16 | 15.93 | 15.91 | 15.18 | 15.66 |
| Machine 4 % Setup | 15.98 | 16.23 | 16 | 16.05 | 16.17 |
| Machine 5 % Setup | 15.81 | 15.59 | 15.76 | 15.83 | 16.42 |
| Machine 6 % Setup | 15.67 | 16.16 | 15.86 | 15.93 | 15.34 |
| Unit Production Cost | $ 1,810.10 | $ 1,829.06 | $ 1,844.33 | $ 1,810.10 | $ 1,832.76 |
| Unit Early Cost | $ 0.35 | $ 0.37 | $ 0.38 | $ 0.33 | $ 0.38 |
| Unit Late Cost | $ 26.88 | $ 8.60 | $ 14.28 | $ 21.15 | $ 19.05 |
| Unit WIP Cost | $ 3.56 | $ 3.53 | $ 3.52 | $ 3.59 | $ 3.52 |
| Total Unit Cost | $ 1,840.89 | $ 1,841.56 | $ 1,862.51 | $ 1,835.16 | $ 1,855.71 |

Table A.2 Main Experiments, WLCFCFSLV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 59.9% | 59.1% | 59.0% | 59.9% | 61.9% |
| PSP Buffer Avg. Size | 546 | 580 | 513 | 585 | 508 |
| Buffer Machine 1 Avg. Size | 8.51 | 5.58 | 5.44 | 4.96 | 6.37 |
| Buffer Machine 2 Avg. Size | 6.41 | 5.69 | 4.34 | 8.77 | 6.87 |
| Buffer Machine 3 Avg. Size | 6.07 | 3.99 | 6.54 | 6.69 | 6.95 |
| Buffer Machine 4 Avg. Size | 6.15 | 7.24 | 5.69 | 7.76 | 6.42 |
| Buffer Machine 5 Avg. Size | 7.19 | 7.68 | 12 | 5.41 | 5.17 |
| Buffer Machine 6 Avg. Size | 5.71 | 9.83 | 5.92 | 6.23 | 7.6 |
| WIP Avg. Size | 40 | 40 | 40 | 40 | 39 |
| Machine 1 % Setup | 16.05 | 16.04 | 16.27 | 15.39 | 15.9 |
| Machine 2 % Setup | 16.68 | 16.15 | 15.65 | 15.78 | 15.82 |
| Machine 3 % Setup | 16.4 | 16 | 16.23 | 15.6 | 15.91 |
| Machine 4 % Setup | 16.09 | 15.95 | 16.21 | 15.59 | 15.86 |
| Machine 5 % Setup | 16.53 | 15.7 | 15.83 | 16.09 | 15.74 |
| Machine 6 % Setup | 15.52 | 16.5 | 15.73 | 16 | 15.8 |
| Unit Production Cost | $ 1,808.32 | $ 1,829.93 | $ 1,821.18 | $ 1,819.31 | $ 1,823.49 |
| Unit Early Cost | $ 0.35 | $ 0.35 | $ 0.36 | $ 0.37 | $ 0.38 |
| Unit Late Cost | $ 16.96 | $ 16.73 | $ 10.42 | $ 15.79 | $ 11.22 |
| Unit WIP Cost | $ 3.51 | $ 3.73 | $ 3.54 | $ 3.57 | $ 3.53 |
| Total Unit Cost | $ 1,829.14 | $ 1,850.75 | $ 1,835.50 | $ 1,839.04 | $ 1,838.62 |

Table A.3 Main Experiments, WLCFCFSHV Treatment, Samples 1 – 5

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 55.5% | 55.2% | 57.2% | 53.1% | 56.3% |
| PSP Buffer Avg. Size | 596 | 606 | 639 | 675 | 588 |
| Buffer Machine 1 Avg. Size | 8.67 | 5.95 | 7.2 | 7.32 | 4.39 |
| Buffer Machine 2 Avg. Size | 7.92 | 8.03 | 6.97 | 5.06 | 10.56 |
| Buffer Machine 3 Avg. Size | 4.86 | 6.78 | 7.92 | 5.01 | 5.05 |
| Buffer Machine 4 Avg. Size | 7.64 | 6.66 | 4.98 | 7.2 | 4.99 |
| Buffer Machine 5 Avg. Size | 5.72 | 4.7 | 4.79 | 8.88 | 7.65 |
| Buffer Machine 6 Avg. Size | 4.98 | 7.18 | 6.84 | 6.79 | 6.39 |
| WIP Avg. Size | 40 | 39 | 39 | 40 | 39 |
| Machine 1 % Setup | 15.36 | 15.62 | 16.01 | 15.26 | 15.38 |
| Machine 2 % Setup | 15.71 | 15.6 | 15.94 | 15.48 | 15.79 |
| Machine 3 % Setup | 16.25 | 15.84 | 15.74 | 15.22 | 15.39 |
| Machine 4 % Setup | 16.15 | 16.01 | 15.86 | 15.79 | 5.91 |
| Machine 5 % Setup | 15.36 | 15.39 | 15.5 | 15.84 | 15.73 |
| Machine 6 % Setup | 15.38 | 15.83 | 15.77 | 15.68 | 15.4 |
| Unit Production Cost | $ 1808.54 | $ 1,821.48 | $ 1,851.12 | $ 1,794.46 | $ 1,827.94 |
| Unit Early Cost | $ 0.36 | $ 0.37 | $ 0.39 | $ 0.33 | $ 0.38 |
| Unit Late Cost | $ 30.28 | $ 10.06 | $ 17.76 | $ 15.44 | $ 12.08 |
| Unit WIP Cost | $ 3.56 | $ 3.49 | $ 3.52 | $ 3.62 | $ 3.55 |
| Total Unit Cost | $ 1,842.73 | $ 1,835.41 | $ 1,872.79 | $ 1,813.86 | $ 1,843.95 |

Table A.4 Main Experiments, WLCFCFSHV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 54.3% | 53.2% | 54.3% | 53.7% | 55.8% |
| PSP Buffer Avg. Size | 606 | 616 | 579 | 642 | 579 |
| Buffer Machine 1 Avg. Size | 7.89 | 6.58 | 5.63 | 3.86 | 7.57 |
| Buffer Machine 2 Avg. Size | 6.21 | 6.28 | 5.3 | 12.17 | 6.82 |
| Buffer Machine 3 Avg. Size | 6.76 | 5.25 | 5.14 | 7.04 | 6.21 |
| Buffer Machine 4 Avg. Size | 7.06 | 7.15 | 6.48 | 5.1 | 6.78 |
| Buffer Machine 5 Avg. Size | 6.1 | 6.19 | 11.11 | 6.19 | 4.57 |
| Buffer Machine 6 Avg. Size | 5.67 | 8.52 | 5.9 | 5.21 | 7.12 |
| WIP Avg. Size | 40 | 40 | 40 | 40 | 39 |
| Machine 1 % Setup | 15.81 | 15.63 | 16 | 15.12 | 15.48 |
| Machine 2 % Setup | 16.68 | 15.79 | 15.55 | 15.78 | 15.43 |
| Machine 3 % Setup | 16.1 | 15.99 | 16.07 | 15.39 | 15.5 |
| Machine 4 % Setup | 16.09 | 15.83 | 16.08 | 15.38 | 15.96 |
| Machine 5 % Setup | 15.9 | 15.43 | 16.02 | 15.62 | 15.23 |
| Machine 6 % Setup | 15.71 | 16.35 | 15.44 | 15.32 | 15.59 |
| Unit Production Cost | $1,806.45 | $1,822.13 | $1,815.38 | $1,809.29 | $1,817.02 |
| Unit Early Cost | $ 0.34 | $ 0.35 | $ 0.35 | $ 0.36 | $ 0.37 |
| Unit Late Cost | $ 17.11 | $ 14.08 | $ 13.58 | $ 25.05 | $ 13.03 |
| Unit WIP Cost | $ 3.00 | $ 3.61 | $ 3.53 | $ 3.57 | $ 3.55 |
| Total Unit Cost | $1,826.90 | $1,840.16 | $1,832.84 | $1,838.27 | $1,833.97 |

Table A.5 Main Experiments, WLCSIMSET1LV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 66.3% | 69.9% | 71.0% | 66.2% | 71.7% |
| PSP Buffer Avg. Size | 38 | 11 | 112 | 93 | 16 |
| Buffer Machine 1 Avg. Size | 7.83 | 5.75 | 5.51 | 8.04 | 5.31 |
| Buffer Machine 2 Avg. Size | 7.02 | 7.24 | 5.43 | 5.75 | 7.62 |
| Buffer Machine 3 Avg. Size | 6.24 | 6.78 | 8.5 | 5.51 | 5.14 |
| Buffer Machine 4 Avg. Size | 7.8 | 6.21 | 5.77 | 6.62 | 5.36 |
| Buffer Machine 5 Avg. Size | 5.69 | 5.06 | 5.72 | 7.67 | 7.62 |
| Buffer Machine 6 Avg. Size | 4.66 | 6.9 | 6.15 | 5.83 | 7.05 |
| WIP Avg. Size | 39 | 38 | 37 | 39 | 38 |
| Machine 1 % Setup | 7.23 | 8.05 | 7.87 | 7.39 | 8.44 |
| Machine 2 % Setup | 7.36 | 7.32 | 8.01 | 8.06 | 7.18 |
| Machine 3 % Setup | 8 | 7.7 | 6.93 | 7.78 | 8.17 |
| Machine 4 % Setup | 7.18 | 7.68 | 8.13 | 7.82 | 7.99 |
| Machine 5 % Setup | 8.02 | 8.15 | 8.04 | 7.23 | 7.16 |
| Machine 6 % Setup | 8.25 | 7.6 | 8.04 | 7.92 | 7.22 |
| Unit Production Cost | $1,675.11 | $1,690.52 | $1,732.01 | $1,688.56 | $1,697.50 |
| Unit Early Cost | $ 0.62 | $ 0.68 | $ 0.69 | $ 0.63 | $ 0.71 |
| Unit Late Cost | $ 25.84 | $ 9.03 | $ 15.03 | $ 43.76 | $ 9.59 |
| Unit WIP Cost | $ 3.01 | $ 2.88 | $ 3.00 | $ 3.07 | $ 2.97 |
| Total Unit Cost | $1,704.58 | $1,703.11 | $1,750.73 | $1,736.02 | $1,710.76 |

Table A.6 Main Experiments, WLCSIMSET1LV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 75.4% | 70.9% | 76.6% | 69.1% | 75.7% |
| PSP Buffer Avg. Size | 7 | 53 | 12 | 97 | 17 |
| Buffer Machine 1 Avg. Size | 6.25 | 6.59 | 5.04 | 5.49 | 5.76 |
| Buffer Machine 2 Avg. Size | 6.3 | 5.89 | 4.12 | 8.52 | 6.44 |
| Buffer Machine 3 Avg. Size | 5.81 | 4.96 | 5.43 | 8.53 | 6.27 |
| Buffer Machine 4 Avg. Size | 6.42 | 6.24 | 6.8 | 5.47 | 6.69 |
| Buffer Machine 5 Avg. Size | 5.78 | 6.41 | 7.32 | 5.8 | 4.83 |
| Buffer Machine 6 Avg. Size | 5.99 | 7.97 | 4.82 | 4.83 | 6.16 |
| WIP Avg. Size | 37 | 38 | 34 | 39 | 36 |
| Machine 1 % Setup | 7.63 | 7.77 | 8.43 | 8.14 | 8.2 |
| Machine 2 % Setup | 7.78 | 8.05 | 8.89 | 6.5 | 7.84 |
| Machine 3 % Setup | 7.79 | 8.54 | 8.02 | 7.17 | 7.62 |
| Machine 4 % Setup | 7.83 | 8.07 | 7.56 | 8.09 | 7.96 |
| Machine 5 % Setup | 8.12 | 7.92 | 7.39 | 8.42 | 8.45 |
| Machine 6 % Setup | 7.92 | 7.02 | 8.63 | 8.25 | 7.92 |
| Unit Production Cost | $1,668.03 | $1,711.57 | $1,694.65 | $1,693.40 | $1,700.16 |
| Unit Early Cost | $ 0.74 | $ 0.67 | $ 0.81 | $ 0.64 | $ 0.76 |
| Unit Late Cost | $ 9.42 | $ 15.93 | $ 6.21 | $ 40.18 | $ 6.25 |
| Unit WIP Cost | $ 2.80 | $ 2.98 | $ 2.60 | $ 3.01 | $ 2.86 |
| Total Unit Cost | $1,680.99 | $1,731.15 | $1,704.26 | $1,737.24 | $1,710.04 |

Table A.7 Main Experiments, WLCSIMSET1HV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 68.1% | 63.6% | 66.3% | 64.9% | 68.6% |
| PSP Buffer Avg. Size | 225 | 224 | 257 | 303 | 234 |
| Buffer Machine 1 Avg. Size | 7.95 | 5.23 | 7.3 | 7.33 | 5.27 |
| Buffer Machine 2 Avg. Size | 6.34 | 7.98 | 5.88 | 5.3 | 7.95 |
| Buffer Machine 3 Avg. Size | 5.47 | 6.55 | 8.22 | 6.28 | 4.9 |
| Buffer Machine 4 Avg. Size | 8.04 | 6.55 | 4.9 | 5.94 | 5.61 |
| Buffer Machine 5 Avg. Size | 5.71 | 4.74 | 5.67 | 7.9 | 6.42 |
| Buffer Machine 6 Avg. Size | 4.44 | 6.88 | 5.28 | 5.75 | 7.11 |
| WIP Avg. Size | 38 | 38 | 37 | 39 | 37 |
| Machine 1 % Setup | 7.12 | 8.02 | 7.21 | 7.81 | 8.4 |
| Machine 2 % Setup | 7.67 | 7.49 | 7.7 | 8.29 | 7.33 |
| Machine 3 % Setup | 7.99 | 7.52 | 6.4 | 7.68 | 8.47 |
| Machine 4 % Setup | 7.25 | 7.46 | 8.783 | 8.34 | 8.11 |
| Machine 5 % Setup | 7.8 | 8.49 | 7.71 | 7.58 | 7.44 |
| Machine 6 % Setup | 8.69 | 7.62 | 8.36 | 8.07 | 7.41 |
| Unit Production Cost | $1,718.92 | $1,712.17 | $1,744.41 | $1,713.38 | $1,745.67 |
| Unit Early Cost | $ 0.66 | $ 0.64 | $ 0.66 | $ 0.63 | $ 0.70 |
| Unit Late Cost | $ 19.20 | $ 21.15 | $ 20.61 | $ 18.05 | $ 13.94 |
| Unit WIP Cost | $ 3.05 | $ 3.01 | $ 3.03 | $ 3.12 | $ 3.06 |
| Total Unit Cost | $1,741.83 | $1,736.97 | $1,768.71 | $1,735.18 | $1,763.38 |

