Engineering Management
Field Project

Investigate the applicability, performance, and implementation strategy of workload control in Y company For Customer Satisfaction

By

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Fall Semester, 2016

An EMGT Field Project thesis submitted to the Engineering Management Program and the Faculty of the Graduate School of the University of Kansas in partial fulfillment of the requirements for the degree of Master's of Science

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Accepted on: 12/23/16

Acknowledgments

I would like to acknowledge the faculty and staff of the University of Kansas Engineering Management Program for giving me the opportunity to study in the US as an international graduate student. Also, many thanks to my instructors for the knowledge and expertise they have provided, which has helped me to acquire knowledge and skills. Special thanks to the committee chair, Professor Herbert Tuttle, for being my principle advisor, and committee members, Dr. Tom Bowlin and Professor Linda Miller, for serving as committee members and also reviewing my work.

I would like to thank the KU Writing Center for reviewing my work, improving the style of writing, and holding workshops to ease the research and writing process. I would also like to thank the University of Kansas Library resources for supplying access to valued databases and recent research papers.

I would like to thank my financial sponsorship, the Higher Committee for Education Development in Iraq (HCED Iraq), for the immense help during the process of admission and supporting me financially.

I would like to thank my wife, who travelled all the way from my country to support and encourage me. Thank you for being optimistic and inspiringly person during hard times and thank you for being in my life.

Executive Summary

Workload control concept (WLC) is well known as a unique production and planning control (PPC) for small and medium-sized enterprises with limited financial resources. WLC is designed to meet the needs of controlling and stabilizing the workload in shop floor for make-to-order and make-to-engineer companies, where job shop configuration is typical.

WLC was developed over the course of three decades and was based on theoretical, conceptual, mathematical, analytical, and simulated situations. Conceptually, WLC consists of four levels or stages. The first stage is customer inquiry management, which is when companies place bids or quotes for an order. The second stage is the job entry stage, where a competitive due date is assigned to each order. The third stage is the order release stage, which consists of reviewing orders in a pre-shop pool until their release date. The last stage is priority dispatching, which prioritizes the released orders on the shop floor.

It has been practically proven that WLC reduces work-in-process and total throughput time by 30-40%, despite the small percentages demonstrated by simulations. Most of the studies focused on developing releasing rules to control order release; however, few successful implementations have been reported. The deviation in performance and theory is known as workload control paradox. This deviation proves that simulations do not reliably calculate expected performance, which should be considered before the implementation of WLC.

This study evaluates the implementation of WLC in Y company. The first part of this study measures the suitability of the Y company as made-to-order business. Then,

further investigation explores the applicability of WLC, which analyses Y company's characteristics using a framework. Testing the applicability of WLC reduces the chance of jeopardizing the implementation of the inconvenient PPC approach that may cost time and money, which may risk the success of the company.

The second part of the study assesses the performance of WLC in the Y company by analyzing one method for the due date assignment, five different rules for releasing orders, and two separate rules for dispatching. The simulation is constructed with high face validity to resemble the actual Y production system and types of orders and routes; however, the data used in this simulation is taken from previous studies (Thurer, Stevenson, Silva, Land, & Fredendall, 2011) since the primary goal is to measure the performance of WLC by using different rules and factors based on a company with a comparable business model.

The third part outlines the implementation of the WLC strategy. Some scholars have reported that some implementation approaches have produced several issues. Even though there have been few successful implementation cases, a detailed application procedure has not been established; therefore, implementation strategies are also outlined in detail. The most recent research on WLC was used to construct the most applicable strategy for successful implementation.

The results indicated that some barriers Y company prevent from implementing WLC. Through the simulation, one releasing rule was identified as the most compatible rule for the Y company. Finally, the limitations and future implications are discussed.

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Chapter One - Introduction

Manufacturing companies compete with each other on product quality, prices, variety, innovation, and delivery times in order to dominate the market and maintain success. Higher product quality means higher production and shipping costs, which dictates a higher price; therefore, all these factors are connected and must be taken into account when executives create company strategies.

C-suit managers are responsible for knowing the current capabilities of the company when they set the company's vision. This vision must be attainable by considering the current company's abilities as well as rivals' strategies. The company's business model converts the company's vision to an actual plan, which determines its competitiveness in the market. An operation strategy allocates resources and dictates production capacity in order to maintain a successful business. Creating a business model without having a defined operational strategy reduces the probability of having a successful business.

On an operational level, manufacturing companies have different methods to meet their demand. Some companies deliver products to their customers from pre-made inventory or stock. These types of companies are Make-To-Stock (MTS) manufacturers with a production environment known as Low Variety- High Volume manufacturing, where companies manufacture a specific number of products by estimating their number of customers, and then store inventory waiting for orders. Most of the lean concepts developed for this type of production reduces waste, which is implemented by manufacturing products based on a Just-In-Time calculation.

Make-To-Order (MTO) companies manufacture products per customer requests. These companies use High Variety- Low Volume (HVLV) manufacturing, where companies manufacture a product with specific quantities depending on existing orders.

MTO companies that utilize HVLV manufacturing are known as Small Medium-Sized Enterprises (SMEs). These companies specialize in creating variations of items in low volumes. MTO companies vary in necessary materials, delivery time, routing, and resource requirements. Orders are completed depending on closest due date, routing, and available capacity on the shop floor. The interarrival time between jobs is periodic and not continuous because products are not standard and customers request different types of product in various quantities. The variety of product customizations and quantities makes it illogical to maintain a continuous production level on the shop floor.

Alternative PPC have been researched and developed over the last three decades to find a system that best suit MTO and reduces fluctuation for SMEs. WLC is one of the PPCs that was designed specifically for MTO industries and job shop manufacturing (Stevenson, Hendry, and Kingsman, 2005; as cited in Fernandes, 2014). WLC is considered as a fundamental concept that handles the performance of MTO companies that experience high workload fluctuation (Thürer, 2014a). WLC focuses on maintaining a small and stable buffer for capacity constraints to create a predictable job pattern in order to meet the due date (DD) assigned during the bidding stage. Fredendall (2010) indicated that WLC reduces 40-50% of the time in the system.

This study investigates the ability to implement WLC in Y company. This investigation examines the applicability of adopting WLC through creating four levels and embedding them within the company's practices. The investigation includes: (1)

understanding the WLC including rules, shop characteristics, and performance measurement, (2) discussing implementation strategy and the issues that might be encountered during implementation, and (3) conducting a simulation to assess the WLC performance.

The Y company specializes in manufacturing oil equipment and vessels. The typical work of the Y company is MTO job shop with HVLV. The company has four main factories within one location, but each section is managed independently from the other three sections. However, the workloads for all four sections are managed under one planning department. Each factory has unique production facilities, so different jobs and products can be created. Products manufactured by Y company range from tanks, vessels, towers, heat exchangers, and fire tube boilers in various sizes. The production procedures vary from item to item due to the fact that some jobs require maintenance, such as changing part of internal components, external shells or nozzles, others manufacturing a full equipment as requested by the client. Since these jobs differ in size, route, procedure, duration, and required floor capacity, it is very complicated to meet the due date and keep track of the floor capacity.

Therefore, two planning controls were created: the first is the planning department and the second is embedded within factory management. Currently, Y company prioritizes jobs to meet the DD. The shop management prioritizes the orders because they consider themselves the most experienced in production; the planning department releases jobs to the shop floor, so the management in the factories can control the workload. The shop fell behind on some jobs because there was not a systematic method to control the workload on the shop floor. To remedy the problem, the factory management allocated all resources to one job, which delayed other jobs.

The primary objective of this project is to find the solution that can be implemented to control the workload on the shop floor while taking into consideration the issues during the adoption of WLC.

Chapter 2 - Literature Review

The WLC was developed within the last ten years. WLC was advanced to overcome the lead time syndrome (Mather and Plossl, 1978, as cited in Thürer 2011b). A relation was first introduced by Little (Thürer 2011b) between throughput time and work-in-process (WIP). This relation is called Little's Law. The particular law concludes that reducing the mean of WIP leads to decreasing the throughput time for any system in a steady state situation irrespective of the variation of input and output orders. WLC is a production concept that is used to control input and output loads to determine a short and predictable lead time to improve the delivery consistency in job shop type of production with MTO. WLC is a policy with a philosophy to maintain short, stable, and predictable queue in a production system to reduce throughput time (Kirchhof & Kirchhof, 2008).

For MTO companies, competition is very common by offering a competitive price and a realistic DD. It is imperative for these companies to have historical data to establish realistic specification for job opportunities. It is crucial before the order entry in the system to consider whether to include this order in the company total workload calculation or not. To meet the assigned DD during manufacturing, a pre-shop pool is created to prioritize jobs, but not to release them until the workload in shop floor was below a predefined threshold level (Bertolini, Romagnoli, & Zammori, 2015). With this releasing mechanism, WIP is controlled in the shop floor, and fluctuation is reduced, which is the aim of using WLC.

Review of The History of WLC

An article by Zapfel and Missbauer (1993, as cited in Thürer, 2011b), was the first publication that used the term WLC, which referred to a group of PPC methods. At that time, WLC was represented as a group of three streamed research fields that were aimed to control the workload. The primary focus was organizing the orders for dispatch instead of the rate of entered workload (Melnyk & Melnyk, 1989).

The first workload control system was introduced and developed in North America, which is called order review and release (ORR). Using ORR controls the order before it is released to the shop floor, which was recommended by Wight (1970), Nicholson and Pullen (1972), Sandman and Hayes (1980), and Melnyk and Ragatz (1987) (as cited in Melnyk & Melnyk, 1989). Other researchers studied the ORR method and found that the idea of controlling order release did not reduce or improve the delivery time or performance more than the dispatching method. However, Bertrand (1983) and Baker (1984) used a very simple order release mechanism as discussed in Melnyk and Ragatz (1988) and referred to in (Melnyk & Melnyk, 1989).

Another workload control technique is the input/ output control (I/OC) system. I/OC was developed at Lancaster University in the UK (Thürer,2011b) and is also known as the LUMS approach.

The third workload control method is referred to as load oriented manufacturing control (LOMC), which was developed in Germany at Hanover University. Later, Land and Gaalman (Thürer, 2011b) reviewed and combined LUMS and LOMC into one system called ORR WLC (Thürer,2011b). Today, WLC refers to the four concepts above (ORR, I/OC, LUMS, LOMC) as one concept and each one is part of WLC.