Table A.8 Main Experiments, WLCSIMSET1HV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 64.7% | 66.3% | 65.4% | 65.4% | 65.5% |
| PSP Buffer Avg. Size | 227 | 234 | 170 | 255 | 188 |
| Buffer Machine 1 Avg. Size | 7.19 | 5.91 | 5.72 | 5.61 | 5.93 |
| Buffer Machine 2 Avg. Size | 6.6 | 5.64 | 4.95 | 8.2 | 7.25 |
| Buffer Machine 3 Avg. Size | 6.38 | 4.86 | 6.09 | 5.81 | 6.14 |
| Buffer Machine 4 Avg. Size | 5.95 | 6.79 | 6.3 | 6.29 | 6.81 |
| Buffer Machine 5 Avg. Size | 6.43 | 6.26 | 9.46 | 6.43 | 5.3 |
| Buffer Machine 6 Avg. Size | 5.39 | 8.17 | 5.8 | 5.49 | 6.23 |
| WIP Avg. Size | 38 | 38 | 38 | 38 | 38 |
| Machine 1 % Setup | 7.13 | 7.92 | 8.38 | 8.09 | 8.26 |
| Machine 2 % Setup | 7.56 | 8.07 | 8.47 | 6.71 | 7.35 |
| Machine 3 % Setup | 7.89 | 8.52 | 8.15 | 7.94 | 7.82 |
| Machine 4 % Setup | 8.1 | 7.73 | 7.93 | 7.55 | 7.57 |
| Machine 5 % Setup | 8.29 | 7.76 | 6.67 | 8.38 | 8.49 |
| Machine 6 % Setup | 8.25 | 7.07 | 8.23 | 8.19 | 7.94 |
| Unit Production Cost | $ 1,694.25 | $ 1,732.87 | $ 1,718.86 | $ 1,728.43 | $ 1,721.20 |
| Unit Early Cost | $ 0.61 | $ 0.65 | $ 0.64 | $ 0.66 | $ 0.63 |
| Unit Late Cost | $ 25.71 | $ 17.60 | $ 15.25 | $ 19.94 | $ 12.60 |
| Unit WIP Cost | $ 3.00 | $ 3.04 | $ 3.02 | $ 3.08 | $ 3.07 |
| Total Unit Cost | $ 1,723.57 | $ 1,754.16 | $ 1,737.78 | $ ,752.11 | $ 1,737.50 |

Table A.9 Main Experiments, WLCSIMSET2LV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 75.6% | 76.9% | 77.0% | 75.5% | 73.9% |
| PSP Buffer Avg. Size | 11 | 7 | 57 | 101 | 18 |
| Buffer Machine 1 Avg. Size | 6.96 | 5.34 | 6.17 | 8.11 | 5.33 |
| Buffer Machine 2 Avg. Size | 6.98 | 6.88 | 5.61 | 6.16 | 5.92 |
| Buffer Machine 3 Avg. Size | 6.51 | 6.17 | 8.8 | 5.37 | 6.59 |
| Buffer Machine 4 Avg. Size | 6.92 | 6.51 | 5.57 | 6.8 | 6.91 |
| Buffer Machine 5 Avg. Size | 5.62 | 5.13 | 5.83 | 7.07 | 7.36 |
| Buffer Machine 6 Avg. Size | 4.72 | 5.64 | 5.64 | 5.35 | 6.77 |
| WIP Avg. Size | 38 | 36 | 38 | 39 | 39 |
| Machine 1 % Setup | 7.15 | 8.15 | 7.9 | 7.44 | 8.36 |
| Machine 2 % Setup | 7.56 | 7.69 | 7.7 | 8.02 | 8.36 |
| Machine 3 % Setup | 7.82 | 7.58 | 6.51 | 8.02 | 7.47 |
| Machine 4 % Setup | 7.36 | 7.6 | 8.24 | 7.96 | 7.42 |
| Machine 5 % Setup | 8.03 | 8.05 | 7.82 | 7.94 | 7.71 |
| Machine 6 % Setup | 8.69 | 8 | 8.03 | 8.17 | 7.83 |
| Unit Production Cost | $ 1,681.03 | $ 1,695.56 | $ 1,721.87 | $ 1,692.78 | $ 1,673.39 |
| Unit Early Cost | $ 0.81 | $ 0.86 | $ 0.86 | $ 0.83 | $ 0.79 |
| Unit Late Cost | $ 4.63 | $ 4.00 | $ 4.16 | $ 5.21 | $ 5.05 |
| Unit WIP Cost | $ 2.91 | $ 2.77 | $ 2.96 | $ 3.05 | $ 2.97 |
| Total Unit Cost | $ 1,689.38 | $ 1,703.19 | $ 1,729.85 | $ 1,701.86 | $ 1,682.19 |

Table A.10 Main Experiments, WLCSIMSET2LV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 74.5% | 79.1% | 81.4% | 76.2% | 73.7% |
| PSP Buffer Avg. Size | 33 | 54 | 23 | 87 | 18 |
| Buffer Machine 1 Avg. Size | 6.54 | 5.53 | 5.08 | 5.31 | 5.78 |
| Buffer Machine 2 Avg. Size | 6.19 | 5.87 | 3.69 | 9.44 | 6.81 |
| Buffer Machine 3 Avg. Size | 6.17 | 4.53 | 5.64 | 7.12 | 6.19 |
| Buffer Machine 4 Avg. Size | 6.42 | 5.49 | 7.32 | 5.51 | 6.4 |
| Buffer Machine 5 Avg. Size | 6.09 | 7.31 | 6.84 | 6.1 | 5.13 |
| Buffer Machine 6 Avg. Size | 5.84 | 8.2 | 4.69 | 4.76 | 5.33 |
| WIP Avg. Size | 37 | 37 | 33 | 38 | 36 |
| Machine 1 % Setup | 7.42 | 7.85 | 8.32 | 8.16 | 8.12 |
| Machine 2 % Setup | 7.87 | 7.96 | 9.03 | 6.57 | 7.59 |
| Machine 3 % Setup | 8.08 | 8.8 | 8.33 | 7.72 | 7.77 |
| Machine 4 % Setup | 7.91 | 8.26 | 7.38 | 8.41 | 7.9 |
| Machine 5 % Setup | 7.78 | 7.65 | 7.58 | 8.05 | 8.57 |
| Machine 6 % Setup | 7.97 | 7.17 | 8.56 | 8.48 | 7.94 |
| Unit Production Cost | $ 1,659.87 | $ 1,712.93 | $ 1,695.85 | $ 1,677.77 | $ 1,699.47 |
| Unit Early Cost | $ 0.77 | $ 0.86 | $ 0.92 | $ 0.82 | $ 0.82 |
| Unit Late Cost | $ 4.32 | $ 4.08 | $ 3.26 | $ 4.85 | $ 4.89 |
| Unit WIP Cost | $ 2.83 | $ 2.91 | $ 2.59 | $ 2.96 | $ 2.82 |
| Total Unit Cost | $ 1,667.79 | $ 1,720.78 | $ 1,702.62 | $ 1,686.41 | $ 1,708.00 |

Table A.11 Main Experiments, WLCSIMSET2HV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 71.9% | 73.2% | 73.3% | 73.2% | 71.5% |
| PSP Buffer Avg. Size | 229 | 204 | 263 | 287 | 245 |
| Buffer Machine 1 Avg. Size | 5.69 | 5.03 | 6.87 | 6.92 | 5.55 |
| Buffer Machine 2 Avg. Size | 5.83 | 7.18 | 5.95 | 5.88 | 5.01 |
| Buffer Machine 3 Avg. Size | 7.53 | 6.59 | 8.09 | 5.2 | 5.99 |
| Buffer Machine 4 Avg. Size | 5.92 | 6.83 | 4.68 | 6.44 | 6.31 |
| Buffer Machine 5 Avg. Size | 4.24 | 5.75 | 5.69 | 7.12 | 8.77 |
| Buffer Machine 6 Avg. Size | 5.92 | 6.08 | 5.76 | 6.06 | 6.52 |
| WIP Avg. Size | 35 | 37 | 37 | 38 | 38 |
| Machine 1 % Setup | 7.19 | 8.46 | 7.41 | 7.95 | 7.96 |
| Machine 2 % Setup | 8.09 | 7.49 | 7.44 | 8.18 | 8.52 |
| Machine 3 % Setup | 8.16 | 7.43 | 6.67 | 8.13 | 7.86 |
| Machine 4 % Setup | 7.4 | 6.97 | 8.93 | 8.36 | 7.81 |
| Machine 5 % Setup | 7.67 | 8.26 | 7.84 | 7.73 | 7.59 |
| Machine 6 % Setup | 8.7 | 7.86 | 8.39 | 7.96 | 7.56 |
| Unit Production Cost | $ 1,721.12 | $ 1,725.35 | $ 1,743.89 | $ 1,714.69 | $ 1,709.81 |
| Unit Early Cost | $ 0.83 | $ 0.83 | $ 0.85 | $ 0.83 | $ 0.81 |
| Unit Late Cost | $ 5.72 | $ 5.17 | $ 5.12 | $ 5.91 | $ 5.79 |
| Unit WIP Cost | $ 2.82 | $ 2.97 | $ 3.01 | $ 3.05 | $ 2.99 |
| Total Unit Cost | $ 1,730.48 | $ 1,734.32 | $ 1,752.88 | $ 1,724.47 | $ 1,719.41 |

Table A.12 Main Experiments, WLCSIMSET2HV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 71.9% | 72.9% | 72.6% | 72.4% | 72.2% |
| PSP Buffer Avg. Size | 242 | 236 | 199 | 258 | 202 |
| Buffer Machine 1 Avg. Size | 7.45 | 5.93 | 5.21 | 5.77 | 5.69 |
| Buffer Machine 2 Avg. Size | 6.31 | 5.32 | 4.27 | 7.8 | 7.19 |
| Buffer Machine 3 Avg. Size | 5.79 | 4.11 | 5.89 | 6.59 | 6.26 |
| Buffer Machine 4 Avg. Size | 6.71 | 6.33 | 7.47 | 6.61 | 6.22 |
| Buffer Machine 5 Avg. Size | 6.24 | 6.18 | 8.4 | 6.2 | 5.68 |
| Buffer Machine 6 Avg. Size | 5.01 | 9.26 | 5.85 | 4.46 | 5.8 |
| WIP Avg. Size | 38 | 37 | 37 | 37 | 37 |
| Machine 1 % Setup | 7.2 | 7.69 | 8.3 | 8.41 | 7.88 |
| Machine 2 % Setup | 8.31 | 8.34 | 9.11 | 7.11 | 7.42 |
| Machine 3 % Setup | 8.45 | 9.1 | 8.32 | 7.63 | 7.65 |
| Machine 4 % Setup | 7.98 | 8.02 | 7.53 | 7.77 | 7.86 |
| Machine 5 % Setup | 8.05 | 7.71 | 7.51 | 8.02 | 8.26 |
| Machine 6 % Setup | 8.35 | 7.05 | 8.15 | 8.74 | 7.87 |
| Unit Production Cost | $ 1,707.19 | $ 1,728.03 | $ 1,721.04 | $ 1,724.47 | $ 1,716.42 |
| Unit Early Cost | $ 0.80 | $ 0.83 | $ 0.83 | $ 0.84 | $ 0.83 |
| Unit Late Cost | $ 5.64 | $ 5.95 | $ 5.30 | $ 5.77 | $ 5.48 |
| Unit WIP Cost | $ 3.02 | $ 3.00 | $ 2.94 | $ 3.05 | $ 3.00 |
| Total Unit Cost | $ 1,716.65 | $ 1,737.82 | $ 1,730.10 | $ 1,734.12 | $ 1,725.74 |

Table A.13 Main Experiments, WLCMCFCFSLV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 77.4% | 75.8% | 76.9% | 76.8% | 79.1% |
| PSP Buffer Avg. Size | 296 | 297 | 314 | 314 | 306 |
| Buffer Machine 1 Avg. Size | 4.11 | 3.07 | 3.36 | 3.54 | 3.01 |
| Buffer Machine 2 Avg. Size | 3.73 | 4.3 | 3.23 | 2.88 | 3.88 |
| Buffer Machine 3 Avg. Size | 3.35 | 3.52 | 6.28 | 3.41 | 3.07 |
| Buffer Machine 4 Avg. Size | 4 | 4.15 | 3.15 | 3.81 | 2.95 |
| Buffer Machine 5 Avg. Size | 3.41 | 3.5 | 3.15 | 3.87 | 4.98 |
| Buffer Machine 6 Avg. Size | 2.86 | 3.93 | 3.55 | 3.78 | 3.62 |
| WIP Avg. Size | 21 | 22 | 23 | 21 | 22 |
| Machine 1 % Setup | 15.35 | 15.4 | 15.48 | 15.16 | 15.25 |
| Machine 2 % Setup | 15.56 | 15.59 | 15.47 | 15.53 | 15.45 |
| Machine 3 % Setup | 15.47 | 15.46 | 15.87 | 15.32 | 15.15 |
| Machine 4 % Setup | 15.61 | 15.91 | 15.4 | 15.4 | 15.5 |
| Machine 5 % Setup | 15.65 | 15.15 | 15.32 | 15.5 | 15.69 |
| Machine 6 % Setup | 21 | 3.98 | 6.98 | 6.08 | 6.2 |
| Unit Production Cost | $ 1,735.35 | $ 1,740.85 | $ 1,763.43 | $ 1,735.97 | $ 1,745.65 |
| Unit Early Cost | $ 0.61 | $ 0.61 | $ 0.62 | $ 0.61 | $ 0.64 |
| Unit Late Cost | $ 19.66 | $ 18.71 | $ 12.66 | $ 21.12 | $ 22.79 |
| Unit WIP Cost | $ 1.83 | $ 1.94 | $ 2.01 | $ 1.85 | $ 1.88 |
| Total Unit Cost | $ 1,757.46 | $ 1,762.12 | $ 1,778.72 | $ 1,759.55 | $ 1,770.97 |

Table A.14 Main Experiments, WLCMCFCFSLV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 75.8% | 77.0% | 78.4% | 73.5% | 76.9% |
| PSP Buffer Avg. Size | 299 | 315 | 284 | 331 | 284 |
| Buffer Machine 1 Avg. Size | 4.16 | 4.05 | 3.28 | 3.81 | 3.43 |
| Buffer Machine 2 Avg. Size | 3.83 | 3.37 | 3.16 | 4.95 | 4.12 |
| Buffer Machine 3 Avg. Size | 4.12 | 2.69 | 3.54 | 3.9 | 3.31 |
| Buffer Machine 4 Avg. Size | 3.25 | 3.42 | 4.45 | 2.99 | 3.59 |
| Buffer Machine 5 Avg. Size | 3.28 | 3.52 | 3.44 | 3.05 | 2.94 |
| Buffer Machine 6 Avg. Size | 3.19 | 4.34 | 2.33 | 3.07 | 3.04 |
| WIP Avg. Size | 22 | 21 | 20 | 22 | 20 |
| Machine 1 % Setup | 15.64 | 15.4 | 15.83 | 15.66 | 15.03 |
| Machine 2 % Setup | 15.56 | 15.6 | 15.49 | 15.47 | 15.66 |
| Machine 3 % Setup | 15.73 | 15.5 | 15.83 | 15.25 | 15.37 |
| Machine 4 % Setup | 15.65 | 15.68 | 15.74 | 14.83 | 15.47 |
| Machine 5 % Setup | 15.83 | 15.36 | 15.69 | 14.53 | 15.31 |
| Machine 6 % Setup | 9.09 | 4.17 | 10.28 | 7.99 | 6.37 |
| Unit Production Cost | $ 1,722.70 | $ 1,747.80 | $ 1,733.58 | $ 1,708.77 | $ 1,733.45 |
| Unit Early Cost | $ 0.60 | $ 0.62 | $ 0.65 | $ 0.58 | $ 0.61 |
| Unit Late Cost | $ 16.94 | $ 13.83 | $ 21.85 | $ 1.86 | $ 20.37 |
| Unit WIP Cost | $ 1.87 | $ 1.87 | $ 1.75 | $ 1.87 | $ 1.79 |
| Total Unit Cost | $ 1,742.11 | $ 1,764.12 | $ 1,757.83 | $ 1,713.08 | $ 1,756.23 |

Table A.15 Main Experiments, WLCMCFCFSHV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 70.0% | 73.4% | 67.5% | 73.3% | 73.8% |
| PSP Buffer Avg. Size | 429 | 375 | 413 | 421 | 409 |
| Buffer Machine 1 Avg. Size | 3.74 | 3.14 | 3.89 | 3.03 | 3.03 |
| Buffer Machine 2 Avg. Size | 5 | 3.91 | 3.08 | 2.96 | 3.54 |
| Buffer Machine 3 Avg. Size | 3.4 | 3.48 | 5.89 | 3.58 | 3.02 |
| Buffer Machine 4 Avg. Size | 3 | 4.23 | 2.86 | 3.63 | 2.84 |
| Buffer Machine 5 Avg. Size | 2.69 | 3.63 | 3.17 | 3.87 | 4.47 |
| Buffer Machine 6 Avg. Size | 3.17 | 3.69 | 3.28 | 3.94 | 3.98 |
| WIP Avg. Size | 21 | 22 | 22 | 21 | 21 |
| Machine 1 % Setup | 14.91 | 15.01 | 15.18 | 14.65 | 14.61 |
| Machine 2 % Setup | 15 | 15.51 | 15.19 | 14.9 | 14.76 |
| Machine 3 % Setup | 14.71 | 15.14 | 15.23 | 14.92 | 14.73 |
| Machine 4 % Setup | 14.23 | 15.47 | 15.31 | 15.16 | 14.78 |
| Machine 5 % Setup | 14.29 | 15.11 | 14.71 | 15.13 | 15.03 |
| Machine 6 % Setup | 14.99 | 15.57 | 14.77 | 14.99 | 14.53 |
| Unit Production Cost | $ 1,744.54 | $ 1,744.60 | $ 1,767.56 | $ 1,739.59 | $ 1,754.28 |
| Unit Early Cost | $ 0.64 | $ 0.60 | $ 0.57 | $ 0.60 | $ 0.61 |
| Unit Late Cost | $ 22.10 | $ 15.60 | $ 18.49 | $ 23.16 | $ 17.92 |
| Unit WIP Cost | $ 1.91 | $ 1.96 | $ 2.02 | $ 1.88 | $ 1.90 |
| Total Unit Cost | $ 1,769.20 | $ 1,762.76 | $ 1,788.64 | $ 1,765.23 | $ 1,774.71 |

Table A.16 Main Experiments, WLCMCFCFSHV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 73.0% | 73.2% | 74.8% | 70.7% | 74.4% |
| PSP Buffer Avg. Size | 393 | 414 | 373 | 428 | 376 |
| Buffer Machine 1 Avg. Size | 3.96 | 3.56 | 3.23 | 3.71 | 3.12 |
| Buffer Machine 2 Avg. Size | 3.5 | 3.25 | 2.99 | 5.02 | 3.95 |
| Buffer Machine 3 Avg. Size | 3.01 | 3.29 | 3.28 | 3.36 | 2.98 |
| Buffer Machine 4 Avg. Size | 3.15 | 3.39 | 4.29 | 2.99 | 3.17 |
| Buffer Machine 5 Avg. Size | 3.8 | 3.94 | 3.67 | 2.75 | 2.71 |
| Buffer Machine 6 Avg. Size | 3.78 | 3.96 | 2.48 | 3.21 | 2.78 |
| WIP Avg. Size | 21 | 21 | 20 | 21 | 19 |
| Machine 1 % Setup | 15.36 | 14.89 | 15.65 | 14.76 | 14.59 |
| Machine 2 % Setup | 15.21 | 15.1 | 14.96 | 14.8 | 14.87 |
| Machine 3 % Setup | 14.93 | 14.92 | 15.56 | 14.69 | 15.01 |
| Machine 4 % Setup | 15.3 | 15.24 | 15.36 | 14.61 | 15.09 |
| Machine 5 % Setup | 14.96 | 15.04 | 15.52 | 14.89 | 14.44 |
| Machine 6 % Setup | 15.39 | 15.19 | 14.33 | 14.9 | 14.71 |
| Unit Production Cost | $ 1,749.58 | $ 1,738.39 | $ 1,736.03 | $ 1,745.34 | $ 1,741.50 |
| Unit Early Cost | $ 0.60 | $ 0.60 | $ 0.62 | $ 0.59 | $ 0.62 |
| Unit Late Cost | $ 15.76 | $ 15.11 | $ 22.14 | $ 20.87 | $ 30.01 |
| Unit WIP Cost | $ 1.91 | $ 1.89 | $ 1.77 | $ 1.91 | $ 1.70 |
| Total Unit Cost | $ 1,767.85 | $ 1,755.99 | $ 1,760.57 | $ 1,768.70 | $ 1,773.84 |

Table A.17 Main Experiments, WLCMCSIMSET1LV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 86.3% | 86.0% | 84.9% | 85.2% | 86.9% |
| PSP Buffer Avg. Size | 139 | 128 | 137 | 141 | 131 |
| Buffer Machine 1 Avg. Size | 3.22 | 3.01 | 3.75 | 3.19 | 2.9 |
| Buffer Machine 2 Avg. Size | 3.56 | 3.61 | 3.2 | 2.92 | 3.7 |
| Buffer Machine 3 Avg. Size | 3.37 | 3 | 4.78 | 3.24 | 2.8 |
| Buffer Machine 4 Avg. Size | 3.46 | 3.36 | 2.9 | 3.2 | 2.95 |
| Buffer Machine 5 Avg. Size | 3.02 | 3.1 | 2.9 | 3.46 | 3.69 |
| Buffer Machine 6 Avg. Size | 2.65 | 3.85 | 3.18 | 3.57 | 3.26 |
| WIP Avg. Size | 19 | 20 | 21 | 20 | 19 |
| Machine 1 % Setup | 9.41 | 9.61 | 9.04 | 9.4 | 9.17 |
| Machine 2 % Setup | 9.42 | 9.26 | 9.53 | 9.91 | 9.03 |
| Machine 3 % Setup | 9.57 | 9.7 | 8.21 | 9.48 | 9.73 |
| Machine 4 % Setup | 9.21 | 9.33 | 9.96 | 9.53 | 10.01 |
| Machine 5 % Setup | 9.29 | 9.57 | 9.79 | 9.47 | 8.94 |
| Machine 6 % Setup | 10.13 | 9.02 | 9.63 | 9.26 | 9.29 |
| Unit Production Cost | $ 1,664.92 | $ 1,671.80 | $ 1,692.24 | $ 1,671.02 | $ 1,678.16 |
| Unit Early Cost | $ 0.85 | $ 0.86 | $ 0.83 | $ 0.85 | $ 0.89 |
| Unit Late Cost | $ 6.26 | $ 6.19 | $ 7.58 | $ 12.19 | $ 8.54 |
| Unit WIP Cost | $ 1.53 | $ 1.57 | $ 1.67 | $ 1.56 | $ 1.54 |
| Total Unit Cost | $ 1,673.56 | $ 1,680.43 | $ 1,702.32 | $ 1,685.62 | $ 1,689.13 |

Table A.18 Main Experiments, WLCMCSIMSET1LV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 85.9% | 86.2% | 86.8% | 84.9% | 86.8% |
| PSP Buffer Avg. Size | 125 | 142 | 135 | 156 | 118 |
| Buffer Machine 1 Avg. Size | 3.53 | 3.18 | 3 | 3.5 | 3.12 |
| Buffer Machine 2 Avg. Size | 3.73 | 3.22 | 2.74 | 3.86 | 3.34 |
| Buffer Machine 3 Avg. Size | 3.1 | 2.73 | 2.94 | 3.48 | 3.18 |
| Buffer Machine 4 Avg. Size | 3.3 | 3.08 | 3.2 | 3 | 3.11 |
| Buffer Machine 5 Avg. Size | 3.14 | 3.23 | 3.55 | 2.82 | 2.79 |
| Buffer Machine 6 Avg. Size | 3.09 | 3.96 | 2.57 | 3.15 | 3.23 |
| WIP Avg. Size | 20 | 19 | 18 | 20 | 19 |
| Machine 1 % Setup | 8.91 | 9.64 | 9.76 | 9.29 | 9.72 |
| Machine 2 % Setup | 9.24 | 9.61 | 9.95 | 8.93 | 9.15 |
| Machine 3 % Setup | 9.69 | 10.03 | 9.87 | 9.52 | 9.29 |
| Machine 4 % Setup | 9.53 | 9.88 | 9.56 | 9.57 | 9.56 |
| Machine 5 % Setup | 9.8 | 9.41 | 9.06 | 9.73 | 9.95 |
| Machine 6 % Setup | 9.93 | 8.87 | 10.07 | 9.43 | 9.71 |
| Unit Production Cost | $ 1,660.41 | $ 1,677.23 | $ 1,665.42 | $ 1,671.91 | $ 1,670.14 |
| Unit Early Cost | $ 0.83 | $ 0.83 | $ 0.86 | $ 0.83 | $ 0.86 |
| Unit Late Cost | $ 8.24 | $ 6.12 | $ 7.81 | $ 8.74 | $ 5.42 |
| Unit WIP Cost | $ 1.56 | $ 1.55 | $ 1.43 | $ 1.58 | $ 1.51 |
| Total Unit Cost | $ 1,671.04 | $ 1,685.74 | $ 1,675.52 | $ 1,683.06 | $ 1,677.93 |

Table A.19 Main Experiments, WLCMCSIMSET1HV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 78.3% | 77.7% | 76.8% | 77.5% | 78.0% |
| PSP Buffer Avg. Size | 238 | 237 | 249 | 256 | 254 |
| Buffer Machine 1 Avg. Size | 3.52 | 2.88 | 3.46 | 2.95 | 2.77 |
| Buffer Machine 2 Avg. Size | 3.73 | 3.92 | 3.27 | 2.93 | 3.29 |
| Buffer Machine 3 Avg. Size | 3.43 | 3.09 | 4.74 | 3.36 | 2.92 |
| Buffer Machine 4 Avg. Size | 3.57 | 3.38 | 2.98 | 3.2 | 2.79 |
| Buffer Machine 5 Avg. Size | 2.69 | 3.35 | 2.91 | 3.63 | 3.44 |
| Buffer Machine 6 Avg. Size | 2.49 | 3.19 | 3.12 | 3.12 | 3.84 |
| WIP Avg. Size | 19 | 20 | 20 | 19 | 19 |
| Machine 1 % Setup | 9.02 | 9.69 | 9.15 | 9.62 | 9.83 |
| Machine 2 % Setup | 9.16 | 8.78 | 9.14 | 9.4 | 9.36 |
| Machine 3 % Setup | 9.23 | 9.56 | 8.38 | 9.45 | 9.6 |
| Machine 4 % Setup | 8.7 | 9.34 | 9.64 | 9.4 | 9.92 |
| Machine 5 % Setup | 10.09 | 9.29 | 9.6 | 9.19 | 9.06 |
| Machine 6 % Setup | 10.05 | 9.62 | 9.41 | 9.29 | 8.68 |
| Unit Production Cost | $ 1,670.99 | $ 1,676.34 | $ 1,699.72 | $ 1,672.78 | $ 1,686.12 |
| Unit Early Cost | $ 0.77 | $ 0.75 | $ 0.76 | $ 0.74 | $ 0.77 |
| Unit Late Cost | $ 8.46 | $ 18.56 | $ 8.66 | $ 18.83 | $ 9.44 |
| Unit WIP Cost | $ 1.55 | $ 1.61 | $ 1.71 | $ 1.58 | $ 1.60 |
| Total Unit Cost | $ 1,681.77 | $ 1,697.26 | $ 1,710.84 | $ 1,693.93 | $ 1,697.92 |

Table A.20 Main Experiments, WLCMCSIMSET1HV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 84.5% | 80.0% | 84.2% | 75.4% | 78.6% |
| PSP Buffer Avg. Size | 233 | 248 | 220 | 253 | 243 |
| Buffer Machine 1 Avg. Size | 3.45 | 3.51 | 3.07 | 3.14 | 2.75 |
| Buffer Machine 2 Avg. Size | 3.93 | 3.42 | 2.82 | 4.29 | 3.55 |
| Buffer Machine 3 Avg. Size | 3.3 | 2.55 | 3.13 | 3.39 | 2.85 |
| Buffer Machine 4 Avg. Size | 2.78 | 2.93 | 3.23 | 3.03 | 3.04 |
| Buffer Machine 5 Avg. Size | 3.09 | 3.18 | 3.23 | 2.86 | 2.61 |
| Buffer Machine 6 Avg. Size | 2.77 | 3.47 | 2.46 | 2.76 | 2.95 |
| WIP Avg. Size | 19 | 19 | 18 | 19 | 18 |
| Machine 1 % Setup | 9.36 | 9.05 | 9.61 | 9.24 | 9.7 |
| Machine 2 % Setup | 8.94 | 9.42 | 9.84 | 8.44 | 9.07 |
| Machine 3 % Setup | 9.6 | 10.06 | 9.52 | 9.25 | 9.4 |
| Machine 4 % Setup | 9.95 | 9.84 | 9.55 | 9.45 | 9.51 |
| Machine 5 % Setup | 9.78 | 9.31 | 9.32 | 9.58 | 9.75 |
| Machine 6 % Setup | 9.36 | 9.24 | 10.04 | 9.77 | 9.52 |
| Unit Production Cost | $ 1,655.99 | $ 1,679.01 | $ 1,668.00 | $ 1,684.72 | $ 1,681.89 |
| Unit Early Cost | $ 0.79 | $ 0.77 | $ 0.82 | $ 0.73 | $ 0.77 |
| Unit Late Cost | $ 9.10 | $ 8.45 | $ 9.17 | $ 9.77 | $ 17.70 |
| Unit WIP Cost | $ 1.57 | $ 1.57 | $ 1.46 | $ 1.38 | $ 1.49 |
| Total Unit Cost | $ 1,667.45 | $ 1,689.81 | $ 1,679.45 | $ 1,696.60 | $ 1,701.84 |