WLC Levels

As different research concepts introduced previously in the literature regarding the history of controlling workload in a job shop through controlling releasing jobs before dispatching, all WLC methods share the same idea of creating pre-shop pools and order releasing mechanisms to reduce throughput time. Figure 1 shows WLC concepts emerged from ORR as the intermediate between the planning system and the shop floor, which have three control levels: job entry, order release, and dispatching. At each WLC level, decisions determine the system flow time or total throughput time because they control the overall time spent in the pool and on the floor shop.

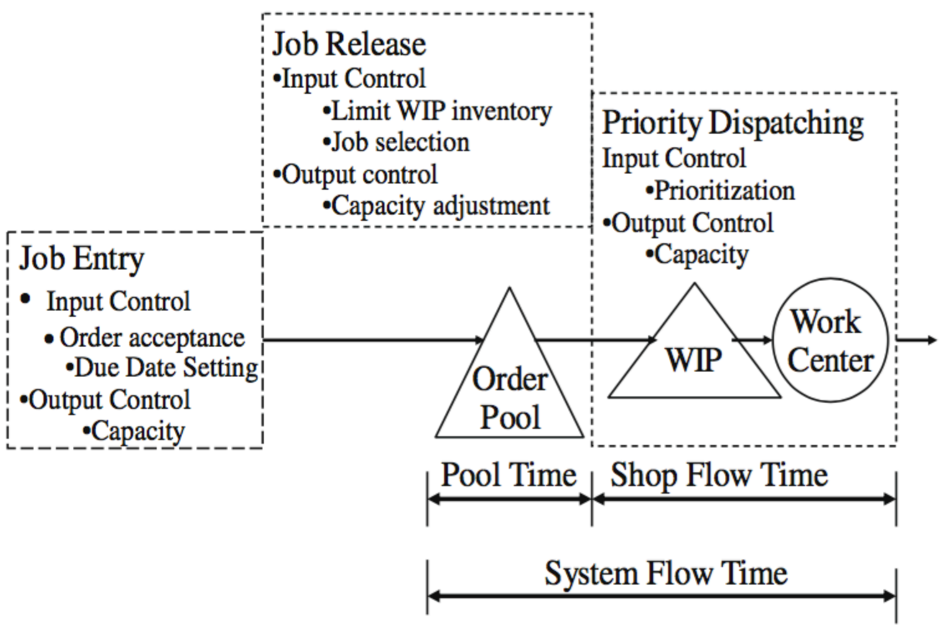

Figure 1. Workload Control Rules.

At the job entry control level, the input control decision is made to accept or reject the order, and the output control decision is to assign the DD for each order and adjust the capacity centers (Fredendall, 2010). Job entry is crucial because input control allows some orders to be rejected in order to reduce congestion in shop floor and improve delivery time. Whereas, output control decisions reduce lead or total throughput time by adjusting the capacity or due date lengthiness (Thürer, 2011b).

Job or order release level is considered a very critical level in the WLC because it controls when and how many orders are released. There are many releasing techniques introduced by researchers, depending on early releasing date (ERD), planned released date (PRD), rush jobs, the length of the route, set-up time, and job size. However, jobs must not violate or exceed the norm predefined for the floor shop. The output control decision is tantamount to adjusting the work capacity when needed. Priority dispatching input control decisions serve to prioritize jobs before entering the shop floor. The importance of dispatching is low, particularly when the order release is strong, and a small queue length is maintained by WLC (Fredendall, 2010)

WLC has the same three levels as the ORR method, though a fourth level was added: customer enquiry management (CEM) within the job entry phase (see Figure 2). The LUMS approach is constructed around controlling the workload through the hierarchy of backlog (Mark Stevenson, 2006). The total backlog represents the proportion of all work content for unconfirmed and accepted jobs during quotation time. The planned backlog is the total work content for jobs during pool time, waiting for materials, or in shop floor jobs. Released backlog represents the total work content for jobs in the shop floor. The four levels of WLC will be discussed in depth in Chapter 3.

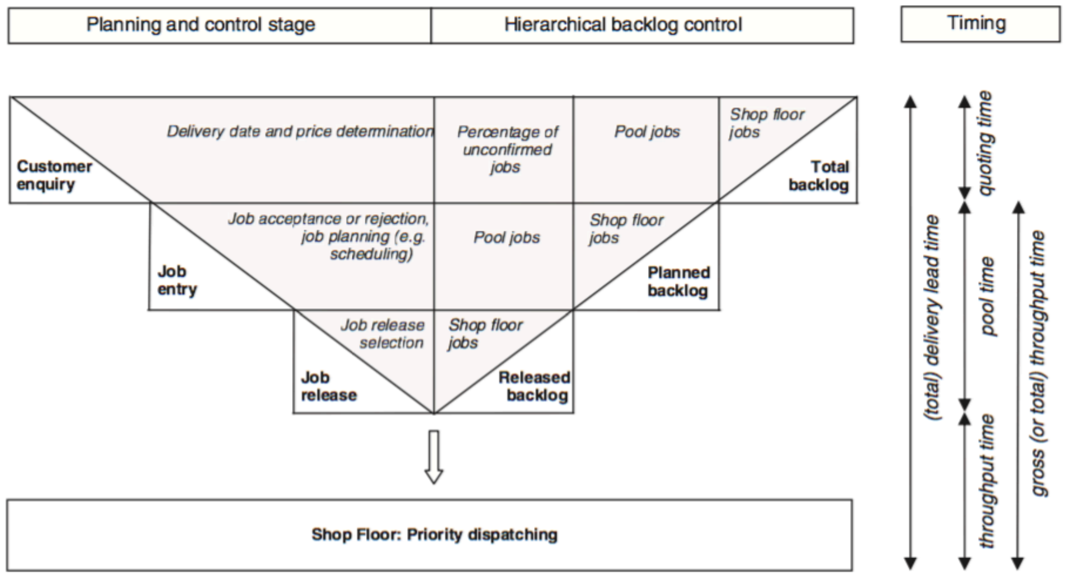

Figure 2. LUMS Approach to WLC.

WLC Research' Categories

Since WLC has been identified as the best PPC for MTO with HVLV, the body of research surrounding WLC focuses on multiple aspects of the system. Some researchers adapt and develop WLC approaches by building on other methods, mechanisms, and performance either by using mathematical models, empirical data, or simulations. Thürer (2011b) classified this type of research into four categories to predict the direction of future inquiries: conceptual research, analytical research, empirical research, and simulation research. Within each category, several research teams work in different categories. Table 1 indicates these categories and the researchers associated with that category.

	Category	Group	Research	Note
1	Conceptual WLC research	- Categorization of WLC	(Henrich, 2004)	A framework introduced to explore the applicability of WLC for MTO with SMEs and analyzing the characteristic of a company.
		- Reviewing different PPC concepts and WLC	(Thürer, 2014a)	New rule to WLC concept to subcontract tardy orders.
		- Developing the theory of the LUMS Approach	(Fernandes, 2014)	Investigate WLC effectiveness in unbalance job shop with different work center utilization
			(Mark Stevenson, 2006)	Re-evaluate and reclassify the LUMS approach using eight criteria.
2	Analytical WLC Research	- Analytical models applying queuing theory	(Z. G. Zhang, 2009)	Study the problem of adjusting workload under an unitized server in queuing system
			(Haskose, 2004)	An approximation algorithm developed to cope with any number workstations with limit buffer capacity.
		- Mathematical analysis of new release methods	(S. Zhang, 2013)	Study order release based on economic perspective
3	Empirical WLC research	- Research based on single cases	(Soepenberg, 2012)	Investigate the method to adapt WLC in job shop with high routing complexity.
		- Research based on multiple cases	Stevenson & (Mark Stevenson, 2011)	Research agenda on for refining WLC to close practice to theory and implementation strategy.
			(Hendry & Linda, 2013)	Present a successful implementation for WLC

			(M. Stevenson, 2008)	Two cases were studied and compared from different countries
4	Simulation-based WLC research	- Testing the influence of WLC on performance to find the best fit between control stages	(Thürer, 2012b)	Investigate the sequence- depend set-up time and develop new oriented dispatched rule and assesses the performance impact on order release.
			(Thürer, 2014a)	Design new subcontract rules and compare them with existing rules and assesses improving performance
			(Thürer, 2014b)	Study on WLC four stages and performance assessment measured by conducting simulation
		- The influence of environmental (external) parameters on performance	(Henrich, 2004)	Develop new framework to demonstrate the company suitability for WLC
			(Oosterman, 2000)	Studying the influence of job shop routing on the performance of WLC
		- The influence of WLC characteristics (internal parameters) on performance	(Thürer, 2011a)	Predict workload norm without feedback form shop floor and analysis the influence of shop floor characteristic workload norms.
			(Land, 2006)	Improve the root of setting parameters and their impact of performance

Table 1 - Summary of Literatures.

Project Literature Review

The four stages of WLC (enquiry management, job entry, order release, and priority dispatching) represent the most comprehensive approach to WLC methods. The primary input control decides how to assign DD, job acceptance, releasing time or period, job release selection, and the number of jobs released at one time. WLC fundamental principles control the total input rate of work in harmony with the total output rate, control and limit the amount of work in shop floor, and stabilize the throughput time by reducing fluctuation in workload in shop floor (Mark Stevenson, 2011)

Many parameters must be managed carefully to support order release decisions within WLC (Land, 2006). Workload norms are essential to implementing successful WLC in practice, which is determined by appropriate workload norms (Land, 2004; Silva, 2006; as cited in Thürer, 2011a). The workload norms are determined by identifying the existing workload at the work center, the planned workload output, and the workload queue for each station on the shop floor. Many workload rules are established based on maximum and minimum workloads. The maximum, or upper bound, limits the maximum workload so no jobs are released if it violates the upper workload limit. The upper bound controls the workload balance to prevent overload and delays on the shop floor. The minimum, or lower bound, prevents a certain section from having an empty workload queue. In addition to workload norms, the length of the releasing period based on the order release decision must be appropriate and provide realistic throughput time and DD.

Simulation is well known for the capability to simulate a real system close enough to glean information on how the system will work or improve the existing system. Also, simulations allow for changes in the system parameters and control factors to identify any potential problems at different points in the system. Most simulation studies have focused on order releasing mechanisms to assess the performance of WLC in HVLV MTO job shop workload norms (Bertolini et al., 2015). Simulations have also been conducted to assess job shops' performance by integrating CEM, assigning DD, and order release under WLC concept and measuring their impact on shop performance (Thürer, 2014b). Simulation have been used to: introduce the importance of shop characteristics for selecting releasing method (Oosterman, 2000) and study the performance of setting DDs for multi-stage assembly shops (Thürer, 2012c). Fredendall (2010) compared 25 WLC rules using a simulation measuring constant WIP, with maximum workload norm, using the Drum-Buffer-Rope (DBR) concept. Also, Thürer and Stevenson (2014) conducted a simulation assessment on introducing new rules for subcontracting orders for MTO companies and compared the performance with the old rules.

Additionally, conceptual and analytical articles provide conceptual arguments and mathematical analysis in order to develop the WLC. Henrich (2004) developed a framework for assessing the applicability of WLC. Stevenson and Hendry (2006) re-evaluated and reclassified the LUMS approach using eight criteria. Fernandes (2014) Investigated WLC effectiveness in an unbalanced job shop with various work center utilizations.

As for mathematical analyses, Z. G. Zhang (2009) used an M/G/1 queuing model to study the problem of adjusting workload under a utilized server in a queuing system. Zhang (2009) used a numerical analysis of a job shop to study the work order release system from an economic perspective by minimizing the sum of order lead time, order lateness, and WIP cost. Haskose (2004) developed an approximate algorithm as an extension of Zhang's (2009) study for WLC where there was a limit buffer capacity in front of workstations for different queuing networks.

As many papers have been published on simulation, there are also many empirical research papers that have examined the use of WLC in practice; however, limited cases report having successful practical implantation. A group of authors found that the performance of WLC observed, in reality, is different from what had been seen in simulation, which called the WLC Paradox (Stevenson * & Stevenson, 2005). As a result, more research required to set a clear process for implementation.

Stevenson (2011) interviewed 41 companies to compile their perceptions of WLC implementation in MTO SMEs. Research outputs provided a research agenda for refining WLC concept to reduce the gap between theory and practice for WLC implantation strategies. Two cases were compared to study the theoretical refinements that had to be made on WLC in order to be implemented efficiently (M. Stevenson, 2008). A study conducted by Hendry & Linda (2013)was the first study to empirically determine performance improvements for implementing WLC with details to the implementation process.

The direction of future studies seems to lean toward implementation and refinement of WLC in order to efficiently embed WLC into existing companies' PPC; however, there is no comprehensive research that reviews a company's suitability and applicability as an MTO and use of WLC using a simulated implementation strategy.

Conducting a simulation to provide insight for performance improvements by utilizing WLC concept in the Y company is not enough to consider if WLC is the right concept of PPC method to implement. Studying the WLC applicability in the company, taking in mind the characteristic of WLC, assessing whether WLC fits the Y company or not, and understanding an implementation strategy which represents the right procedure for the Y company is the goal of this project.

Chapter 3 - Research Procedure

PPC systems are essential tools for companies to maintain a higher competitive position and meet customer's demands and expectations. Archetypal functions of any PPC system include demand management, capacity planning, schedule planning, and planning material requirements (Stevenson * & Stevenson, 2005). The purposes of these functions are to reduce WIP, decrease shop floor throughput time, reduce costs, meet the DD, and improve alertness for demanding change; therefore, choosing a suitable PPC approach that copes with the type of company is a critical decision. Since there are many PPC methods and software producers, determining the suitability of the PPC system has been a complex decision for companies.

Many alternative PPC approaches usually put companies in a desperate situation due to the lack of indication of the type of the company, which reduces the probability of gaining any benefit from implementing a certain PPC approach. Also, some software packages, which are programmed earlier with specific features, do not always present the right choice because they are built on exterior features that do not represent the required features for an industry. Therefore, companies must decide which would be the correct path because of the high cost of the implementation, the amount of time, and the need to change the culture and work practice.

MTO companies have a higher probability in making a mistake in choosing the right PPC approach because of the variation in the number of customized products and size of jobs. Unlike MTO, MTS sector tends to have a continuous production and repeatable business that simplify the method of planning and controlling the ability to predict or estimate customer demands. Competition between MTO companies has increased because of the advancement in requesting customized products, which leads to growth. Hence, the characteristics and requirements of the MTO sector to select the right PPC system should be addressed because of the importance of MTO. Also, MTO companies are SMEs with limited financial resources, which may have negative consequences of implementing unappropriated PPC approach.

Selecting and applying a suitable PPC concept requires going over three stages that represent a systematic approach in order to overcome the difficulties in choosing PPC decision making (see Figure 3). The three stages are the research procedure utilized in this project.

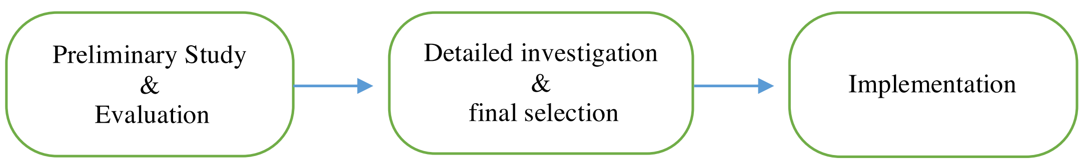

Figure. 3. Stages in Selecting and Implementing a PPC Concept.

1. Preliminary study and evaluation: selecting a PPC concept among PPC concepts. This stage is a pre-selecting stage where Y company is going to be classified whether it belongs to MTO sector or not before exploring the applicability of WLC.
2. Detailed investigation and final selection: investigating WLC four levels, CEM, job entry, order release, and dispatching in more depth, and simulating WLC concept to assess its performance.
3. Implementation: in this stage, presenting the implementation strategy and discussing successful implantation cases and issues.

Preliminary Study and Evaluation

The first step is to ascertain that Y company is MTO before exploring the characteristics of Y company with WLC levels.

The characteristics of MTO Sector

MTO as a term includes within it companies that are ready to manufacture or assemble products at the moment the order takes place. Also, MTO refers to companies that need to design a product upon request before manufacturing a product. In this study, MTO refers to the type of companies that need to design and manufacture a product only after confirming an order. For a Y company, the design work takes place only after confirming the order and sign a contract with the requested manufacturing specifications and terms. A Y company's customers are linked with strong ties since it is the only existing company on a national level with capabilities of manufacturing customized oil products. This link is known as an earlier order penetration point (OPP).

Customization

The earlier OPP meant that a company could offer a high degree of customization products. This capability is an essential strategic objective for this company to maintain its position in the market and sustain competitive advantages. However, ability leads to production difficulties because of the non- standardized products routing inside the shop floor; unlike MTS companies, therefore, forecasting demand accurately, applying a probably batch production methods, and ordering materials in advance cannot be done. MTO sector or "highly customized" industry can be divided into two types: Repeat

Business Customizers (RBC) and Versatile Manufacturing Companies (VMC) (Stevenson * & Stevenson, 2005). RBC refers to the manufacturing of customized products on a continuous basis where a contract is made for a specific number of products, repeatedly. VMC, on the other hand, refers to products with high customization that require a sophisticated production control because of the small quantity and large variety where orders compete individually (see Figure 4).

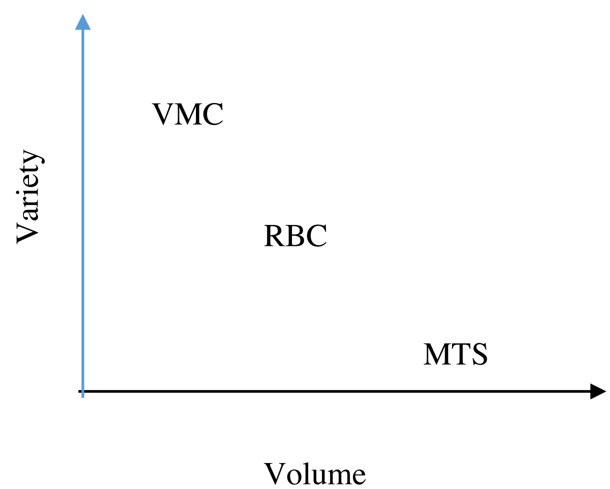

Figure 4. Classification Based on Variety and Volume.

The Y company is a type of company with VMC that does not have a range of customized product to offer, high variety of products. In the oil field, specifically in refineries, there are many types of equipment and products queued to manufacture mixers, towers, vessels, storage tanks, drums, boilers, heat exchangers, oil separators, and pipe networking. This variety of products puts the company in a challenging position in regards to planning and controlling jobs and providing required materials ahead of order or on time. Also, the unavailability in the local market represents the major issues for the Y company and most of MTO companies.

Shop Configuration

Shop configurations are important factors in determining the PPC applicability. MTO companies vary in the degree of customization and variety of products. Standard products, for some companies, are manufactured only when they are ordered because of the high cost associated with low demand, so such companies are not able to stock this type of product. Standard products are more likely to be manufactured in a single assembly line, where products move in one direction. This assembly line is called a flow shop. There are two types of flow shop: pure flow shop (PFS) and general flow shop (GFS). PFS refers to any product that is assembled in one strict direction, so the product stops at each workstation. GFS relates to the type of production where each job is allowed to stop over the subset of a work center in one direction allowing limited customization as for RBC.

A purely customized product is a product that is industrialized for each customer, and almost every product has a unique manufacturing method and routing on the shop floor. For MTO, job shop represents the appropriate configuration that can be divided into two types: pure job shop (PJS) and general job shop (GJS). PJS accounts for manufacturing customized product with random routing sequences. Many authors have stated that such shop (PJS) exists in real life. GJS represents manufacturing customized products in a multi-directional path, relevant to VMC and RBC.

For a Y company, products are developed and made from scratch, so the complexity of production procedure in shop floor differs based on the type and the size of order. PJS represents a Y company shop configuration. For maintenance, many types of orders might be requested from changing something simple like a nozzle to an internal component. For manufacturing a new product, it could be vessels, towers, bridge girders, steel structures, and tanks. Each product has different route inside the shop floor, but all products must visit the work center on the shop floor.

Company Size

Company sizes have a significant impact on PPC applicability. MTO companies are often SMEs companies with an employee number that ranges between 15 to 250 (Stevenson * & Stevenson, 2005). For a Y company, each factory has an employee number that ranges between 25 to 90.

Company Characteristics

To explore the applicability of a company before implementing the WLC concept, the company characteristics that comply with elements of the WLC concept must be identified in order to realize whether the company fits WLC standards or not. Henrich (2004) developed a framework that identifies the best fit for WLC through recognizing relevant characteristics for a single order and using it to build the characteristics of the flow order. Each order can be characterized by an arrival date, due date, and technological requirement. Technological requirement decides the set of operations and routing, which is performed for each order. The framework uses indicators for these characteristics for every single order and reflects them to a group of orders. Thus, due to the complexity of MTO companies, variability indicators were added to the characterization of order requirement to explore the applicability of WLC (see Table 2).