Table A.21 Main Experiments, WLCMCSIMSET2LV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 86.2% | 84.8% | 84.4% | 84.6% | 86.1% |
| PSP Buffer Avg. Size | 130 | 135 | 148 | 147 | 137 |
| Buffer Machine 1 Avg. Size | 3.44 | 3.16 | 3.37 | 3.28 | 2.78 |
| Buffer Machine 2 Avg. Size | 3.54 | 3.48 | 3.2 | 2.62 | 3.44 |
| Buffer Machine 3 Avg. Size | 3.13 | 3.34 | 4.81 | 3.23 | 3.14 |
| Buffer Machine 4 Avg. Size | 3.55 | 3.34 | 2.97 | 3.27 | 2.8 |
| Buffer Machine 5 Avg. Size | 2.86 | 3.53 | 2.85 | 3.32 | 3.64 |
| Buffer Machine 6 Avg. Size | 2.87 | 3.63 | 3.17 | 3.56 | 3.43 |
| WIP Avg. Size | 19 | 20 | 20 | 19 | 19 |
| Machine 1 % Setup | 9.32 | 9.95 | 9.69 | 9.79 | 9.82 |
| Machine 2 % Setup | 9.44 | 9.74 | 9.6 | 10.29 | 9.62 |
| Machine 3 % Setup | 9.83 | 9.66 | 8.44 | 9.75 | 9.75 |
| Machine 4 % Setup | 9.75 | 9.8 | 10.18 | 9.92 | 10.14 |
| Machine 5 % Setup | 9.98 | 9.43 | 9.96 | 9.87 | 9.24 |
| Machine 6 % Setup | 10.07 | 9.62 | 9.99 | 9.71 | 9.66 |
| Unit Production Cost | $ 1,675.34 | $ 1,680.44 | $ 1,696.93 | $ 1,673.83 | $ 1,683.04 |
| Unit Early Cost | $ 0.86 | $ 0.85 | $ 0.82 | $ 0.83 | $ 0.85 |
| Unit Late Cost | $ 11.29 | $ 9.12 | $ 6.07 | $ 9.34 | $ 9.90 |
| Unit WIP Cost | $ 1.54 | $ 1.34 | $ 1.65 | $ 1.55 | $ 1.55 |
| Total Unit Cost | $ 1,689.02 | $ 1,691.74 | $ 1,705.46 | $ 1,685.55 | $ 1,695.34 |

Table A.22 Main Experiments, WLCMCSIMSET2LV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 85.9% | 85.0% | 87.2% | 85.6% | 86.3% |
| PSP Buffer Avg. Size | 141 | 147 | 130 | 162 | 129 |
| Buffer Machine 1 Avg. Size | 3.55 | 3.56 | 3.19 | 3.27 | 3.02 |
| Buffer Machine 2 Avg. Size | 3.5 | 3.19 | 2.55 | 3.86 | 3.49 |
| Buffer Machine 3 Avg. Size | 3.48 | 2.54 | 3.03 | 3.2 | 2.95 |
| Buffer Machine 4 Avg. Size | 3.15 | 3.01 | 3.31 | 3.11 | 3.24 |
| Buffer Machine 5 Avg. Size | 2.8 | 3.1 | 3.56 | 2.73 | 2.7 |
| Buffer Machine 6 Avg. Size | 3.07 | 3.9 | 2.47 | 3.02 | 3.05 |
| WIP Avg. Size | 20 | 19 | 18 | 19 | 18 |
| Machine 1 % Setup | 9.61 | 9.54 | 9.92 | 9.9 | 9.93 |
| Machine 2 % Setup | 9.56 | 9.9 | 10.46 | 9.26 | 9.62 |
| Machine 3 % Setup | 9.78 | 10.73 | 10.23 | 10.16 | 9.81 |
| Machine 4 % Setup | 9.87 | 10.16 | 9.76 | 10.04 | 9.9 |
| Machine 5 % Setup | 10.26 | 9.96 | 9.41 | 10.33 | 10.16 |
| Machine 6 % Setup | 9.97 | 9.27 | 10.38 | 9.85 | 9.98 |
| Unit Production Cost | $ 1,660.55 | $ 1,680.68 | $ 1,671.61 | $ 1,680.11 | $ 1,670.59 |
| Unit Early Cost | $ 0.81 | $ 0.84 | $ 0.86 | $ 0.84 | $ 0.84 |
| Unit Late Cost | $ 8.84 | $ 5.66 | $ 6.15 | $ 6.65 | $ 4.40 |
| Unit WIP Cost | $ 1.54 | $ 1.55 | $ 1.44 | $ 1.54 | $ 1.49 |
| Total Unit Cost | $ 1,671.75 | $ 1,688.73 | $ 1,680.06 | $ 1,689.14 | $ 1,677.32 |

Table A.23 Main Experiments, WLCMCSIMSET2HV Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 77.4% | 74.9% | 75.8% | 77.0% | 78.2% |
| PSP Buffer Avg. Size | 246 | 235 | 260 | 274 | 259 |
| Buffer Machine 1 Avg. Size | 3.71 | 3.02 | 3.38 | 2.81 | 3.01 |
| Buffer Machine 2 Avg. Size | 3.33 | 4.02 | 3.39 | 2.82 | 3.37 |
| Buffer Machine 3 Avg. Size | 3.46 | 2.93 | 4.43 | 3.52 | 2.82 |
| Buffer Machine 4 Avg. Size | 3.64 | 3.83 | 2.61 | 3.36 | 3.64 |
| Buffer Machine 5 Avg. Size | 2.61 | 2.9 | 3.14 | 3.19 | 2.95 |
| Buffer Machine 6 Avg. Size | 2.74 | 3.55 | 2.98 | 3.17 | 2.99 |
| WIP Avg. Size | 19 | 20 | 20 | 19 | 19 |
| Machine 1 % Setup | 9.1 | 9.67 | 9.64 | 9.87 | 9.87 |
| Machine 2 % Setup | 9.76 | 9.16 | 9.24 | 10.27 | 9.51 |
| Machine 3 % Setup | 9.73 | 9.77 | 8.86 | 9.18 | 9.63 |
| Machine 4 % Setup | 9.29 | 9.71 | 10.26 | 9.68 | 5.74 |
| Machine 5 % Setup | 10.04 | 9.87 | 9.6 | 9.89 | 10.32 |
| Machine 6 % Setup | 10.06 | 9.24 | 9.88 | 9.68 | 9.35 |
| Unit Production Cost | $ 1,677.39 | $ 1,680.19 | $ 1,704.34 | $ 1,675.65 | $ 1,671.94 |
| Unit Early Cost | $ 0.76 | $ 0.74 | $ 0.73 | $ 0.72 | $ 0.75 |
| Unit Late Cost | $ 13.90 | $ 15.29 | $ 13.65 | $ 18.70 | $ 11.18 |
| Unit WIP Cost | $ 1.60 | $ 1.65 | $ 1.68 | $ 1.56 | $ 1.55 |
| Total Unit Cost | $ 1,693.66 | $ 1,697.87 | $ 1,720.40 | $ 1,696.64 | $ 1,685.42 |

Table A.24 Main Experiments, WLCMCSIMSET2HV Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 84.1% | 77.3% | 78.0% | 74.4% | 76.9% |
| PSP Buffer Avg. Size | 233 | 251 | 227 | 275 | 249 |
| Buffer Machine 1 Avg. Size | 3.53 | 3.18 | 3.72 | 2.98 | 2.72 |
| Buffer Machine 2 Avg. Size | 3.47 | 3.51 | 2.52 | 4.22 | 3.12 |
| Buffer Machine 3 Avg. Size | 3.2 | 2.51 | 2.87 | 3.23 | 2.84 |
| Buffer Machine 4 Avg. Size | 2.82 | 2.93 | 3.37 | 2.93 | 3.08 |
| Buffer Machine 5 Avg. Size | 3.15 | 3.23 | 3.45 | 2.75 | 2.73 |
| Buffer Machine 6 Avg. Size | 2.82 | 3.5 | 2.68 | 2.84 | 2.88 |
| WIP Avg. Size | 19 | 19 | 19 | 19 | 17 |
| Machine 1 % Setup | 9.09 | 9.61 | 10.3 | 9.89 | 10.33 |
| Machine 2 % Setup | 9.51 | 9.76 | 9.9 | 9.12 | 9.96 |
| Machine 3 % Setup | 9.67 | 10.2 | 10.18 | 9.76 | 10.41 |
| Machine 4 % Setup | 9.82 | 10.09 | 9.83 | 9.97 | 9.67 |
| Machine 5 % Setup | 9.7 | 9.61 | 9.7 | 10.09 | 10.11 |
| Machine 6 % Setup | 9.89 | 10.01 | 10.22 | 10.01 | 10.26 |
| Unit Production Cost | $ 1,663.38 | $ 1,686.68 | $ 1,679.63 | $ 1,684.97 | $ 1,683.97 |
| Unit Early Cost | $ 0.78 | $ 0.72 | $ 0.74 | $ 0.70 | $ 0.73 |
| Unit Late Cost | $ 7.36 | $ 9.61 | $ 16.14 | $ 8.78 | $ 13.66 |
| Unit WIP Cost | $ 1.54 | $ 1.30 | $ 1.49 | $ 1.59 | $ 1.47 |
| Total Unit Cost | $ 1,673.08 | $ 1,698.31 | $ 1,698.01 | $ 1,696.04 | $ 1,699.83 |

Table A.25 Sensitivity Experiments, WLCFCFSHU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 58.6% | 56.2% | 53.6% | 54.4% | 56.1% |
| PSP Buffer Avg. Size | 1042 | 1022 | 1089 | 1121 | 1048 |
| Buffer Machine 1 Avg. Size | 7.51 | 4.35 | 2.52 | 7.13 | 5.83 |
| Buffer Machine 2 Avg. Size | 7.92 | 9.59 | 6.4 | 4.34 | 7.74 |
| Buffer Machine 3 Avg. Size | 7.5 | 7.59 | 9.94 | 4.14 | 6.37 |
| Buffer Machine 4 Avg. Size | 8.75 | 6.53 | 4.44 | 7.61 | 4.06 |
| Buffer Machine 5 Avg. Size | 4.99 | 6.22 | 4.96 | 12.55 | 9.02 |
| Buffer Machine 6 Avg. Size | 5 | 7.36 | 8.87 | 6.31 | 8.5 |
| WIP Avg. Size | 42 | 42 | 37 | 42 | 42 |
| Machine 1 % Setup | 16.42 | 16.44 | 16.61 | 16.79 | 16.1 |
| Machine 2 % Setup | 17.14 | 16.77 | 16.39 | 16.88 | 16.41 |
| Machine 3 % Setup | 17 | 17 | 16.87 | 16.35 | 16.66 |
| Machine 4 % Setup | 16.4 | 16.22 | 16.73 | 16.49 | 15.97 |
| Machine 5 % Setup | 16.35 | 16.5 | 16.11 | 16.21 | 16.35 |
| Machine 6 % Setup | 16.29 | 16.49 | 16.55 | 16.78 | 16.4 |
| Unit Production Cost | $ 1,758.82 | $ 1,772.78 | $ 1,796.85 | $ 1,742.20 | $ 1,772.53 |
| Unit Early Cost | $ 0.32 | $ 0.30 | $ 0.29 | $ 0.29 | $ 0.31 |
| Unit Late Cost | $ 31.63 | $ 9.36 | $ 15.90 | $ 13.57 | $ 15.40 |
| Unit WIP Cost | $ 3.42 | $ 3.48 | $ 3.30 | $ 3.28 | $ 3.46 |
| Total Unit Cost | $ 1,794.19 | $ 1,785.93 | $ 1,816.35 | $ 1,759.34 | $ 1,791.71 |

Table A.26 Sensitivity Experiments, WLCFCFSHU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 58.3% | 51.4% | 51.2% | 54.5% | 55.4% |
| PSP Buffer Avg. Size | 1052 | 1068 | 1073 | 1092 | 1077 |
| Buffer Machine 1 Avg. Size | 6.99 | 4.55 | 5.84 | 5.84 | 5.91 |
| Buffer Machine 2 Avg. Size | 7.03 | 6.8 | 4.83 | 9.65 | 8.54 |
| Buffer Machine 3 Avg. Size | 6.32 | 6.36 | 6.76 | 6.66 | 6.39 |
| Buffer Machine 4 Avg. Size | 7.08 | 7.59 | 7.93 | 6.55 | 8.77 |
| Buffer Machine 5 Avg. Size | 7.82 | 6.9 | 9.52 | 8.74 | 6.57 |
| Buffer Machine 6 Avg. Size | 6.76 | 9.63 | 5.7 | 4.56 | 6.76 |
| WIP Avg. Size | 42 | 42 | 41 | 42 | 43 |
| Machine 1 % Setup | 16.96 | 16.37 | 16.99 | 16.4 | 17 |
| Machine 2 % Setup | 16.42 | 16.68 | 16.89 | 16.54 | 16.22 |
| Machine 3 % Setup | 16.36 | 16.71 | 16.23 | 16.18 | 16.56 |
| Machine 4 % Setup | 16.82 | 16.72 | 16.65 | 16.09 | 16.91 |
| Machine 5 % Setup | 16.11 | 16.22 | 16.88 | 16.56 | 16.35 |
| Machine 6 % Setup | 16.56 | 16.98 | 16.39 | 16.38 | 16.44 |
| Unit Production Cost | $ 1,752.24 | $ 1,772.53 | $ 1,770.79 | $ 1,745.84 | $ 1,759.26 |
| Unit Early Cost | $ 0.30 | $ 0.28 | $ 0.27 | $ 0.29 | $ 0.31 |
| Unit Late Cost | $ 17.43 | $ 22.00 | $ 11.87 | $ 21.24 | $ 13.33 |
| Unit WIP Cost | $ 3.44 | $ 3.48 | $ 3.40 | $ 3.45 | $ 3.48 |
| Total Unit Cost | $ 1,773.42 | $ 1,798.29 | $ 1,786.33 | $ 1,770.82 | $ 1,776.37 |

Table A.27 Sensitivity Experiments, WLCFCFSLU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 59.2% | 60.8% | 62.5% | 54.4% | 60.7% |
| PSP Buffer Avg. Size | 525 | 526 | 533 | 598 | 520 |
| Buffer Machine 1 Avg. Size | 8.5 | 5.77 | 7.25 | 7.5 | 5.15 |
| Buffer Machine 2 Avg. Size | 7.35 | 8.25 | 6.22 | 5.21 | 9.42 |
| Buffer Machine 3 Avg. Size | 6.11 | 6.84 | 7.93 | 4.89 | 4.42 |
| Buffer Machine 4 Avg. Size | 7.34 | 6.89 | 5.6 | 9.13 | 5.66 |
| Buffer Machine 5 Avg. Size | 6.15 | 4.85 | 5.4 | 8.22 | 9.08 |
| Buffer Machine 6 Avg. Size | 4.94 | 7.44 | 6.9 | 5.42 | 5.76 |
| WIP Avg. Size | 40 | 40 | 39 | 40 | 39 |
| Machine 1 % Setup | 15.93 | 16.02 | 16.03 | 15.62 | 15.65 |
| Machine 2 % Setup | 15.91 | 16.32 | 16.05 | 16.05 | 15.88 |
| Machine 3 % Setup | 16.16 | 15.93 | 15.91 | 15.18 | 15.66 |
| Machine 4 % Setup | 15.98 | 16.23 | 16 | 16.05 | 16.17 |
| Machine 5 % Setup | 15.81 | 15.59 | 15.76 | 15.83 | 16.42 |
| Machine 6 % Setup | 15.67 | 16.16 | 15.86 | 15.93 | 15.34 |
| Unit Production Cost | $ 1,810.10 | $ 1,829.06 | $ 1,844.33 | $ 1,810.10 | $ 1,832.76 |
| Unit Early Cost | $ 0.35 | $ 0.37 | $ 0.38 | $ 0.33 | $ 0.38 |
| Unit Late Cost | $ 26.88 | $ 8.60 | $ 14.28 | $ 21.15 | $ 19.05 |
| Unit WIP Cost | $ 3.56 | $ 3.53 | $ 3.52 | $ 3.59 | $ 3.52 |
| Total Unit Cost | $ 1,840.89 | $ 1,841.56 | $ 1,862.51 | $ 1,835.16 | $ 1,855.71 |