Characteristic	Indicator
1- Order arrival dates	1.1 Arrival intensity 1.2 Inter-arrival time variability
2- Due date requirements	2.1 Due date tightness 2.2 Variability of due date allowances
3- Operations	3.1 Processing time lumpiness 3.2 Processing time variability 3.3 Set-up processing time ratio
4- Routing	4.1 Routing sequence variability 4.2 Routing length 4.3 Routing length variability 4.4 Routing flexibility 4.5 Level of convergence

Table 2. Characteristic and Indicators.

Second, the characteristic of WLC must be identified, so we can understand the relationships between company and WLC characteristics in order to use the framework properly.

The Characteristic of WLC

WLC concept is known for controlling the input and output of workload. Input control relates to order acceptance and order release. Accepting an order depends on offering a competitive due date and price, which then depends on the efficiency of the CEM. After accepting an order, a pre-shop operation (design, process planning) is required before sending the order to the pre-shop pool, where orders wait for release. Order release determines the time, quantity, and type of orders that need to be released to the shop floor. Different releasing rules have been developed and implemented in simulations to prioritize orders, and simple rules have been used to dispatch orders. The primary purpose of WLC is to reduce WIP by releasing orders by the assigned time and under the capacity limited or workload norm in order to reduce backed up queues on the shop floor and congestions.

Release Criteria

There are two types of order classified based on DD: (1) orders that are assigned operation completion date (OCD) by the company, and orders that are assigned an OCD by the customer. For order releasing, two release due dates must be identified according to the operation completion date: Early Releasing Date (ERD) and Planned Releasing Date (PRD). For the order DD assigned by the company, ERD must be calculated; therefore, releasing the order is based on the closest ERD, when the order is confirmed, and if the materials are ready. For an order DD assigned by the customer, PRD must be calculated by subtracting the process time from the DD given by the customer, which decides whether the order is urgent or not. Releasing orders must not exceed the workload norms; otherwise, orders would wait in the pool until they fit within the workload norms as a group or individually.

Release Procedure

Order release based on periodic release is one the best methods in controlling the WIP level on the shop floor. Periodic release means considering releasing orders after each period. Orders should be arranged in the pool in sequence based on releasing methods such as closest ERD, PRD, set-up time, route length, and process time. If an order workload does not fit within the workload norms, then it must wait for another periodic release time to be considered again.

There are five most distinguishing elements of the WLC concept. Figure 5 shows the functional relationship between these elements and the company characteristic indicators.

Control point release, which considers the most important element, represents the release decision. After releasing, a simple priority rule must be selected in order to control the progress of jobs on the shop floor. WLC best supports small set-up time, high sequence variability, short route length, and a small level of convergence.

Workload norm controls the decision of releasing orders to the shop floor. An order workload can be calculated by summing the individual processing time required for each operation. The aggregate workload is a method for calculating workload on the shop floor by summing up the processing times for orders waiting in front of a capacity group, which are called downstream or direct loads. Processing the time of orders that are going to be in a direct load in the future is referred to as an upstream or an indirect load. Capacity group refers to one or group of machines. Since the WLC approach functions perfectly when workloads consist of a large number of small processing times, the best fit for WLC is when there are high order arrival rate and short processing times.

Characteristic Indicator		Control point at release	Aggregate measures	Resource buffering	Shop floor buffering	Central load balancing
a) arrivals	(a1) arrival intensity		X			X
	(a2) inter-arrival time variability				X	
b) due dates	(b1) due date tightness			X	X	
	(b2) variability of due date allowances				X	
c) operations	(c1) processing time lumpiness		X			X
	(c2) processing time variability			X	X	X
	(c3) set-up/processing time ratio	X				X
d) routings	(d1) routing sequence variability	X		X	X	X
	(d2) routing length	X				
	(d3) routing length variability			X	X	X
	(d4) routing flexibility					X
	(d5) level of convergence	X				X

Figure 5. Relevant Relationship.

The purpose of WLC is to stabilize the workload level on the shop floor and to a capacity group. The workload norms do not only represent the capacity limitation of capacity groups, but also the workload in transit and then the workload in front of each capacity group. Queues occur in front of each work center. These queues lead to variability in inter-arrival time. Releasing orders decisions controls the internal order arrival variability. Since resources buffering for WLC are designed to work better in situations where queues in a capacity group are inevitable, the WLC best fits the low DD tightness, and the DD allowance or planning factor controls a very tight due date allowance which then increases buffer waiting time. Also, WLC best fits high variability of processing times, routing sequences, and routing length.

Shop floor buffering, as the resource buffering, exists to support the controlling of processing time and routing variability, which is affected directly by the due date tightness. Shop floor buffering also absorbs the inter-arrival time variability, and works perfectly when there is a mixture of urgent and non-urgent jobs or orders.

Comparing control load balances between capacity groups and order urgency is the central focus when releasing an order, which requires a global view of the shop. This function, with pool buffer, controls variability in arrivals, processing time, routing lengths, and sequences. Control load balancing works best when there is a high arrival intensity and small processing times. Additionally, set-up time and routing flexibility must be taken into consideration by keeping short set-up times and using routing flexibility to control load balance across capacity groups.

Using the Framework

After explaining the characteristics and requirements for MTO companies, the characteristics of a company that comply with the elements of WLC, relationships between a company characteristic indicator and elements of WLC, the next step is to project the characteristics of a Y company onto the framework in order to explore the applicability of WLC on a Y company. The figure indicate that the Y company fits within the WLC expectations on process time lumpiness due to the long process time for some jobs. More discussion about the results of the framework are addressed in the next chapter.

Detailed Investigation and Final Selection

In the second stage of the project's research procedure, more investigations about the selected concept, WLC are going to be conducted through understanding the WLC levels and conducting a simulation to derive the final selection before planning the implementation strategy.

Customer Enquiry Management

The first level of workload control, which presented by the LUMS approach, is concerned with DDs and production lead time. CEM ensures providing a realistic due date and lead time when a quote is requested by planning required production capacity for unconfirmed orders with the total workload. The total workload consists of workloads for confirmed orders (i.e., orders currently in the shop floor and yet to be released) and unconfirmed orders. CEM represents the best methodology that integrates production and marketing in order to reduce conflicts. For example, a company sales department seeks to maximize the profit or sale revenues by assuring unrealistic short due dates while the production tries to stabilize the production level on the shop floor in expenses of a high backlog and long lead time. CEM can be divided into two parts: strike rate analysis and aggregate production planning.

<u>Strike Rate Analysis</u>

Strike rate analysis represents the probability of winning a tender at different prices, and DDs, which is assessed by using historical data. The idea of using the winning factor exists because of the uncertainty surrounding the acceptance of an offer from a potential customer. For any company, it is critical to anticipate future jobs because having a solid capacity management and delivery date estimations does not mean there is no chance for improved performance whether in the provided delivery date or the capacity utilization because of the imbalance in the mix of orders. The imbalance occurs when a company added future jobs' workloads to the total workload in order to create a continuous production level, then waiting for a confirmation from the customer. If the bid is rejected, then the total workload must be recalculated by subtracting the rejected order. Unconfirmed orders that are included in the total workload must be taken into account in the calculation based on the representative factor in order to prevent or reduce the imbalance. Each company should identify the strike rate or the percentage of bids the company makes in order to win an order, which represents a forecasting method that predicts future workload.

The simplest method to determine strike rates is by dividing the market in which the company is competing in segments, such as job size, customer size, and customer relationship, with a similar order winning probabilities using historical data for each segment. After segmentation, a matrix must be developed to link the strike rate for a specific segment with particular outcomes. Figure 6, for example, is a matrix for the percentage of mark-up on Y-axis and delivery lead time on X-axis (Thurer et al., 2011). Point (X, Y) represents the winning bid at (Y) percentage mark-up (the price minus the incurred cost) and (X), which is the delivery lead time. As more historical data becomes available, the strike rate matrix must be updated, so for each winning bid, the (X, Y) cell increases by one. Also, all cells with lower X-value and Y-value that are most likely to win with a more competitive bid (lower price and short due date) become increased by one. For an unsuccessful bid, the matrix would not be updated. The quotient of a cell (X, Y) and the number of total bids, whether they were successful or unsuccessful, for a given period, represents the estimated strike rate for a particular market segment and outcome.

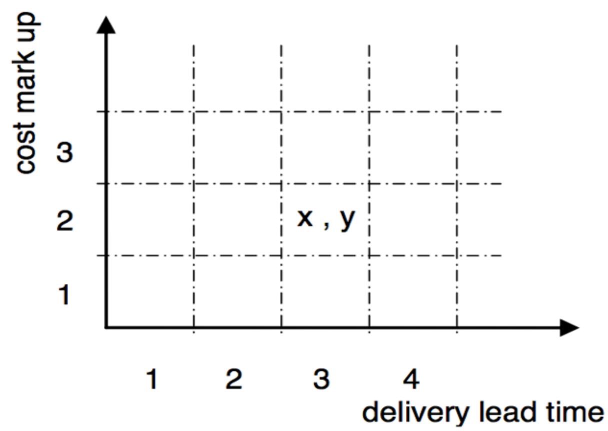

Figure 6. Strike Rate Matrix.

The strike rate analysis was not included in this project due to the lack of historical data. For Y company, however, it is imperative to take strike rate in its calculation in order to determine the probability at which orders are not expected to win. For a particular segment, for example, any strike rate below 6% is most likely not a winning bid. The strike rate could help the company save time and effort spent in preparing for bidding. It may also prevent the company from overbidding for all jobs. In this project, two methods are used for order acceptance: (1) the total acceptance method

(TA), where all arriving orders are accepted, and (2) the percentage acceptance, where 5-10% of arriving orders are rejected.

Aggregate Production Planning

Once the strike rate is determined, estimated future orders will add to the total workload under unconfirmed orders, which requires capacity management and delivery date considerations. There are two types of orders that should be taken into consideration: (1) orders with DDs determined by the company (negotiable), and (2) orders with DDs requested by the customer (nonnegotiable). From a capacity management perspective, production scheduling takes different approaches based on the order DD type. For the DDs determined by the company, forward scheduling is used. However, for the DDs requested by the customer, backward scheduling is used, where capacity is planned and controlled over time.