Table A.28 Sensitivity Experiments, WLCFCFSLU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 59.9% | 59.1% | 59.0% | 59.9% | 61.9% |
| PSP Buffer Avg. Size | 546 | 580 | 513 | 585 | 508 |
| Buffer Machine 1 Avg. Size | 8.51 | 5.58 | 5.44 | 4.96 | 6.37 |
| Buffer Machine 2 Avg. Size | 6.41 | 5.69 | 4.34 | 8.77 | 6.87 |
| Buffer Machine 3 Avg. Size | 6.07 | 3.99 | 6.54 | 6.69 | 6.95 |
| Buffer Machine 4 Avg. Size | 6.15 | 7.24 | 5.69 | 7.76 | 6.42 |
| Buffer Machine 5 Avg. Size | 7.19 | 7.68 | 12 | 5.41 | 5.17 |
| Buffer Machine 6 Avg. Size | 5.71 | 9.83 | 5.92 | 6.23 | 7.6 |
| WIP Avg. Size | 40 | 40 | 40 | 40 | 39 |
| Machine 1 % Setup | 16.05 | 16.04 | 16.27 | 15.39 | 15.9 |
| Machine 2 % Setup | 16.68 | 16.15 | 15.65 | 15.78 | 15.82 |
| Machine 3 % Setup | 16.4 | 16 | 16.23 | 15.6 | 15.91 |
| Machine 4 % Setup | 16.09 | 15.95 | 16.21 | 15.59 | 15.86 |
| Machine 5 % Setup | 16.53 | 15.7 | 15.83 | 16.09 | 15.74 |
| Machine 6 % Setup | 15.52 | 16.5 | 15.73 | 16 | 15.8 |
| Unit Production Cost | $ 1,808.32 | $ 1,829.93 | $ 1,821.18 | $ 1,819.31 | $ 1,823.49 |
| Unit Early Cost | $ 0.35 | $ 0.35 | $ 0.36 | $ 0.37 | $ 0.38 |
| Unit Late Cost | $ 16.96 | $ 16.73 | $ 10.42 | $ 15.79 | $ 11.22 |
| Unit WIP Cost | $ 3.51 | $ 3.73 | $ 3.54 | $ 3.57 | $ 3.53 |
| Total Unit Cost | $ 1,829.14 | $ 1,850.75 | $ 1,835.50 | $ 1,839.04 | $ 1,838.62 |

Table A.29 Sensitivity Experiments, WLCSIMSET1HU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 65.2% | 66.8% | 66.1% | 66.4% | 65.9% |
| PSP Buffer Avg. Size | 551 | 564 | 630 | 632 | 581 |
| Buffer Machine 1 Avg. Size | 7.46 | 4.64 | 7.03 | 6.01 | 6.01 |
| Buffer Machine 2 Avg. Size | 5.96 | 6.9 | 5.61 | 7.95 | 8.29 |
| Buffer Machine 3 Avg. Size | 7.4 | 6.32 | 7.98 | 4.95 | 5.56 |
| Buffer Machine 4 Avg. Size | 7.27 | 8.96 | 5.39 | 5.27 | 5.3 |
| Buffer Machine 5 Avg. Size | 5.75 | 5.78 | 6.31 | 5.45 | 7.31 |
| Buffer Machine 6 Avg. Size | 6.45 | 6.92 | 7.02 | 7.76 | 7.56 |
| WIP Avg. Size | 40 | 40 | 39 | 37 | 40 |
| Machine 1 % Setup | 7.36 | 7.72 | 7.83 | 8.26 | 8.34 |
| Machine 2 % Setup | 8.21 | 7.23 | 8.6 | 7.94 | 7.42 |
| Machine 3 % Setup | 7.8 | 8.19 | 7.11 | 8.01 | 8.36 |
| Machine 4 % Setup | 7.71 | 7.85 | 8.87 | 7.39 | 8.5 |
| Machine 5 % Setup | 7.89 | 7.36 | 7.91 | 7.81 | 8.15 |
| Machine 6 % Setup | 8.02 | 7.44 | 8.03 | 7.22 | 7.51 |
| Unit Production Cost | $ 1,650.42 | $ 1,662.22 | $ 1,695.30 | $ 1,664.88 | $ 1,662.83 |
| Unit Early Cost | $ 0.57 | $ 0.60 | $ 0.61 | $ 0.60 | $ 0.59 |
| Unit Late Cost | $ 21.40 | $ 12.65 | $ 15.37 | $ 13.97 | $ 12.97 |
| Unit WIP Cost | $ 2.88 | $ 2.87 | $ 2.89 | $ 2.70 | $ 2.90 |
| Total Unit Cost | $ 1,675.26 | $ 1,678.34 | $ 1,714.17 | $ 1,682.15 | $ 1,679.29 |

Table A.30 Sensitivity Experiments, WLCSIMSET1HU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 65.7% | 67.0% | 67.2% | 65.3% | 66.1% |
| PSP Buffer Avg. Size | 595 | 629 | 533 | 640 | 590 |
| Buffer Machine 1 Avg. Size | 6.69 | 5.69 | 6.09 | 5.69 | 6.78 |
| Buffer Machine 2 Avg. Size | 7.1 | 5.67 | 7.76 | 7.8 | 7.22 |
| Buffer Machine 3 Avg. Size | 5.95 | 5.7 | 4.89 | 7.51 | 5.98 |
| Buffer Machine 4 Avg. Size | 6.26 | 7.04 | 5.37 | 8 | 5.79 |
| Buffer Machine 5 Avg. Size | 4.5 | 7.62 | 7.13 | 6.18 | 6.5 |
| Buffer Machine 6 Avg. Size | 4.76 | 7.84 | 5.47 | 4.84 | 7.44 |
| WIP Avg. Size | 35 | 40 | 37 | 40 | 40 |
| Machine 1 % Setup | 7.75 | 8.41 | 7.38 | 8.35 | 7.46 |
| Machine 2 % Setup | 7.92 | 8.56 | 8.16 | 7.82 | 8.12 |
| Machine 3 % Setup | 7.33 | 8.81 | 7.78 | 7.45 | 8.22 |
| Machine 4 % Setup | 7.63 | 7.84 | 7.4 | 7.44 | 7.39 |
| Machine 5 % Setup | 7.92 | 7.24 | 7.81 | 8.64 | 7.41 |
| Machine 6 % Setup | 8.07 | 7.74 | 7.35 | 9.09 | 7.85 |
| Unit Production Cost | $ 1,645.26 | $ 1,671.96 | $ 1,636.25 | $ 1,650.73 | $ 1,654.88 |
| Unit Early Cost | $ 0.56 | $ 0.60 | $ 0.59 | $ 0.58 | $ 0.58 |
| Unit Late Cost | $ 15.93 | $ 14.48 | $ 14.52 | $ 27.78 | $ 11.70 |
| Unit WIP Cost | $ 2.62 | $ 2.31 | $ 2.64 | $ 2.88 | $ 2.88 |
| Total Unit Cost | $ 1,664.36 | $ 1,689.35 | $ 1,654.00 | $ 1,681.96 | $ 1,670.04 |

Table A.31 Sensitivity Experiments, WLCSIMSET1LU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 66.3% | 69.9% | 71.0% | 66.2% | 71.7% |
| PSP Buffer Avg. Size | 38 | 11 | 112 | 93 | 16 |
| Buffer Machine 1 Avg. Size | 7.83 | 5.75 | 5.51 | 8.04 | 5.31 |
| Buffer Machine 2 Avg. Size | 7.02 | 7.24 | 5.43 | 5.75 | 7.62 |
| Buffer Machine 3 Avg. Size | 6.24 | 6.78 | 8.5 | 5.51 | 5.14 |
| Buffer Machine 4 Avg. Size | 7.8 | 6.21 | 5.77 | 6.62 | 5.36 |
| Buffer Machine 5 Avg. Size | 5.69 | 5.06 | 5.72 | 7.67 | 7.62 |
| Buffer Machine 6 Avg. Size | 4.66 | 6.9 | 6.15 | 5.83 | 7.05 |
| WIP Avg. Size | 39 | 38 | 37 | 39 | 38 |
| Machine 1 % Setup | 7.23 | 8.05 | 7.87 | 7.39 | 8.44 |
| Machine 2 % Setup | 7.36 | 7.32 | 8.01 | 8.06 | 7.18 |
| Machine 3 % Setup | 8 | 7.7 | 6.93 | 7.78 | 8.17 |
| Machine 4 % Setup | 7.18 | 7.68 | 8.13 | 7.82 | 7.99 |
| Machine 5 % Setup | 8.02 | 8.15 | 8.04 | 7.23 | 7.16 |
| Machine 6 % Setup | 8.25 | 7.6 | 8.04 | 7.92 | 7.22 |
| Unit Production Cost | $1,675.11 | $1,690.52 | $1,732.01 | $1,688.56 | $1,697.50 |
| Unit Early Cost | $ 0.62 | $ 0.68 | $ 0.69 | $ 0.63 | $ 0.71 |
| Unit Late Cost | $ 25.84 | $ 9.03 | $ 15.03 | $ 43.76 | $ 9.59 |
| Unit WIP Cost | $ 3.01 | $ 2.88 | $ 3.00 | $ 3.07 | $ 2.97 |
| Total Unit Cost | $1,704.58 | $1,703.11 | $1,750.73 | $1,736.02 | $1,710.76 |

Table A.32 Sensitivity Experiments, WLCSIMSET1LU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 75.4% | 70.9% | 76.6% | 69.1% | 75.7% |
| PSP Buffer Avg. Size | 7 | 53 | 12 | 97 | 17 |
| Buffer Machine 1 Avg. Size | 6.25 | 6.59 | 5.04 | 5.49 | 5.76 |
| Buffer Machine 2 Avg. Size | 6.3 | 5.89 | 4.12 | 8.52 | 6.44 |
| Buffer Machine 3 Avg. Size | 5.81 | 4.96 | 5.43 | 8.53 | 6.27 |
| Buffer Machine 4 Avg. Size | 6.42 | 6.24 | 6.8 | 5.47 | 6.69 |
| Buffer Machine 5 Avg. Size | 5.78 | 6.41 | 7.32 | 5.8 | 4.83 |
| Buffer Machine 6 Avg. Size | 5.99 | 7.97 | 4.82 | 4.83 | 6.16 |
| WIP Avg. Size | 37 | 38 | 34 | 39 | 36 |
| Machine 1 % Setup | 7.63 | 7.77 | 8.43 | 8.14 | 8.2 |
| Machine 2 % Setup | 7.78 | 8.05 | 8.89 | 6.5 | 7.84 |
| Machine 3 % Setup | 7.79 | 8.54 | 8.02 | 7.17 | 7.62 |
| Machine 4 % Setup | 7.83 | 8.07 | 7.56 | 8.09 | 7.96 |
| Machine 5 % Setup | 8.12 | 7.92 | 7.39 | 8.42 | 8.45 |
| Machine 6 % Setup | 7.92 | 7.02 | 8.63 | 8.25 | 7.92 |
| Unit Production Cost | $1,668.03 | $1,711.57 | $1,694.65 | $1,693.40 | $1,700.16 |
| Unit Early Cost | $ 0.74 | $ 0.67 | $ 0.81 | $ 0.64 | $ 0.76 |
| Unit Late Cost | $ 9.42 | $ 15.93 | $ 6.21 | $ 40.18 | $ 6.25 |
| Unit WIP Cost | $ 2.80 | $ 2.98 | $ 2.60 | $ 3.01 | $ 2.86 |
| Total Unit Cost | $1,680.99 | $1,731.15 | $1,704.26 | $1,737.24 | $1,710.04 |

Table A.33 Sensitivity Experiments, WLCSIMSET2HU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 72.9% | 71.2% | 71.6% | 73.6% | 72.8% |
| PSP Buffer Avg. Size | 574 | 601 | 602 | 662 | 591 |
| Buffer Machine 1 Avg. Size | 6.92 | 7.15 | 7.26 | 7.33 | 5.9 |
| Buffer Machine 2 Avg. Size | 6.47 | 5.75 | 5.38 | 5.01 | 6.29 |
| Buffer Machine 3 Avg. Size | 6.5 | 8.69 | 8.62 | 5.42 | 6.37 |
| Buffer Machine 4 Avg. Size | 7.19 | 7.4 | 5.25 | 6.76 | 6.39 |
| Buffer Machine 5 Avg. Size | 5.6 | 5.32 | 6.63 | 9.38 | 7.96 |
| Buffer Machine 6 Avg. Size | 6.64 | 6.21 | 6.98 | 5.79 | 6.8 |
| WIP Avg. Size | 39 | 41 | 40 | 40 | 40 |
| Machine 1 % Setup | 7.86 | 8.23 | 7.5 | 8.26 | 8.1 |
| Machine 2 % Setup | 7.84 | 8.27 | 8.68 | 8.63 | 7.88 |
| Machine 3 % Setup | 7.47 | 7.37 | 6.88 | 7.74 | 8.02 |
| Machine 4 % Setup | 7.83 | 7.97 | 9.04 | 7.36 | 7.58 |
| Machine 5 % Setup | 8.51 | 7.74 | 7.93 | 7.89 | 7.86 |
| Machine 6 % Setup | 7.85 | 8.92 | 7.92 | 7.99 | 7.7 |
| Unit Production Cost | $ 1,649.61 | $ 1,666.13 | $ 1,678.53 | $ 1,656.97 | $ 1,655.68 |
| Unit Early Cost | $ 0.73 | $ 0.74 | $ 0.76 | $ 0.76 | $ 0.84 |
| Unit Late Cost | $ 4.71 | $ 5.26 | $ 4.74 | $ 5.24 | $ 4.99 |
| Unit WIP Cost | $ 2.81 | $ 2.82 | $ 2.92 | $ 2.89 | $ 2.83 |
| Total Unit Cost | $ 1,657.86 | $ 1,674.95 | $ 1,686.95 | $ 1,665.85 | $ 1,664.33 |