Forward scheduling is used to determine the total operation completion dates (ODC) for each operation in the order routing. The primary goal is to identify the earliest release date (ERD) or release date (RD), which refers to the date when an order is confirmed and materials are made available. There are two types of forward scheduling: infinite and finite loading. The difference between the two is the consideration of information in the real system. This project considers the forward infinite scheduling, which examines the number of operations in an order route to assign the DDs. Equation (1) represents the mathematical equation that calculates RD using forward infinite scheduling:

$$OCD_i = OCD_{i-1} + k + \text{Processing Time} \qquad OC_0 = ERD \quad (1)$$

Where k represents the flow time allowance estimated the set-up time and operation waiting time.

Backward scheduling is used to determine the planned release date (PRD) for an order where DD is given by the customer. PRD represents the time or the date when an order must be released for the pool to be delivered on time. There are two types of backward scheduling: infinite and finite. Backward infinite scheduling is considered in this project to determine the PRD or RD by equation (2):

$$RD_i = DD_i - kn_i \qquad (2)$$

i = the job number

k = planning factor

ni = the number of operation in job I route.

Capacity management must identify the ERD and PRD for each job individually. In the case that the PRD is beyond the ERD, the production cost will be a standard cost as estimated. In the case that PRD is before ERD, the capacity must be adjusted to meet the DD, so the production cost becomes higher. Orders with DDs requested by customers are considered urgent orders that need to get special capacity scheduling attention and priorities. The decisions related to urgent orders when there is an overload as a result of using backward scheduling are adjusting the capacity, accepting the higher cost of production, rejecting the order, subcontracting the order with a reliable contractor, and changing the DD by negotiating the customer and switching to forward scheduling.

In this project, the decision to assign due date is made by considering a single rule with different planning factors because the variation in planning factors can convert one rule into another. Total workload rule (TWK) is the only rule used in this study to determine the DDs for orders. Equation (3) represents the mathematical equation that calculates DD for i order:

$$DD_i = AD_i + k_{TWK} * P_i \qquad (3)$$

DD_i = due date of job i

AD_i = arrival date of job i

P_i = processing time of job i

K_{TWK} = planning factor or flow time allowance

The value of the planning factor is set at 7.6, 15, 38.4, and 79.3. These values are determined by running the simulation with (TA, IMR, FIFO) and obtained the 5%, 10%, 25%, and 50% of late jobs, respectively. The goal is to investigate the performance of Y company under a variety of values for due date tightness. When the K_{TWK}= 7.6, the due date is considered very tight, and pressure on the production is high. Using 7.6 increases the waiting line and the possibility of getting a higher number of late jobs. When K_{TWK}= 79.3, the due date becomes loose and this increases the lead times.

Order Release

After the confirmation of an order, it gets sent to the pre-shop pool, where orders wait for releasing into the shop floor. Orders in the pool must be sorted before releasing, which depends on the Releasing Rule (RR) and the shop floor workload norm. The RR determines the releasing time, quantity, and selection by releasing orders according to the RD or ERD, matching the shop floor workload availability with the released workload, and selecting a particular order to be released.

Different types of RR were selected for this project to control the order release stage including forward infinite loading (FIL), backward infinite loading (BIL), immediate release (IMM), modified infinite loading (MIL), and WLC rule (WLCDD). FIL releases the job based on its ERD that is determined by summarizing its OCD. FIL is a releasing method that depends on the process time for orders to determine the RD, but it neglects the current workload in the shop. BIL is a releasing method that depends on the due date and the number of operations in the route of the job. BIL, closely related to FIL, neglects the current workload in the shop floor. For benchmarking, IMM is selected as the base method to compare the performance of the different releasing rules. IMM is a releasing method that releases jobs as soon as they are accepted in the shop floor without RR, so all jobs get gathered in the dispatching pool on the shop floor.

MIL rule was reposed by Ragatz and Mabert (1988). It is a releasing rule that depends on planning factors, like BIL and FIL, so it neglects the current workload in the shop floor; however, it predicts the job flow time by taking the calculation of the number of operations and number of jobs queued in job routing. Mathematically, MIL can be determined using equation 4.

$$RDi = DDi - K_{1MIL} * ni - K_{2MIL} * Qi \quad (4)$$

i = job number

RDi = release due date for job i

DD_i = due date for job i

n_i = number of operations in job i routing

Q_i = number of jobs in queue in job I routing

K_{1MIL}, K_{2MIL} = planning factors

K_{1MIL}, a constant value, represents a good prediction for the time spend for a job to transfer between operations on the shop floor. K_{2MIL}, a constant value, is identified to estimate the time spent in the queue of job routing.

WLC DD rule, which refers to LUMS OR, is a releasing method that releases orders based on the routing length and RD. Orders with long routing are released first as to meet the completion date. WLC DD is a releasing method that combines two rules and ranks orders in the pool according to this regulation.

The second factor that controls the order release are workload norms. The workload norms control the workload in the shop floor by setting an upper and a lower boundary in order to prevent workload overloading and starvation. There are three approaches to calculate the workload. The first approach is the probabilistic approach, which estimates the indirect loads that will be a direct load at the work center as soon as the job is released. The probabilistic approach is considered a complex approach. The second approach is the aggregate load approach, which takes the indirect and direct loads in workload calculations. The most known approaches of aggregate load are classic and converted aggregate load. The classic aggregate load approach is considered a workload norm for each work center, so each work center has a unique workload limit. Converted aggregate load approach is a converted approach that uses one workload norm for all work centers. The current workload is calculated by dividing the indirect load in each visited work center in the route of a job by the order number of work centers in a job's routing. The third approach is the time bucket approach, which divides the work into a time bucket, so each workload must fit within the time bucket. For example, the time bucket is divided to 4 with a utilization of 90% then the time bucket is 3.6, so each job must fit within the 3.6-time unit.

In this project, the simulation uses aggregate load in order to calculate the workload and release orders whenever there is enough shop floor capacity.

Dispatching

After releasing an order with a specific quantity, the order waits in the shop floor for processing. The priority dispatching rule is to prioritize released orders before production. In this project, two simple priority dispatching rules were used: first-in-first-out (FIFO) where orders were sorted and dispatched based on the arriving orders and earlier due date (EDD), where orders or jobs were sorted and dispatched based on the earlier due date.

Simulation

A simulation model was built using ExtenSim software. The model was built based on the following seven modeling fundamentals.

<u>Model Purpose</u>

The purpose of the model is to assess the performance of implementing WLC concept on Y company by accounting for the \ work centers and the actual route. This simulation does not reflect the real inputs of Y company such as arrival times, inter-arrival times, processing times, and waiting times; however, the system and the production lines, behaviors, and routes are resembling the actual in the Y company. The goal is to measure the performance and the improvement of implementing WLC concepts under different RR. The metrics used to measure the performance are the mean percentage of tardy jobs, mean of slack time, mean estimated lead time, mean of actual lead time, average waiting time in the pool before, and average waiting time in shop floor (see Table 3). The result is to be compared with a model works with (TA-IMM-FIFO) as a benchmarking.

Name	Description
Percentage tardy	Number of late jobs divided by the total jobs
Slack time	Equal to the DD minus the current time at last operation completion. The result could be negative or positive
Mean estimated lead time	The time estimate for completion including waiting time and process time
Mean of actual lead time	Time takes to finish a product by going through the production activities and waiting in the pool
OR queue	Average waiting time for product in the pool before releasing
Queue in shop	Average waiting time in front of each workstation before processing in the shop floor

Table 3. Summary of Performance Measures.

Collecting Information

Information here can be classified as production information and modeling information. Production information includes the type of production route and activities. Y company is a job shop type company, where materials have to be transferred from work station to another to perform production activities. Shop floor production activities in this project represent only one of four factories. There are eight primary work centers in this facility (see Table 4).

	Name	Brief Description
1	Production Preparation	Shop floor technical preparation mostly engineering related activities
2	Cleaning	Cleaning steel materials by using sandblast or shot blast
3	Cutting	Fabricating steel plate in shape according to the design
4	Rolling	Rolling rectangular steel plate to forming a cylindrical shape
5	Die end forming	Pressing and flanging die ends
6	Machinery steel works	Turning, drilling, milling, boring
7	Assembly	Assembly all parts and welding them together
8	Testing	Group of tests including X-ray, ultra violet, pressure water test, and pressure air test.

Table 4. Summary of Work Centers.

Orders usually visit three to eight work centers depending on the type of order. The number of work centers must be determined before assigning a delivery due date by using random number generators to generate the number of work centers required to deliver a product. In the simulation model, the number of work centers is referred to as a route number. Figure 7 shows the graphical representation of order flow in the Y company considered the shop floor.

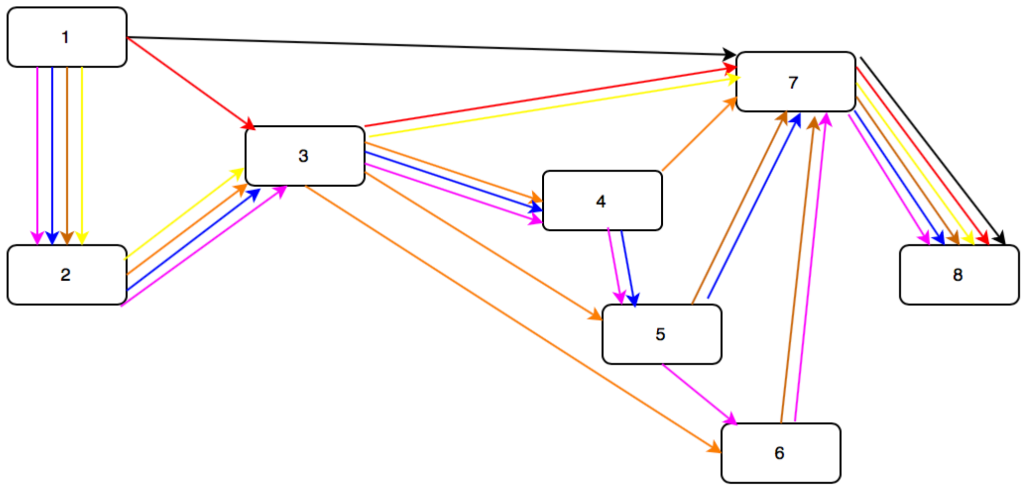

Figure 7. Graphical Representation of Order Flow in the Y Company.

Modeling information can be divided into shop and job characteristics. Shop characteristic refers to the type of the shop, number of machines capacity, and release rules. Job characteristics refers to distributions and other simulation related information (see Tables 5 and 6).