Table A.34 Sensitivity Experiments, WLCSIMSET2HU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 73.3% | 71.6% | 74.0% | 73.5% | 74.3% |
| PSP Buffer Avg. Size | 589 | 616 | 577 | 645 | 590 |
| Buffer Machine 1 Avg. Size | 6.95 | 4.97 | 5.81 | 6.68 | 6.71 |
| Buffer Machine 2 Avg. Size | 6.39 | 5.78 | 4.98 | 7.85 | 6.26 |
| Buffer Machine 3 Avg. Size | 6.58 | 6.02 | 6.24 | 6.66 | 5.6 |
| Buffer Machine 4 Avg. Size | 5.85 | 7.52 | 6.59 | 7.52 | 6.17 |
| Buffer Machine 5 Avg. Size | 6.72 | 8.15 | 9.95 | 5.67 | 6.68 |
| Buffer Machine 6 Avg. Size | 6.73 | 8.02 | 5.11 | 4.99 | 7.64 |
| WIP Avg. Size | 39 | 40 | 39 | 39 | 39 |
| Machine 1 % Setup | 7.79 | 8.61 | 7.85 | 8.32 | 7.88 |
| Machine 2 % Setup | 7.47 | 8.24 | 8.49 | 7.37 | 6.99 |
| Machine 3 % Setup | 8.32 | 8.3 | 7.81 | 7.93 | 8.2 |
| Machine 4 % Setup | 9.01 | 7.84 | 7.91 | 7.76 | 7.86 |
| Machine 5 % Setup | 7.86 | 7.24 | 7.86 | 8.91 | 7.41 |
| Machine 6 % Setup | 8.29 | 7.77 | 7.49 | 8.72 | 7.67 |
| Unit Production Cost | $ 1,646.87 | $ 1,670.02 | $ 1,662.68 | $ 1,649.65 | $ 1,656.72 |
| Unit Early Cost | $ 0.74 | $ 0.75 | $ 0.76 | $ 0.74 | $ 0.76 |
| Unit Late Cost | $ 4.87 | $ 5.32 | $ 5.13 | $ 5.00 | $ 4.97 |
| Unit WIP Cost | $ 2.79 | $ 2.95 | $ 2.82 | $ 2.83 | $ 2.89 |
| Total Unit Cost | $ 1,655.26 | $ 1,679.03 | $ 1,671.39 | $ 1,658.22 | $ 1,665.33 |

Table A.35 Sensitivity Experiments, WLCSIMSET2LU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 75.6% | 76.9% | 77.0% | 75.5% | 73.9% |
| PSP Buffer Avg. Size | 11 | 7 | 57 | 101 | 18 |
| Buffer Machine 1 Avg. Size | 6.96 | 5.34 | 6.17 | 8.11 | 5.33 |
| Buffer Machine 2 Avg. Size | 6.98 | 6.88 | 5.61 | 6.16 | 5.92 |
| Buffer Machine 3 Avg. Size | 6.51 | 6.17 | 8.8 | 5.37 | 6.59 |
| Buffer Machine 4 Avg. Size | 6.92 | 6.51 | 5.57 | 6.8 | 6.91 |
| Buffer Machine 5 Avg. Size | 5.62 | 5.13 | 5.83 | 7.07 | 7.36 |
| Buffer Machine 6 Avg. Size | 4.72 | 5.64 | 5.64 | 5.35 | 6.77 |
| WIP Avg. Size | 38 | 36 | 38 | 39 | 39 |
| Machine 1 % Setup | 7.15 | 8.15 | 7.9 | 7.44 | 8.36 |
| Machine 2 % Setup | 7.56 | 7.69 | 7.7 | 8.02 | 8.36 |
| Machine 3 % Setup | 7.82 | 7.58 | 6.51 | 8.02 | 7.47 |
| Machine 4 % Setup | 7.36 | 7.6 | 8.24 | 7.96 | 7.42 |
| Machine 5 % Setup | 8.03 | 8.05 | 7.82 | 7.94 | 7.71 |
| Machine 6 % Setup | 8.69 | 8 | 8.03 | 8.17 | 7.83 |
| Unit Production Cost | $ 1,681.03 | $ 1,695.56 | $ 1,721.87 | $ 1,692.78 | $ 1,673.39 |
| Unit Early Cost | $ 0.81 | $ 0.86 | $ 0.86 | $ 0.83 | $ 0.79 |
| Unit Late Cost | $ 4.63 | $ 4.00 | $ 4.16 | $ 5.21 | $ 5.05 |
| Unit WIP Cost | $ 2.91 | $ 2.77 | $ 2.96 | $ 3.05 | $ 2.97 |
| Total Unit Cost | $ 1,689.38 | $ 1,703.19 | $ 1,729.85 | $ 1,701.86 | $ 1,682.19 |

Table A.36 Sensitivity Experiments, WLCSIMSET2LU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 74.5% | 79.1% | 81.4% | 76.2% | 73.7% |
| PSP Buffer Avg. Size | 33 | 54 | 23 | 87 | 18 |
| Buffer Machine 1 Avg. Size | 6.54 | 5.53 | 5.08 | 5.31 | 5.78 |
| Buffer Machine 2 Avg. Size | 6.19 | 5.87 | 3.69 | 9.44 | 6.81 |
| Buffer Machine 3 Avg. Size | 6.17 | 4.53 | 5.64 | 7.12 | 6.19 |
| Buffer Machine 4 Avg. Size | 6.42 | 5.49 | 7.32 | 5.51 | 6.4 |
| Buffer Machine 5 Avg. Size | 6.09 | 7.31 | 6.84 | 6.1 | 5.13 |
| Buffer Machine 6 Avg. Size | 5.84 | 8.2 | 4.69 | 4.76 | 5.33 |
| WIP Avg. Size | 37 | 37 | 33 | 38 | 36 |
| Machine 1 % Setup | 7.42 | 7.85 | 8.32 | 8.16 | 8.12 |
| Machine 2 % Setup | 7.87 | 7.96 | 9.03 | 6.57 | 7.59 |
| Machine 3 % Setup | 8.08 | 8.8 | 8.33 | 7.72 | 7.77 |
| Machine 4 % Setup | 7.91 | 8.26 | 7.38 | 8.41 | 7.9 |
| Machine 5 % Setup | 7.78 | 7.65 | 7.58 | 8.05 | 8.57 |
| Machine 6 % Setup | 7.97 | 7.17 | 8.56 | 8.48 | 7.94 |
| Unit Production Cost | $ 1,659.87 | $ 1,712.93 | $ 1,695.85 | $ 1,677.77 | $ 1,699.47 |
| Unit Early Cost | $ 0.77 | $ 0.86 | $ 0.92 | $ 0.82 | $ 0.82 |
| Unit Late Cost | $ 4.32 | $ 4.08 | $ 3.26 | $ 4.85 | $ 4.89 |
| Unit WIP Cost | $ 2.83 | $ 2.91 | $ 2.59 | $ 2.96 | $ 2.82 |
| Total Unit Cost | $ 1,667.79 | $ 1,720.78 | $ 1,702.62 | $ 1,686.41 | $ 1,708.00 |

Table A.37 Sensitivity Experiments, WLCMCFCFSHU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 68.1% | 69.4% | 66.5% | 68.5% | 93.0% |
| PSP Buffer Avg. Size | 638 | 648 | 988 | 662 | 664 |
| Buffer Machine 1 Avg. Size | 4.52 | 3.84 | 3.68 | 3.46 | 2.93 |
| Buffer Machine 2 Avg. Size | 4.35 | 3.86 | 3.61 | 3.65 | 3.6 |
| Buffer Machine 3 Avg. Size | 4.07 | 3.63 | 7.14 | 4.28 | 4.39 |
| Buffer Machine 4 Avg. Size | 3.97 | 4.23 | 3.42 | 3.81 | 3.18 |
| Buffer Machine 5 Avg. Size | 3.52 | 4.23 | 3.48 | 4.26 | 6.21 |
| Buffer Machine 6 Avg. Size | 3.82 | 5.07 | 3.85 | 4.85 | 4.32 |
| WIP Avg. Size | 24 | 25 | 25 | 24 | 25 |
| Machine 1 % Setup | 16.21 | 16.05 | 16.03 | 15.89 | 15.54 |
| Machine 2 % Setup | 16.51 | 15.89 | 15.47 | 19.89 | 16.06 |
| Machine 3 % Setup | 16.36 | 15.49 | 15.97 | 16.01 | 15.98 |
| Machine 4 % Setup | 16.06 | 16 | 15.61 | 15.97 | 16 |
| Machine 5 % Setup | 15.84 | 16.08 | 15.46 | 15.68 | 16.33 |
| Machine 6 % Setup | 16.4 | 15.75 | 15.99 | 16.1 | 15.76 |
| Unit Production Cost | $ 1,671.33 | $ 1,667.65 | $ 1,679.28 | $ 1,666.06 | $ 1,666.44 |
| Unit Early Cost | $ 0.45 | $ 0.47 | $ 0.45 | $ 0.47 | $ 0.62 |
| Unit Late Cost | $ 36.76 | $ 32.60 | $ 32.23 | $ 34.05 | $ 6.66 |
| Unit WIP Cost | $ 1.96 | $ 2.06 | $ 2.07 | $ 1.98 | $ 2.00 |
| Total Unit Cost | $ 1,710.50 | $ 1,702.79 | $ 1,714.03 | $ 1,702.55 | $ 1,675.72 |

Table A.38 Sensitivity Experiments, WLCMCFCFSHU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 66.1% | 67.9% | 69.9% | 65.8% | 68.6% |
| PSP Buffer Avg. Size | 659 | 634 | 619 | 657 | 623 |
| Buffer Machine 1 Avg. Size | 2.99 | 4.43 | 3.46 | 3.78 | 3.49 |
| Buffer Machine 2 Avg. Size | 3.85 | 3.81 | 3.12 | 5.5 | 4.76 |
| Buffer Machine 3 Avg. Size | 4.19 | 3.45 | 3.8 | 4.53 | 3.51 |
| Buffer Machine 4 Avg. Size | 3.96 | 3.92 | 5.09 | 3.74 | 3.66 |
| Buffer Machine 5 Avg. Size | 4.13 | 4.07 | 3.75 | 3.36 | 4.06 |
| Buffer Machine 6 Avg. Size | 4.28 | 4.34 | 3.05 | 3.59 | 3.76 |
| WIP Avg. Size | 23 | 24 | 22 | 25 | 23 |
| Machine 1 % Setup | 16.14 | 16.93 | 16.15 | 16.02 | 16.01 |
| Machine 2 % Setup | 16.4 | 15.93 | 15.62 | 16.39 | 15.97 |
| Machine 3 % Setup | 16.53 | 16.17 | 15.81 | 16.15 | 15.68 |
| Machine 4 % Setup | 16.22 | 15.78 | 16.96 | 15.64 | 16.51 |
| Machine 5 % Setup | 16.51 | 15.58 | 15.94 | 15.94 | 16.36 |
| Machine 6 % Setup | 15.98 | 16.13 | 16.21 | 16.32 | 16.06 |
| Unit Production Cost | $ 1,671.03 | $ 1,685.64 | $ 1,663.78 | $ 1,658.55 | $ 1,669.16 |
| Unit Early Cost | $ 0.45 | $ 0.47 | $ 0.50 | $ 0.43 | $ 0.46 |
| Unit Late Cost | $ 30.99 | $ 25.87 | $ 39.08 | $ 45.74 | $ 54.32 |
| Unit WIP Cost | $ 1.97 | $ 1.98 | $ 1.91 | $ 1.95 | $ 1.95 |
| Total Unit Cost | $ 1,704.44 | $ 1,713.96 | $ 1,705.26 | $ 1,706.68 | $ 1,725.89 |

Table A.39 Sensitivity Experiments, WLCMCFCFSLU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 77.4% | 75.8% | 76.9% | 76.8% | 79.1% |
| PSP Buffer Avg. Size | 296 | 297 | 314 | 314 | 306 |
| Buffer Machine 1 Avg. Size | 4.11 | 3.07 | 3.36 | 3.54 | 3.01 |
| Buffer Machine 2 Avg. Size | 3.73 | 4.3 | 3.23 | 2.88 | 3.88 |
| Buffer Machine 3 Avg. Size | 3.35 | 3.52 | 6.28 | 3.41 | 3.07 |
| Buffer Machine 4 Avg. Size | 4 | 4.15 | 3.15 | 3.81 | 2.95 |
| Buffer Machine 5 Avg. Size | 3.41 | 3.5 | 3.15 | 3.87 | 4.98 |
| Buffer Machine 6 Avg. Size | 2.86 | 3.93 | 3.55 | 3.78 | 3.62 |
| WIP Avg. Size | 21 | 22 | 23 | 21 | 22 |
| Machine 1 % Setup | 15.35 | 15.4 | 15.48 | 15.16 | 15.25 |
| Machine 2 % Setup | 15.56 | 15.59 | 15.47 | 15.53 | 15.45 |
| Machine 3 % Setup | 15.47 | 15.46 | 15.87 | 15.32 | 15.15 |
| Machine 4 % Setup | 15.61 | 15.91 | 15.4 | 15.4 | 15.5 |
| Machine 5 % Setup | 15.65 | 15.15 | 15.32 | 15.5 | 15.69 |
| Machine 6 % Setup | 21 | 3.98 | 6.98 | 6.08 | 6.2 |
| Unit Production Cost | $ 1,735.35 | $ 1,740.85 | $ 1,763.43 | $ 1,735.97 | $ 1,745.65 |
| Unit Early Cost | $ 0.61 | $ 0.61 | $ 0.62 | $ 0.61 | $ 0.64 |
| Unit Late Cost | $ 19.66 | $ 18.71 | $ 12.66 | $ 21.12 | $ 22.79 |
| Unit WIP Cost | $ 1.83 | $ 1.94 | $ 2.01 | $ 1.85 | $ 1.88 |
| Total Unit Cost | $ 1,757.46 | $ 1,762.12 | $ 1,778.72 | $ 1,759.55 | $ 1,770.97 |

Table A.40 Sensitivity Experiments, WLCMCFCFSLU Treatment, Samples 6 – 10.

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 75.8% | 77.0% | 78.4% | 73.5% | 76.9% |
| PSP Buffer Avg. Size | 299 | 315 | 284 | 331 | 284 |
| Buffer Machine 1 Avg. Size | 4.16 | 4.05 | 3.28 | 3.81 | 3.43 |
| Buffer Machine 2 Avg. Size | 3.83 | 3.37 | 3.16 | 4.95 | 4.12 |
| Buffer Machine 3 Avg. Size | 4.12 | 2.69 | 3.54 | 3.9 | 3.31 |
| Buffer Machine 4 Avg. Size | 3.25 | 3.42 | 4.45 | 2.99 | 3.59 |
| Buffer Machine 5 Avg. Size | 3.28 | 3.52 | 3.44 | 3.05 | 2.94 |
| Buffer Machine 6 Avg. Size | 3.19 | 4.34 | 2.33 | 3.07 | 3.04 |
| WIP Avg. Size | 22 | 21 | 20 | 22 | 20 |
| Machine 1 % Setup | 15.64 | 15.4 | 15.83 | 15.66 | 15.03 |
| Machine 2 % Setup | 15.56 | 15.6 | 15.49 | 15.47 | 15.66 |
| Machine 3 % Setup | 15.73 | 15.5 | 15.83 | 15.25 | 15.37 |
| Machine 4 % Setup | 15.65 | 15.68 | 15.74 | 14.83 | 15.47 |
| Machine 5 % Setup | 15.83 | 15.36 | 15.69 | 14.53 | 15.31 |
| Machine 6 % Setup | 9.09 | 4.17 | 10.28 | 7.99 | 6.37 |
| Unit Production Cost | $ 1,722.70 | $ 1,747.80 | $ 1,733.58 | $ 1,708.77 | $ 1,733.45 |
| Unit Early Cost | $ 0.60 | $ 0.62 | $ 0.65 | $ 0.58 | $ 0.61 |
| Unit Late Cost | $ 16.94 | $ 13.83 | $ 21.85 | $ 1.86 | $ 20.37 |
| Unit WIP Cost | $ 1.87 | $ 1.87 | $ 1.75 | $ 1.87 | $ 1.79 |
| Total Unit Cost | $ 1,742.11 | $ 1,764.12 | $ 1,757.83 | $ 1,713.08 | $ 1,756.23 |

Table A.41 Sensitivity Experiments, WLCMCSIMSET1HU Treatment, Samples 1 – 5.