Shop characteristic	
Shop type	Pure job shop
Shop characteristic	Real
Routing variability	Random routing, no re-entrant flows
Number of work centers	8
Work center capacities	All equal
Work center utilization	Unfixed
Order acceptance	TA, rejection 5%,10%
Order release	IMM,FIL,MIL,BIL,WLCDD
Dispatching	FCFO, EDD

Table 5. Summary of Simulated Shop Characteristic.

Job characteristic	
Simulation type	Discrete event
Order Inter-arrival time	Exponential distribution, mean=3.7
Process Time	Uniform distribution (1,6)
No. of operation per job	Uniform distribution (3,8)
Set-up time	Not considered
Due Date determination procedure	AD+ K_{TWK}*Process time
Job characteristic	Hypothetical

Table 6. Summary of Simulated Job Characteristic.

A model first was created to find the process time distribution based on the number of work center in route of the job. Table 7 shows the process time distributions.

Route Number	Order work center Number	Distribution
3	1,7,8	[JohnsonSU;0.178;0.355;1.55;Location(10.6)]
4	1,3,7,8	[Logistic;;;0;Location(13)]
5	1,2,3,7,8	[Weibull;0.486;2.38;;Location(17.1)]
6	1,2,3,4,7,8 1,2,3,5,7,8 1,2,3,6,7,8	[Lognormal;0.943;0.191;;Location(20.1)]
7	1,2,3,4,5,7,8	[Weibull;0.818;3.45;;Location(23.8);Seed(T;238)]
8	1,2,3,4,5,6,7,8	[JohnsonSU;0.13;-1.18;1.17;Location(27.8)]

Table 7. Summary of Process Time Distribution.

Model Formulation

Before formulating the model using ExtendSim, a logic structure was created (as shown in Figure 8).

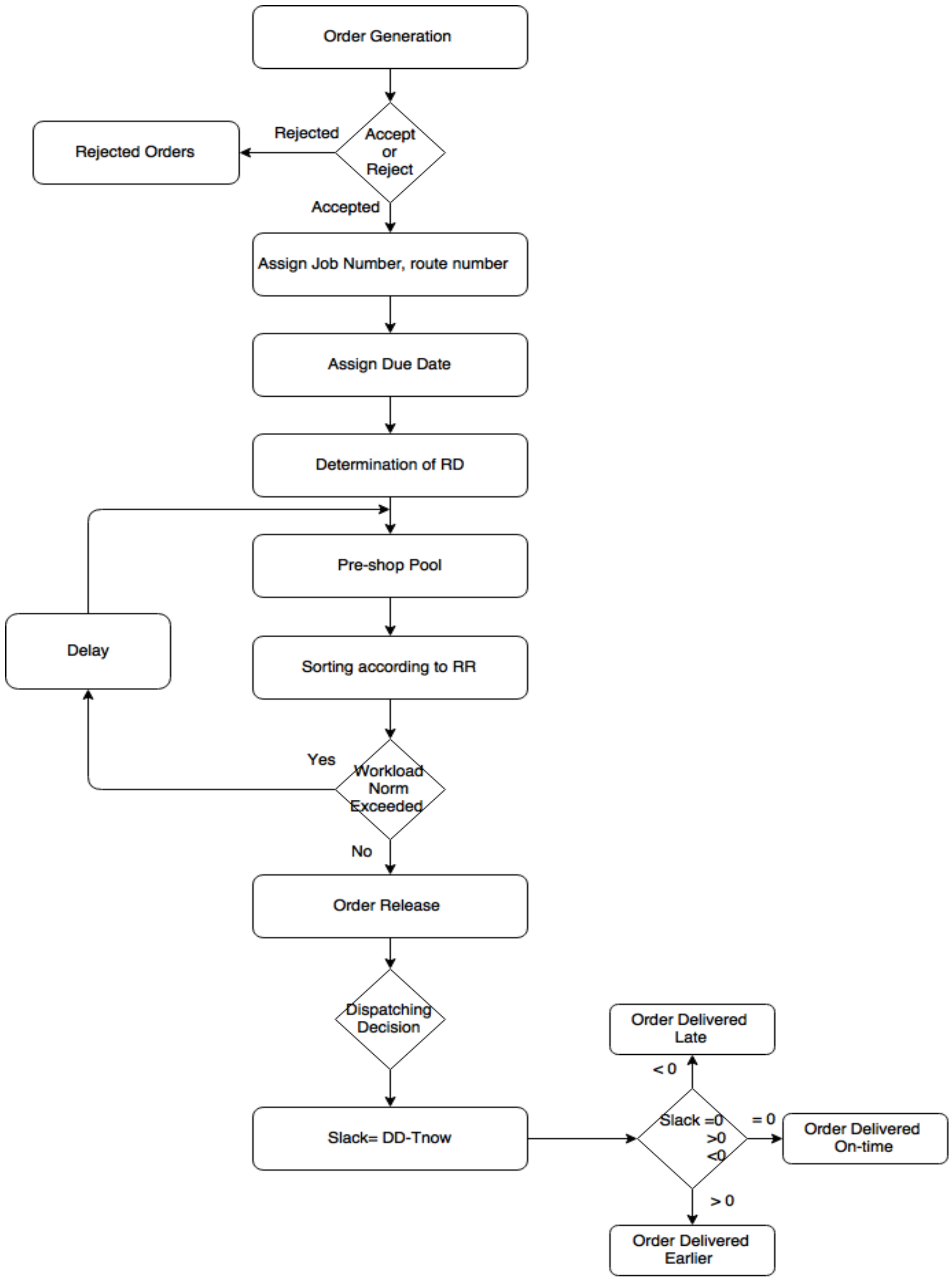

Figure 8. Simulation Model Logic Structure.

Validating Model

First of all, the model was built by ensuring that the conceptual model was reflected accurately in the software. This was achieved by following the common sense through creating simulation logic structure (see Figure 8). Also, the model was built based on the possible logical actions of what might happen when an event accrues within the system. Also, the model output was carefully examined for reasonableness.

The model was validated by using input-output transformation method. First, the model was modified to generate ten orders only within TA, IMM, and FIFO. Second, process time, arrival time, and route number were collected within the output measurements. Third, using the mathematical method, explained in the previous section, due date and completion date were calculated. Fourth, the results from simulation and calculated mathematically compared and were close enough; however, for the other release rules, validations were not performed due to the increased complexity.

Exercise Model

One hundred twenty different models were built by using three order acceptances, five releasing, and two dispatching rules. First, 40 models were run with TA order acceptance. Second, 40 models were run with the probability of 5% rejection of generated orders. The last 40 ran with 10% probability of rejection generated. The idea of adding 5% and 10% rejection probability is to understand the importance of strike rate during the bidding period, and how it might affect the performance of the order release. The run time was set to 10,000 time units with 3,000 time units as the warm-up period to avoid start-up effects. The simulation experiment or each model were run for 50 times. Data was collected and summarized in tables based on the type of measurements.

Implementation

After exploring the applicability of WLC concept on Y company, understanding WLC levels, and conducting a simulation to have a better insight into the performance, considering implementation strategy cannot be neglected in this study because few successful implementations of WLC have been reported by researchers (Mark Stevenson, 2011). The considerable gap between theory and practice of WLC is known as the "Workload Control Paradox." Despite the successful implementations and empirical research reports that have proven reductions in total throughput time of 40-50%, some simulations have failed to capture that because they show an increase in total throughput time, while some of the successful simulations have shown reductions of only a few percent.

This gap has occurred because of the misalignment between theory and practice. In theory, WLC has been advanced through simulations to study the effectiveness and efficiency of WLC before implementation in order to reduce time and cost. However, researchers have encountered a complex system in the field during implementation because simulations that have been used to capture real system performance have tended to simulate simple systems that do not have enough depth to reflect actual implementation challenges. Second, there has not been any comprehensive implementation strategy developed in a way that escorts successful implementation. The absence of implementation strategy leads to uncertainties and challenges during implementation reported by researchers, which are known as implementation issues. These problems have been gathered and classified into different categories. Many researchers have confirmed that these issues have been faced during different implementation attempts.

In the implementation section of this research, an implementation strategy model developed by Stevenson (2011) provides an overview of the implementation process for WLC, which is explored along with implementations issues to have a comprehensive overview of implementing WLC in the Y company.

Implementation Strategy

To implement WLC successfully, an implementation strategy should overcome the challenges and uncertainties that accompany the implementation process. The model consists of three stages: pre-implementation, the mid-implementation or implementation process, and post-implementation. As shown in Figure 9, these stages represent the start-up procedure to support WLC implementation. Researchers called for more investigation in addressing the correct methodology in order to implement successful WLC in a more systematic approach, so this section outlines the implementation strategy along with the arising issues.