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 78.6% | 78.9% | 77.6% | 77.4% | 78.8% |
| PSP Buffer Avg. Size | 402 | 414 | 431 | 421 | 417 |
| Buffer Machine 1 Avg. Size | 3.8 | 3.29 | 3.5 | 3.78 | 2.91 |
| Buffer Machine 2 Avg. Size | 2.72 | 3.89 | 3.94 | 3.24 | 3.59 |
| Buffer Machine 3 Avg. Size | 3.98 | 3.86 | 5.45 | 3.47 | 4.22 |
| Buffer Machine 4 Avg. Size | 4.07 | 4.19 | 3.59 | 3.56 | 3.01 |
| Buffer Machine 5 Avg. Size | 3.17 | 3.55 | 3.28 | 4.54 | 4.39 |
| Buffer Machine 6 Avg. Size | 3.48 | 3.62 | 3.68 | 3.76 | 3.9 |
| WIP Avg. Size | 21 | 22 | 23 | 22 | 22 |
| Machine 1 % Setup | 9.37 | 8.89 | 9.6 | 9.68 | 9.88 |
| Machine 2 % Setup | 9.39 | 9.27 | 9.25 | 10.01 | 9.32 |
| Machine 3 % Setup | 9.22 | 9.43 | 7.84 | 9.49 | 9.03 |
| Machine 4 % Setup | 9.2 | 9.91 | 9.47 | 8.92 | 9.97 |
| Machine 5 % Setup | 9.54 | 9.57 | 9.7 | 8.86 | 8.72 |
| Machine 6 % Setup | 9.83 | 9.43 | 9.37 | 9.35 | 9.14 |
| Unit Production Cost | $ 1,598.93 | $ 1,592.82 | $ 1,613.58 | $ 1,593.54 | $ 1,600.72 |
| Unit Early Cost | $ 0.65 | $ 0.66 | $ 0.65 | $ 0.64 | $ 0.68 |
| Unit Late Cost | $ 12.62 | $ 11.92 | $ 13.43 | $ 15.29 | $ 13.45 |
| Unit WIP Cost | $ 1.59 | $ 1.61 | $ 1.73 | $ 1.65 | $ 1.60 |
| Total Unit Cost | $ 1,613.80 | $ 1,607.01 | $ 1,629.40 | $ 1,611.12 | $ 1,616.45 |

Table A.42 Sensitivity Experiments, WLCMCSIMSET1HU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 77.5% | 79.4% | 78.9% | 76.4% | 79.1% |
| PSP Buffer Avg. Size | 418 | 414 | 401 | 439 | 387 |
| Buffer Machine 1 Avg. Size | 3.56 | 3.85 | 3.36 | 4 | 3.32 |
| Buffer Machine 2 Avg. Size | 3.49 | 3.65 | 3.09 | 4.6 | 4.02 |
| Buffer Machine 3 Avg. Size | 4.23 | 3.25 | 3.65 | 4.06 | 3.19 |
| Buffer Machine 4 Avg. Size | 3.67 | 3.6 | 4.18 | 3.43 | 3.28 |
| Buffer Machine 5 Avg. Size | 4.7 | 3.71 | 3.36 | 2.89 | 3.74 |
| Buffer Machine 6 Avg. Size | 3.27 | 4.1 | 2.99 | 3.47 | 3.47 |
| WIP Avg. Size | 23 | 22 | 21 | 22 | 21 |
| Machine 1 % Setup | 9.21 | 9.34 | 9.63 | 9.24 | 9.08 |
| Machine 2 % Setup | 9.24 | 9.61 | 9.31 | 8.77 | 9.52 |
| Machine 3 % Setup | 9.63 | 9.92 | 9.38 | 8.88 | 9.63 |
| Machine 4 % Setup | 9.44 | 9.3 | 9.42 | 9.52 | 9.24 |
| Machine 5 % Setup | 9.7 | 9.16 | 9.71 | 10.07 | 9.83 |
| Machine 6 % Setup | 9.21 | 8.87 | 9.24 | 9.58 | 9.32 |
| Unit Production Cost | $ 1,692.06 | $ 1,605.45 | $ 1,591.05 | $ 1,586.07 | $ 1,595.73 |
| Unit Early Cost | $ 0.68 | $ 0.67 | $ 0.66 | $ 0.61 | $ 0.66 |
| Unit Late Cost | $ 17.40 | $ 9.65 | $ 18.66 | $ 17.05 | $ 12.05 |
| Unit WIP Cost | $ 1.74 | $ 1.63 | $ 1.57 | $ 1.62 | $ 1.57 |
| Total Unit Cost | $ 1,711.89 | $ 1,617.39 | $ 1,611.94 | $ 1,605.35 | $ 1,610.00 |

Table A.43 Sensitivity Experiments, WLCMCSIMSET1LU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 86.3% | 86.0% | 84.9% | 85.2% | 86.9% |
| PSP Buffer Avg. Size | 139 | 128 | 137 | 141 | 131 |
| Buffer Machine 1 Avg. Size | 3.22 | 3.01 | 3.75 | 3.19 | 2.9 |
| Buffer Machine 2 Avg. Size | 3.56 | 3.61 | 3.2 | 2.92 | 3.7 |
| Buffer Machine 3 Avg. Size | 3.37 | 3 | 4.78 | 3.24 | 2.8 |
| Buffer Machine 4 Avg. Size | 3.46 | 3.36 | 2.9 | 3.2 | 2.95 |
| Buffer Machine 5 Avg. Size | 3.02 | 3.1 | 2.9 | 3.46 | 3.69 |
| Buffer Machine 6 Avg. Size | 2.65 | 3.85 | 3.18 | 3.57 | 3.26 |
| WIP Avg. Size | 19 | 20 | 21 | 20 | 19 |
| Machine 1 % Setup | 9.41 | 9.61 | 9.04 | 9.4 | 9.17 |
| Machine 2 % Setup | 9.42 | 9.26 | 9.53 | 9.91 | 9.03 |
| Machine 3 % Setup | 9.57 | 9.7 | 8.21 | 9.48 | 9.73 |
| Machine 4 % Setup | 9.21 | 9.33 | 9.96 | 9.53 | 10.01 |
| Machine 5 % Setup | 9.29 | 9.57 | 9.79 | 9.47 | 8.94 |
| Machine 6 % Setup | 10.13 | 9.02 | 9.63 | 9.26 | 9.29 |
| Unit Production Cost | $ 1,664.92 | $ 1,671.80 | $ 1,692.24 | $ 1,671.02 | $ 1,678.16 |
| Unit Early Cost | $ 0.85 | $ 0.86 | $ 0.83 | $ 0.85 | $ 0.89 |
| Unit Late Cost | $ 6.26 | $ 6.19 | $ 7.58 | $ 12.19 | $ 8.54 |
| Unit WIP Cost | $ 1.53 | $ 1.57 | $ 1.67 | $ 1.56 | $ 1.54 |
| Total Unit Cost | $ 1,673.56 | $ 1,680.43 | $ 1,702.32 | $ 1,685.62 | $ 1,689.13 |

Table A.44 Sensitivity Experiments, WLCMCSIMSET1LU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 85.9% | 86.2% | 86.8% | 84.9% | 86.8% |
| PSP Buffer Avg. Size | 125 | 142 | 135 | 156 | 118 |
| Buffer Machine 1 Avg. Size | 3.53 | 3.18 | 3 | 3.5 | 3.12 |
| Buffer Machine 2 Avg. Size | 3.73 | 3.22 | 2.74 | 3.86 | 3.34 |
| Buffer Machine 3 Avg. Size | 3.1 | 2.73 | 2.94 | 3.48 | 3.18 |
| Buffer Machine 4 Avg. Size | 3.3 | 3.08 | 3.2 | 3 | 3.11 |
| Buffer Machine 5 Avg. Size | 3.14 | 3.23 | 3.55 | 2.82 | 2.79 |
| Buffer Machine 6 Avg. Size | 3.09 | 3.96 | 2.57 | 3.15 | 3.23 |
| WIP Avg. Size | 20 | 19 | 18 | 20 | 19 |
| Machine 1 % Setup | 8.91 | 9.64 | 9.76 | 9.29 | 9.72 |
| Machine 2 % Setup | 9.24 | 9.61 | 9.95 | 8.93 | 9.15 |
| Machine 3 % Setup | 9.69 | 10.03 | 9.87 | 9.52 | 9.29 |
| Machine 4 % Setup | 9.53 | 9.88 | 9.56 | 9.57 | 9.56 |
| Machine 5 % Setup | 9.8 | 9.41 | 9.06 | 9.73 | 9.95 |
| Machine 6 % Setup | 9.93 | 8.87 | 10.07 | 9.43 | 9.71 |
| Unit Production Cost | $ 1,660.41 | $ 1,677.23 | $ 1,665.42 | $ 1,671.91 | $ 1,670.14 |
| Unit Early Cost | $ 0.83 | $ 0.83 | $ 0.86 | $ 0.83 | $ 0.86 |
| Unit Late Cost | $ 8.24 | $ 6.12 | $ 7.81 | $ 8.74 | $ 5.42 |
| Unit WIP Cost | $ 1.56 | $ 1.55 | $ 1.43 | $ 1.58 | $ 1.51 |
| Total Unit Cost | $ 1,671.04 | $ 1,685.74 | $ 1,675.52 | $ 1,683.06 | $ 1,677.93 |

Table A.45  Sensitivity Experiments, WLCMCSIMSET2HU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 76.4% | 74.0% | 73.2% | 73.6% | 77.5% |
| PSP Buffer Avg. Size | 421 | 433 | 462 | 454 | 433 |
| Buffer Machine 1 Avg. Size | 3.86 | 3.68 | 3.78 | 3.56 | 3.6 |
| Buffer Machine 2 Avg. Size | 3.85 | 4.12 | 4.03 | 3.03 | 3.84 |
| Buffer Machine 3 Avg. Size | 3.94 | 3.97 | 5.39 | 3.63 | 5.29 |
| Buffer Machine 4 Avg. Size | 4.25 | 4.23 | 3.2 | 3.65 | 3.71 |
| Buffer Machine 5 Avg. Size | 3.24 | 3.72 | 3.43 | 4.85 | 3.33 |
| Buffer Machine 6 Avg. Size | 3.4 | 3.64 | 3.72 | 3.93 | 4.01 |
| WIP Avg. Size | 23 | 23 | 24 | 23 | 24 |
| Machine 1 % Setup | 10.18 | 9.85 | 10.54 | 10.92 | 9.29 |
| Machine 2 % Setup | 10.12 | 10.32 | 10.65 | 10.49 | 9.49 |
| Machine 3 % Setup | 9.95 | 10.28 | 9.45 | 10.32 | 9.21 |
| Machine 4 % Setup | 9.71 | 10.19 | 10.99 | 10.38 | 7.86 |
| Machine 5 % Setup | 10.28 | 10.49 | 10.64 | 9.96 | 9.51 |
| Machine 6 % Setup | 10.27 | 10.36 | 10.57 | 10.53 | 9.39 |
| Unit Production Cost | $ 1,604.03 | $ 1,600.15 | $ 1,627.49 | $ 1,597.82 | $ 1,613.58 |
| Unit Early Cost | $ 0.64 | $ 0.61 | $ 0.56 | $ 0.59 | $ 0.65 |
| Unit Late Cost | $ 14.24 | $ 17.91 | $ 17.34 | $ 16.16 | $ 1.29 |
| Unit WIP Cost | $ 1.65 | $ 1.68 | $ 1.75 | $ 1.67 | $ 1.74 |
| Total Unit Cost | $ 1,620.56 | $ 1,620.35 | $ 1,647.15 | $ 1,616.24 | $ 1,617.27 |

Table A.46  Sensitivity Experiments, WLCMCSIMSET2HU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 74.7% | 74.5% | 74.4% | 71.8% | 74.3% |
| PSP Buffer Avg. Size | 439 | 442 | 425 | 476 | 420 |
| Buffer Machine 1 Avg. Size | 3.74 | 3.66 | 3.41 | 3.83 | 3.12 |
| Buffer Machine 2 Avg. Size | 3.96 | 3.41 | 3.33 | 4.86 | 4.27 |
| Buffer Machine 3 Avg. Size | 2.76 | 3.22 | 3.74 | 4.17 | 3.65 |
| Buffer Machine 4 Avg. Size | 4.2 | 3.6 | 4.41 | 3.65 | 3.83 |
| Buffer Machine 5 Avg. Size | 3.94 | 3.84 | 3.92 | 3.1 | 3.76 |
| Buffer Machine 6 Avg. Size | 4.56 | 4.54 | 2.75 | 3 | 3.32 |
| WIP Avg. Size | 23 | 22 | 22 | 23 | 22 |
| Machine 1 % Setup | 10.26 | 10.31 | 10.67 | 10.52 | 10.38 |
| Machine 2 % Setup | 10.31 | 10.46 | 10.54 | 9.84 | 10.32 |
| Machine 3 % Setup | 9.87 | 10.16 | 10.89 | 10.45 | 10.88 |
| Machine 4 % Setup | 9.91 | 10.33 | 9.63 | 10.45 | 10.78 |
| Machine 5 % Setup | 10.32 | 10.26 | 10.56 | 10.47 | 9.86 |
| Machine 6 % Setup | 9.86 | 9.81 | 10.58 | 10.84 | 10.26 |
| Unit Production Cost | $ 1,612.96 | $ 1,619.86 | $ 1,597.20 | $ 1,599.05 | $ 1,604.21 |
| Unit Early Cost | $ 0.60 | $ 0.59 | $ 0.62 | $ 0.55 | $ 0.61 |
| Unit Late Cost | $ 16.43 | $ 12.24 | $ 15.99 | $ 16.78 | $ 14.44 |
| Unit WIP Cost | $ 1.67 | $ 1.66 | $ 1.62 | $ 1.66 | $ 1.66 |
| Total Unit Cost | $ 1,631.67 | $ 1,634.36 | $ 1,615.42 | $ 1,618.05 | $ 1,620.92 |