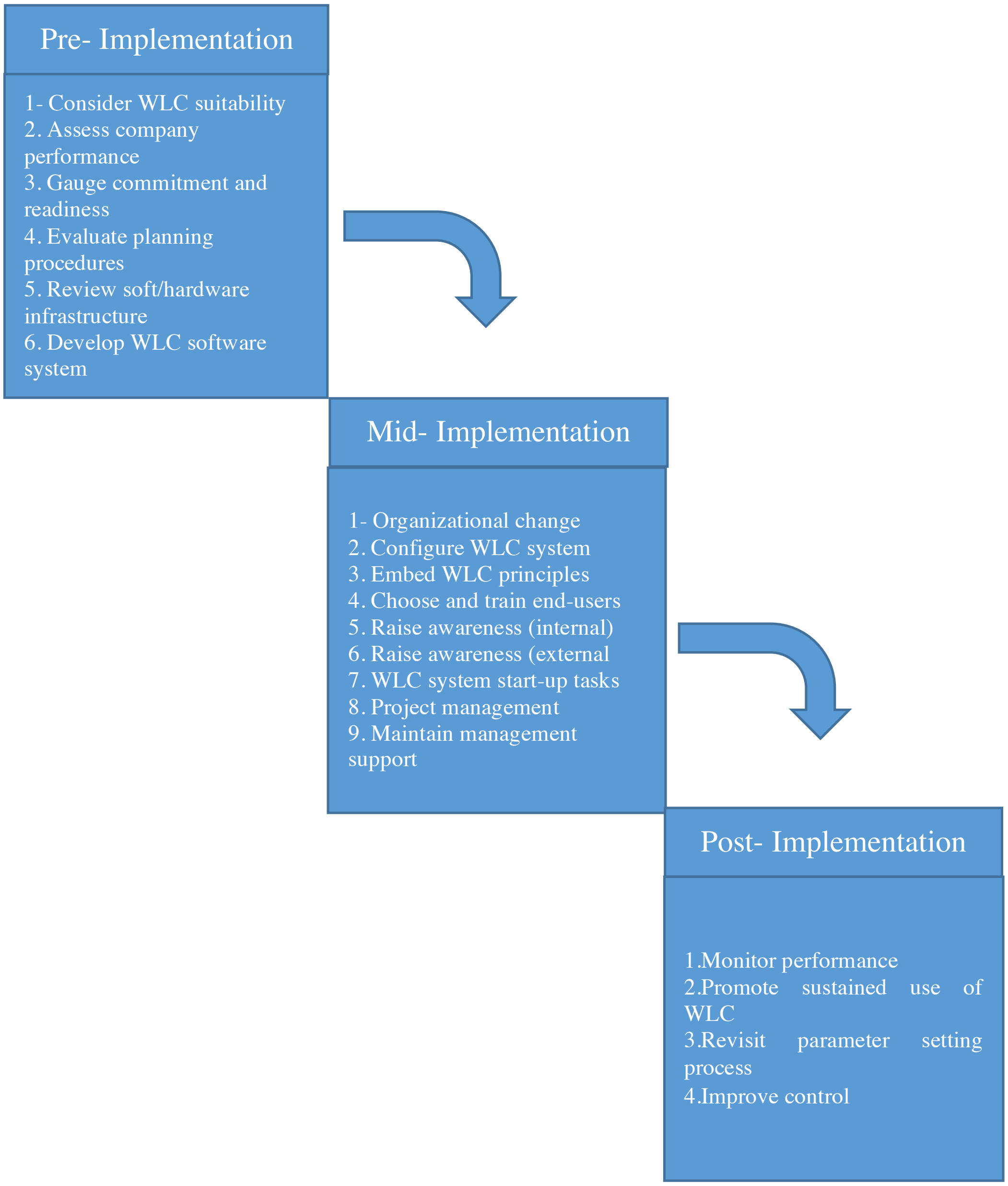

Figure 9. Implementation Strategy for WLC

Pre-Implementation Stage (Diagnosis Phase)

The pre-implementation stage is considered the most important and essential stage before implementing WLC because it tests the applicability and suitability of WLC to a company. The decision related to taking a further step toward choosing WLC as the proper PPC approach is made during this stage. For MTO companies with SMEs and limited financial resources, implementing WLC may cost more money, time, and effort than the companies can handle, especially if WLC was not suitable. The first section of this chapter explains the framework that has been developed to explore the applicability of WLC, while taking into consideration the characteristics and requirement of MTO companies, company characteristics, and elements of WLC.

The second step is to create a team capable of handling the project of WLC implementation. The team must have enough knowledge of WLC and LUMS approaches and original methodology. Team members must have a clear idea of how to assign a feasible due date, calculate the workload, practice strike rate, etc. Team members should know their roles and responsibilities. All members must have enough motivation to overcome the challenges that they might be encountered during the implementation, which might take more effort and time than expected because human factor, which has been neglected during simulation, has a significant role in the implementation of WLC. Also, the relationships between team members should be strong in order to support each other. The team must identify its objectives and goals, set the internal rules, and choose meeting times and places.

An appropriate plan to collect data should be developed. The plan should decide who will collect data, the type of data, time for data collection, and how often per hour, day, etc. The data collection plan should indicate collecting data before WLC implementation to assess company performance. Also, the data collection plan should state collecting data after the implementation to assess company performance after WLC implementation in order to measure the improvement level. The data collection plan should consider the availability and credibility of historical data for the last few years to decide whether to use them to derive past company performance or not.

To measure the performance of a company before, during, and after implementation, an agreement on the type of data to be collected should be settled. Many researchers have used different measurements that are included in their simulations and implementation attempts. These performance measurements can be categorized into groups including time-related, dependability cost-related, shop load-related, market-related, and internal coordination (see Table 8).

Category	Measures	Description
Time-related	Manufacturing lead time	Total job time spends in pool and shop floor
	Shop floor throughput time	Total job time spends in shop floor
	Pool delay	Waiting time spends in pre-shop order release
	Shop floor queuing time	Waiting time spends in front of the work centers
	Time to process customer orders	Total time from job entry to completion an order
Dependability	Mean Lateness	Average time of completion date minus DD. The mean might be negative or positive
	Mean Tardiness	Average time of completion date minus DD for late orders only. The average always positive
	Percentage of tardy	Number of late order divided by total orders

Cost-related	Work-in-progress Overtime	Refers for the partially finished items in shop floor waiting in front of work centers. Minimizing WIP leads to reduce the need to overtime and further capacity adjustment. Time requires to finish order behind that is behind the schedule
Shop load-related	No. of jobs on the shop floor Shop utilization over time Bottleneck shiftiness Reallocation of operators	 Change of bottleneck over time Reallocating operators of unutilized machines
Market-related	Proportion of rejected orders	
Internal co-ordination	Co-ordination between production and marketing	Time taken to process customer enquiries and the disagreement between production and marketing department.

Table 8. Performance Measures Used in Previous Studies.

Besides the use of appropriate measurements, a plan should be developed to consider the right methodology to identify successful implementation. There are different measurements that have been used in many studies; therefore, it is essential not only to select appropriate measurements, but also to determine an effective method that compares between measurements on proper bases, which is important to recognize boundaries of successful implementation.

Management commitment is a fundamental element of the implementation process, so maintaining managers' support is essential. Managers should be ready with an open mind for accepting an internal and external change because introducing the idea of creating a pool and keeping orders for a specific day to be released might encounter an objection from some managers. Additionally, reviewing the current method of communication internally, communication between employees or departments, and externally communication with customers before implementation are imperative because of the LUMS approach and the importance of getting feedback from the shop floor regarding current workload and jobs' operations. Also, keeping the customer informed about the current stage of manufacturing of an order is one of the requirements of the LUMS approach.

Mid-Implementation

The second stage of WLC implementation strategy is known as the theory and practice alignment stage, where implementation takes place in such a way that reduces the space between theory and practice. First of all, organizational change must be implemented carefully because of the uncertainties surrounding this step. Organizational change might include change in customer enquiry management, order entry, machine layouts, data, or feedback collection.

In customer enquiry management and order entry, it is critical that a company has a feasible order due date estimation, that is calculated by detailed information about processing, machine set-up times, and routing length, which require realistic data, and then delivered on routine before order entry. Some implementation research has found that around 50% of repeated orders requested for quotations, and was assigned a due date estimated on previous references. Some of the companies have calculated the DD roughly based on experience or standard lead time. The method of calculating DD must be planned based on the detailed information about actual processing times, the amount of set-up time required to set-up the machines in the route of the order, and the number of operations in the route of the order, while considering the calculation of the utilization factor. Therefore, end-user training is crucial in understanding the importance of detailed planning during this stage, and ensuring the correct prediction. It may also require reducing the amount of data in a way that does not affect the total performance.

Additionally, under an organizational change, a company must find a method that checks the DD proposed by a customer and support decision-making on behaving of whether the DD offered by the client is feasible and applicable. Rush orders, for some companies, may cause a delay in regular order because of the given priority. A company must deal with rush orders through involving customers in order to encourage them to inform the suppliers with early notice in the future order, which gives vendors time to manage their current orders and plan for incoming rush orders. The second method in dealing with rush orders is renegotiating the proposed DD, which is considered the most conventional method. Third, companies can deal with rush orders by rejecting orders when there is overload in the shop floor or the pre-shop pool, which requires further rush orders evaluations before it is time for decision-making. Rejecting orders is not typically the companies' decisions because companies usually do not reject orders, and the customers decide the order due but quoted with higher price or a longer DD. Fourth, companies can deal with rush orders by subcontracting a whole or partial order, which is the most common choice. The last method in dealing with rush orders is capacity adjustment, which may be costly and requires overtime.

Also, the change must include the use of a strike rate to estimate the proportion of potential orders waiting for confirmation in order to add their workload to the total workload, which includes capacity management planning. Orders with a low strike rate, some researchers consider 10% and below, might be subject to ignorance. Besides, it is important to consider confirmation or rejection time because it is found that order confirmation or rejection durations are high, which may affect the quoted DD, so some companies set the start-up time from the day of confirmation. Moreover, the time required to purchase material and design or engineer must be considered in DD calculation. Finally, the communication mechanism for organizations must be updated in such a way that companies use email and websites, so customers can place their orders and track the progress of their orders as well.

The Second Step in the mid-implementation stage is the configuration of WLC, which includes shop floor configuration, assembly operations and routing convergence, order release behavior, machine characteristics, capacity calculation, and outputs control measure.

A part of shop floor configuration is the routing direction because it affects the suitability of WLC and order release methods. It is crucial to identify shop type before implementation. Most simulations consider pure job shop; however, researchers have found that the availability of pure job shop in a real job shop is rare. Also, identifying the bottleneck in the shop floor and whether it is shifting after a particular time or not are essential to choosing an appropriate release method.

During implementation, the material releasing method should be considered. For a sophisticated product with sub-assemblies before convergence in the final assembly stage, releasing materials entirely or partially is applicable. The coordination between releasing and production is necessary in order to maintain a steady level of the production state. Some researchers have studied the impact of releasing materials and found that releasing all materials at once improve the performance by considering the structure of the end-product as a network that helps in calculating the critical path for each order and identifying the releasing time and focus on activities within the critical path.

Configuration should also consider order release methodology by choosing an effective and efficient releasing method. The process of selecting a suitable order releasing mechanism should be implemented based on the type and behavior of the production system. In most cases that have been studied in the past, they have considered five different releasing criterions including the DD of the job with current machine loads consider; job size, complexity, and routing length; customer relationship and level of importance; material availability; and job profitability. Also, it is very important for a planner to estimate an accurate waiting time in the pool before releasing and the effectiveness of rush orders versus average waiting time. Another configuration that effects order release is the machines characteristics. Most of the researchers in recent papers started investigating the role of sequence-dependent set-up time and machine grouping and how they affect the order releasing mechanism. For orders that require long machine set-up time, considering processing order with the same machine set-up or less set-up time have been found to be effective; however, arguments have ensued on whether to manage the decision locally (in dispatching) or centrally (in order release). A grouping machine has been found to be very effective in reducing the amount of feedback required for order release and relocating machine operators according to the routing.

Capacity calculation and capacity flexibility have a useful role in assigning DD and order release. In most implementation cases of WLC, the methods used to calculate the capacity are assigning a constant number of hours from one day to the next constrained by machine hours only, assigning a constant number of hours constrained by operators, and assigning a combination of machines and labor. The capacity calculation is considered complicated enough that some researchers called for more investigations, especially in what we know as Duel Resource constrained shops (Mark Stevenson, 2011).