Table A.47 Sensitivity Experiments, WLCMCSIMSET2LU Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 86.2% | 84.8% | 84.4% | 84.6% | 86.1% |
| PSP Buffer Avg. Size | 130 | 135 | 148 | 147 | 137 |
| Buffer Machine 1 Avg. Size | 3.44 | 3.16 | 3.37 | 3.28 | 2.78 |
| Buffer Machine 2 Avg. Size | 3.54 | 3.48 | 3.2 | 2.62 | 3.44 |
| Buffer Machine 3 Avg. Size | 3.13 | 3.34 | 4.81 | 3.23 | 3.14 |
| Buffer Machine 4 Avg. Size | 3.55 | 3.34 | 2.97 | 3.27 | 2.8 |
| Buffer Machine 5 Avg. Size | 2.86 | 3.53 | 2.85 | 3.32 | 3.64 |
| Buffer Machine 6 Avg. Size | 2.87 | 3.63 | 3.17 | 3.56 | 3.43 |
| WIP Avg. Size | 19 | 20 | 20 | 19 | 19 |
| Machine 1 % Setup | 9.32 | 9.95 | 9.69 | 9.79 | 9.82 |
| Machine 2 % Setup | 9.44 | 9.74 | 9.6 | 10.29 | 9.62 |
| Machine 3 % Setup | 9.83 | 9.66 | 8.44 | 9.75 | 9.75 |
| Machine 4 % Setup | 9.75 | 9.8 | 10.18 | 9.92 | 10.14 |
| Machine 5 % Setup | 9.98 | 9.43 | 9.96 | 9.87 | 9.24 |
| Machine 6 % Setup | 10.07 | 9.62 | 9.99 | 9.71 | 9.66 |
| Unit Production Cost | $ 1,675.34 | $ 1,680.44 | $ 1,696.93 | $ 1,673.83 | $ 1,683.04 |
| Unit Early Cost | $ 0.86 | $ 0.85 | $ 0.82 | $ 0.83 | $ 0.85 |
| Unit Late Cost | $ 11.29 | $ 9.12 | $ 6.07 | $ 9.34 | $ 9.90 |
| Unit WIP Cost | $ 1.54 | $ 1.34 | $ 1.65 | $ 1.55 | $ 1.55 |
| Total Unit Cost | $ 1,689.02 | $ 1,691.74 | $ 1,705.46 | $ 1,685.55 | $ 1,695.34 |

Table A.48 Sensitivity Experiments, WLCMCSIMSET2LU Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 85.9% | 85.0% | 87.2% | 85.6% | 86.3% |
| PSP Buffer Avg. Size | 141 | 147 | 130 | 162 | 129 |
| Buffer Machine 1 Avg. Size | 3.55 | 3.56 | 3.19 | 3.27 | 3.02 |
| Buffer Machine 2 Avg. Size | 3.5 | 3.19 | 2.55 | 3.86 | 3.49 |
| Buffer Machine 3 Avg. Size | 3.48 | 2.54 | 3.03 | 3.2 | 2.95 |
| Buffer Machine 4 Avg. Size | 3.15 | 3.01 | 3.31 | 3.11 | 3.24 |
| Buffer Machine 5 Avg. Size | 2.8 | 3.1 | 3.56 | 2.73 | 2.7 |
| Buffer Machine 6 Avg. Size | 3.07 | 3.9 | 2.47 | 3.02 | 3.05 |
| WIP Avg. Size | 20 | 19 | 18 | 19 | 18 |
| Machine 1 % Setup | 9.61 | 9.54 | 9.92 | 9.9 | 9.93 |
| Machine 2 % Setup | 9.56 | 9.9 | 10.46 | 9.26 | 9.62 |
| Machine 3 % Setup | 9.78 | 10.73 | 10.23 | 10.16 | 9.81 |
| Machine 4 % Setup | 9.87 | 10.16 | 9.76 | 10.04 | 9.9 |
| Machine 5 % Setup | 10.26 | 9.96 | 9.41 | 10.33 | 10.16 |
| Machine 6 % Setup | 9.97 | 9.27 | 10.38 | 9.85 | 9.98 |
| Unit Production Cost | $ 1,660.55 | $ 1,680.68 | $ 1,671.61 | $ 1,680.11 | $ 1,670.59 |
| Unit Early Cost | $ 0.81 | $ 0.84 | $ 0.86 | $ 0.84 | $ 0.84 |
| Unit Late Cost | $ 8.84 | $ 5.66 | $ 6.15 | $ 6.65 | $ 4.40 |
| Unit WIP Cost | $ 1.54 | $ 1.55 | $ 1.44 | $ 1.54 | $ 1.49 |
| Total Unit Cost | $ 1,671.75 | $ 1,688.73 | $ 1,680.06 | $ 1,689.14 | $ 1,677.32 |

# APPENDIX B

# PHASE TWO SIMULATION EXPERIMENTS OUTPUT DATA

Table B.1 Phase 2 Simulation Output, IMMFCFS Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 59.1% | 59.4% | 63.3% | 62.8% | 60.2% |
| PSP Buffer Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 1 Avg. Size | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 |
| Buffer Machine 2 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 3 Avg. Size | 13.46 | 13.88 | 10.69 | 9.46 | 10.16 |
| Buffer Machine 4 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 5 Avg. Size | 53.77 | 50.32 | 47.11 | 50.08 | 49 |
| Buffer Machine 6 Avg. Size | 0.43 | 0.24 | 0.3 | 0.31 | 0.28 |
| Buffer Machine 7 Avg. Size | 1.09 | 0.82 | 0.66 | 0.54 | 0.92 |
| Buffer Machine 8 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 9 Avg. Size | 35.44 | 38.64 | 38.41 | 40.63 | 43.22 |
| Buffer Machine 10 Avg. Size | 0.96 | 0.97 | 1.17 | 0.96 | 1.04 |
| WIP Avg. Size | 105.17 | 104.89 | 98.36 | 101.99 | 104.64 |
| Machine 1 % Setup | 4.2% | 4.0% | 4.2% | 4.2% | 4.1% |
| Machine 2 % Setup | 4.3% | 4.2% | 4.5% | 4.3% | 4.4% |
| Machine 3 % Setup | 21.9% | 21.9% | 21.9% | 21.8% | 21.9% |
| Machine 4 % Setup | 2.6% | 2.6% | 2.7% | 2.6% | 2.7% |
| Machine 5 % Setup | 9.6% | 9.5% | 9.6% | 9.3% | 9.5% |
| Machine 6 % Setup | 13.4% | 13.9% | 13.9% | 13.9% | 14.0% |
| Machine 7 % Setup | 10.6% | 10.6% | 10.5% | 10.5% | 10.6% |
| Machine 8 % Setup | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Machine 9 % Setup | 16.4% | 15.9% | 15.2% | 15.7% | 15.7% |
| Machine 10 % Setup | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Unit Production Cost | $ 664.60 | $ 674.33 | $ 660.01 | $ 772.18 | $ 669.10 |
| Unit Early Cost | $ 0.25 | $ 0.29 | $ 0.32 | $ 0.35 | $ 0.30 |
| Unit Late Cost | $ 3.54 | $ 3.74 | $ 3.10 | $ 3.97 | $ 3.75 |
| Unit WIP Cost | $ 10.66 | $ 11.07 | $ 10.31 | $ 12.47 | $ 11.20 |
| Total Unit Cost | $ 679.05 | $ 689.43 | $ 673.72 | $ 788.97 | $ 684.36 |

Table B.2 Phase 2 Simulation Output, IMMFCFS Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 63.1% | 61.8% | 59.9% | 56.6% | 61.7% |
| PSP Buffer Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 1 Avg. Size | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 |
| Buffer Machine 2 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 3 Avg. Size | 12.77 | 10.03 | 13.34 | 14.58 | 10.57 |
| Buffer Machine 4 Avg. Size | 0 | 0 | 0 | 0 | 0.01 |
| Buffer Machine 5 Avg. Size | 47.7 | 50.99 | 48.79 | 53.6 | 52.76 |
| Buffer Machine 6 Avg. Size | 0.19 | 0.39 | 0.42 | 0.26 | 0.28 |
| Buffer Machine 7 Avg. Size | 0.6 | 0.56 | 0.82 | 0.49 | 0.75 |
| Buffer Machine 8 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 9 Avg. Size | 41.5 | 40.42 | 41.3 | 35.92 | 36.17 |
| Buffer Machine 10 Avg. Size | 0.95 | 1.01 | 1.02 | 0.99 | 1.03 |
| WIP Avg. Size | 103.72 | 103.42 | 105.7 | 105.85 | 101.59 |
| Machine 1 % Setup | 4.2% | 4.1% | 4.1% | 4.2% | 4.0% |
| Machine 2 % Setup | 44.1% | 4.5% | 4.3% | 4.3% | 4.2% |
| Machine 3 % Setup | 21.8% | 21.8% | 21.9% | 22.0% | 21.3% |
| Machine 4 % Setup | 2.6% | 2.6% | 2.6% | 2.6% | 2.5% |
| Machine 5 % Setup | 9.5% | 9.6% | 9.5% | 9.7% | 9.5% |
| Machine 6 % Setup | 13.9% | 13.7% | 14.0% | 13.9% | 13.8% |
| Machine 7 % Setup | 10.5% | 10.6% | 10.7% | 10.4% | 10.7% |
| Machine 8 % Setup | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Machine 9 % Setup | 15.6% | 15.6% | 15.5% | 15.4% | 14.9% |
| Machine 10 % Setup | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Unit Production Cost | $ 664.70 | $ 668.21 | $ 668.71 | $ 670.14 | $ 655.38 |
| Unit Early Cost | $ 0.30 | $ 0.29 | $ 0.29 | $ 0.26 | $ 0.28 |
| Unit Late Cost | $ 3.65 | $ 3.43 | $ 3.76 | $ 3.67 | $ 3.19 |
| Unit WIP Cost | $ 11.00 | $ 10.97 | $ 11.20 | $ 10.80 | $ 10.32 |
| Total Unit Cost | $ 679.65 | $ 682.90 | $ 683.96 | $ 684.88 | $ 669.18 |

Table B.3  Phase 2 Simulation Output, WLCMCSIMSET1 Treatment, Samples 1 – 5

| | Sample 1 | Sample 2 | Sample3 | Sample 4 | Sample5 |
|---|---|---|---|---|---|
| % On Time | 92.9% | 93.6% | 89.7% | 91.5% | 93.2% |
| PSP Buffer Avg. Size | 433.31 | 440.78 | 366.6 | 387.58 | 375.39 |
| Buffer Machine 1 Avg. Size | 0.04 | 0.04 | 0.02 | 0.03 | 0.04 |
| Buffer Machine 2 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 3 Avg. Size | 5.02 | 4.78 | 4.55 | 4.53 | 4.94 |
| Buffer Machine 4 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 5 Avg. Size | 4.73 | 4.18 | 4.85 | 4.8 | 5.13 |
| Buffer Machine 6 Avg. Size | 0.24 | 0.22 | 0.16 | 0.22 | 0.13 |
| Buffer Machine 7 Avg. Size | 0.47 | 0.38 | 0.36 | 0.4 | 0.22 |
| Buffer Machine 8 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 9 Avg. Size | 11.85 | 12.21 | 12.09 | 12.4 | 12.03 |
| Buffer Machine 10 Avg. Size | 0.83 | 0.82 | 0.87 | 0.87 | 0.82 |
| WIP Avg. Size | 23.18 | 22.63 | 22.9 | 23.25 | 23.31 |
| Machine 1 % Setup | 3.0% | 3.0% | 3.3% | 4.2% | 3.2% |
| Machine 2 % Setup | 3.4% | 3.3% | 3.5% | 3.1% | 3.4% |
| Machine 3 % Setup | 11.8% | 11.7% | 12.7% | 12.1% | 12.4% |
| Machine 4 % Setup | 1.7% | 1.6% | 1.9% | 1.7% | 1.7% |
| Machine 5 % Setup | 5.6% | 5.5% | 6.1% | 5.5% | 5.7% |
| Machine 6 % Setup | 11.9% | 11.1% | 12.4% | 11.4% | 12.2% |
| Machine 7 % Setup | 8.0% | 7.7% | 8.2% | 7.7% | 8.0% |
| Machine 8 % Setup | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Machine 9 % Setup | 6.3% | 5.9% | 5.9% | 6.0% | 6.0% |
| Machine 10 % Setup | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Unit Production Cost | $ 570.72 | $ 568.71 | $ 567.73 | $ 564.74 | $ 571.01 |
| Unit Early Cost | $ 0.83 | $ 0.82 | $ 0.81 | $ 0.81 | $ 0.85 |
| Unit Late Cost | $ 1.83 | $ 1.38 | $ 1.62 | $ 1.48 | $ 0.97 |
| Unit WIP Cost | $ 2.50 | $ 2.48 | $ 2.46 | $ 2.47 | $ 2.51 |
| Total Unit Cost | $ 575.87 | $ 573.39 | $ 572.62 | $ 569.49 | $ 575.33 |

Table B.4 Phase 2 Simulation Output, WLCMCSIMSET1 Treatment, Samples 6 – 10

| | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 |
|---|---|---|---|---|---|
| % On Time | 91.5% | 93.6% | 92.1% | 92.6% | 91.4% |
| PSP Buffer Avg. Size | 374.2 | 475.01 | 394.87 | 392.88 | 357.79 |
| Buffer Machine 1 Avg. Size | 0.03 | 0.02 | 0.03 | 0.02 | 0.03 |
| Buffer Machine 2 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 3 Avg. Size | 5.3 | 4.94 | 4.36 | 4.96 | 4.54 |
| Buffer Machine 4 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 5 Avg. Size | 5.15 | 4.35 | 4.87 | 4.61 | 4.66 |
| Buffer Machine 6 Avg. Size | 0.11 | 0.18 | 0.21 | 0.13 | 0.2 |
| Buffer Machine 7 Avg. Size | 0.33 | 0.4 | 0.44 | 0.28 | 0.53 |
| Buffer Machine 8 Avg. Size | 0 | 0 | 0 | 0 | 0 |
| Buffer Machine 9 Avg. Size | 12.11 | 12.25 | 12.61 | 12.47 | 12.05 |
| Buffer Machine 10 Avg. Size | 0.8 | 0.93 | 0.77 | 0.83 | 0.88 |
| WIP Avg. Size | 23.83 | 23.07 | 23.29 | 23.3 | 22.89 |
| Machine 1 % Setup | 3.1% | 3.2% | 3.1% | 3.1% | 3.2% |
| Machine 2 % Setup | 3.3% | 3.4% | 3.3% | 3.2% | 3.5% |
| Machine 3 % Setup | 12.0% | 12.0% | 12.3% | 11.8% | 12.2% |
| Machine 4 % Setup | 1.8% | 1.7% | 1.9% | 1.7% | 1.7% |
| Machine 5 % Setup | 5.7% | 5.3% | 5.9% | 5.6% | 5.5% |
| Machine 6 % Setup | 6.8% | 11.2% | 12.1% | 12.0% | 11.6% |
| Machine 7 % Setup | 7.9% | 7.4% | 8.2% | 8.1% | 7.9% |
| Machine 8 % Setup | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Machine 9 % Setup | 6.1% | 5.9% | 5.8% | 5.7% | 6.3% |
| Machine 10 % Setup | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Unit Production Cost | $ 567.26 | $ 567.69 | $ 568.48 | $ 571.62 | $ 563.78 |
| Unit Early Cost | $ 0.82 | $ 0.82 | $ 0.83 | $ 0.82 | $ 0.81 |
| Unit Late Cost | $ 1.40 | $ 1.78 | $ 1.68 | $ 1.09 | $ 1.04 |
| Unit WIP Cost | $ 2.51 | $ 2.50 | $ 2.51 | $ 2.52 | $ 2.47 |
| Total Unit Cost | $ 571.98 | $ 572.79 | $ 573.50 | $ 576.06 | $ 568.09 |

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