Finally, regarding the configuration of WLC, the major output control measures recommended for WLC are relocating operators from underload to overload work centers, overtime, subcontracting operations or jobs, and re-routing jobs. Based on empirical data collect from 41 different companies (Mark Stevenson, 2011), it has been found that overtime is the most commonly output control measure used in practice, followed by re-locating operators and re-routing because they are less costly. The decision of selecting and using an output control measure depends mainly on the company's culture and the type of production. In the comparison between two companies, which implemented WLC, Stevenson (2008) has found that each company had more emphasis on different uses of capacity control. For example, while company X depended heavily on overtime and subcontracting, company M considered subcontracting a last resort or option.

Returning to the steps of mid-implementation strategy, measuring the performance of previous PPC systems is the key toward convincing managements that the current system needs to be improved. Most of the WLC implementation attempts found that the existing PPC system is not suitable for the type of the company, such as PPC-related to lean concept or material requirements planning (MRP); therefore, embedding WLC concept is the best method in improving the performance of any MTO company. Embedding the WLC concept requires a high motivation and commitment in order to adapt WLC successfully. Also, motivation may also entail raising the awareness of WLC concept because, unlike Lean or Kanban, the WLC concept is not highly recognized as a concept for an MTO sector with SMEs. The team is responsible for working hard towards raising the awareness of the WLC concept by exploring the similarity between WLC and the Lean philosophy in terms of reducing WIP and meeting the DD.

The success factors for PCC implementation, as identified by questionnaire interviewers from different companies (Stevenson, (2011), are strong leadership and championing, appropriating end-user selection, understanding the WLC concept, and monitoring on a regular basis the performance of PPC system. Without the support of leadership in the company and the existence of the champions, any new implementation for any PPC would fail due to the lack of motivation and commitment. Also, selecting an appropriate end-user must be done based on skills that accommodate the type of job and must also acquire the ability to perform highly after adequate training. The goal is to eventually train the champions in order for them to train others, so as to maintain a continuous flow of knowledge. Besides, end-user and workers must be trained on how to understand the importance of the providing timely feedback of information from the shop floor to central planning regarding the current load in order to consider releasing new orders. The speed determines the method of releasing, periodic or continuous. For slow feedback, periodic releasing must take into account the frequency of the order, such as daily or weekly.

There are many WLC parameters, which need to be set-up before implementation, specifically workload norms. Workload norms represent the most challenging factor among other parameters because participators may be unaware of the meaning of workloads and the process behind setting them; and the condition of a workload at the shop floor before implementation (whether the shop is underload or overload). Setting workload norms when the shop is underload means that tight norms are going to be set. On the other hand, if the shop is overload, then a loose norm will be set. The best method to follow is to set the norms of the shop loose or infinite during the first step of implementation and then gradually tightening them over time of the post-implementation. In other words, this method is subject to result in failure, which consumes the time and efforts of the company.

Additionally, the mid-implementation stage must be implemented quickly enough to cope with the current book of orders because it may affect the overall performance, and so participators give up earlier in the process due to the critical situation of delayed orders. The mid-implementation stage requires project management skills for initiating, planning, executing, monitoring, and controlling to achieve project goals in desired times, costs, effort, and performance. Lastly, implementation requires top company managers' support by ensuring that key workers have an idea about the benefits of WLC for themselves and the company.

Post-Implementation

The last stage of the WLC implementation strategy is sustaining and improving the control stages. There is not enough literature related to this stage in previous studies because the majority of the research has focused on the successful implementations and not sustaining WLC after implementation. At this stage, collecting data must continue to measure the performance of the final stage. The best methodology for measuring the performance of WLC is by comparing the performance of the PPC system during the three stages altogether, and the performance of the final stage, post-implementation, should be at least equal to the mid-implementation stage. Also, a comparison must be performed between the fulfillment of the PPC system before and after the WLC implementation for the same period in different years. For example, comparing the performance for last May, before implementation, with the current May, after WLC implementation, to ensure that the demand is close enough and there is no pressure in the number of orders.

Holding meetings on a continuous basis on the shop floor and with upper management, to present the performance in post-implementation stage, helps in promoting the sustained use of WLC. Most simulations have neglected the human factor or represented it as constant factor whereas human factor effects WLC implementation directly. Some authors have argued that WLC reduces employees' involvement in decision making; however, meetings give participators and workers in the shop floor a role in participating in decision making related to order release, priority, capacity adjustment, and overtime. In fact, in some implementation cases, refining the WLC original approach has been conducted by the company in order to cope with the type of production and company culture.

In the final stage, revisiting parameters are required to optimize the performance of WLC. For example, the revisiting of workload norms to tighten it to reduce WIP and throughput time in floor shop improves releasing mechanisms. Also, the control of using subcontracting in term of estimating subcontracting lead time, relocating operators, and the use of overtime, is constantly improving. Finally, the post-implementation stage should be monitored closely with the cost associated with an order's lead time, the tardiness and WIP in the shop floor. The last stage is about optimizing performance in all aspects, time, cost, market, orders, and shop load bases.

Chapter 4 – Results

In this chapter the results collected from investigating the suitability of Y company as MTO company, the applicability of WLC, performance assessment using discrete event simulation, and implementation strategy will be detailed and discussed.

The Suitability of Y Company as MTO

The first step of this research was to test the suitability of a Y company to be considered as an MTO company. The characteristics of the Y company must meet the characteristics of the MTO sector in order to establish the suitability of this label for the Y company. This decided whether WLC is applicable because WLC can only be adopted in the MTO sector. The investigation was based on customization, shop configuration, and company size.

The Y company is a company with a VMC type of production where orders come from various customers in small volumes with high customizations. Y company's products are usually manufactured for governmental sector, so the demand is moderate, but the repetition of any order is very low because oil equipment has a life span of ten years or more, which reduces the chance of repeated requests over the course of one year. Many products vary in degree of customization. Products with high customization have a long process time, from one week to six months, because most orders request a large volume that requires multi-assembly processes, internally and externally. Customization is not only in production level, but also in the design level because Y company engineers products before production, which is a characteristic of an MTE company as well. As a result, the characteristic of a Y company in a customization section meets MTO requirements.

The Y company has eight work centers, which is the only part included in this research. The flow of production is PJS type where orders take different routes according to the type of products and number of operations. Even though preparation assembling, testing work centers, and activities might be dominate routes, the production flow type is closer to PJS than GJS due to the degree of high customization. As a result, Y company meets the shop configuration for an MTO company.

Finally, under company size, a small enterprise has between 15 and 50 employees or a turnover of less than or equal to 10 million Euros; whereas, the medium enterprise has between 50 and 250 employees or turnover of less than or equal to 50 million Euros. For the Y company, the number of employees is higher than a medium enterprise. Therefore, the Y company, in terms of company size, does not align with the MTO sector qualifications. This means that labor utilization is going to be low, and no benefit is gained from relocating operator's on the shop floor; however, the author was unable to find research related to company size and how the number of employees affects MTO sector and thus WLC implementation.

Applicability of WLC in Y Company

The framework introduced by Henrich (2004) was applied to the Y company. the results are displayed in Figure 10.

Characteristic Indicator		Low	High
a) Arrivals	(a1) arrival intensity		
	(a2) inter-arrival time variability		X
b) Due dates	(b1) due date tightness	X	
	(b2) variability of due date allowances		
c) Operations	(c1) processing time lumpiness		X
	(c2) processing time variability		X
	(c3) set-up/processing time ratio	X	
d) Routings	(d1) routing sequence variability		
	(d2) routing length		
	(d3) routing length variability		X
	(d4) routing flexibility		
	(d5) level of convergence		

"best fit"

more extreme values of the company X

Figure 10. Evaluation Framework Indicating 'Best Fit' for WLC.

- Arrival

Approximately, the number of orders arriving per week is about 3-4 orders. These jobs vary in confirmation days and DD, so the arrival intensity is neither low nor high; however, the inter-arrival time variability is extremely high because of the variation in confirmation, designing, and material availability time requirements. The variation in approval times is related to the type and location of customer, type of equipment, customer approval, and material types and availability, which may require the purchasing of easily accessible materials or importing specialty materials. The best fit for WLC is when the arrival intensity is high and the process time is low; therefore; a Y company must work on increasing the demand and reducing WIP, which requires providing a very competitive offer and quick material availability before implementation.

- Due Date

WLC is a PPC approach designed for MTO companies where queues are inevitable. For a Y company, due date tightness is extremely low because the planning center calculates the expected waiting time for materials and processes. The flexibility in DD allowances affects the Y company's ability to place competitive bids. Even though there is high variability in processing times, routing sequences and lengths, which best fits WLC, the variability of DD allowances is not high because of the flexibility in DD allowances.

- Operations

Processing time is extremely high, whereas the best fit for WLC is when it is low. The reason for high processing time is due to the absence of a pre-shop pool that prevents orders from being released until releasing conditions such as the planned DD and the availability of the materials and tools are set. Currently, the Y company release orders based on first-in-first-out; however, because of the unavailability of materials at that time. The lack of a pre-shop pool leads to discord in work centers where some of the orders are stuck on the work centers waiting for materials, which negatively affect the shop floor process time. The Y company must speed up materials availability before implementing pre-shop pool, which will reduce processing time. Moreover, the process time variability is high, due to the variation in product complexity and the level of customization.

Additionally, the ratio of set-up time on processing time is extremely low because the ratio of orders with high processing times is much more in demand than products with low processing times.

- Routings

For routing sequence variability, length, flexibility, and convergence, there is no extreme level among these indicators. Despite the chance that more than one flow comes together at the assembly work center at the same time, a moderate level of convergence was considered. On the other hand, routing length variability is extremely high because types of orders vary from supplying, assembling, and manufacturing to replacing parts or maintenance, so the orders routing are interchangeable according to the type of order and number of operations.

According to the results collected from the use of the applicability framework, the Y company may consider WLC as a suitable PPC approach; however, it must speed up material accessibility before implementing WLC to adopt successful implementation and high performance in a short time.

Performance Assessment Results

A simulation was conducted to assess the performance of implementing WLC in the Y company using the same production activities and work centers; however, there are some assumptions and limitations that will be discussed later in this section. The simulation results show that, when the K_{TWK} = 7.6 and order acceptance TA (100%), latency is negative for all releasing and dispatching rules. Therefore, 7.6 is too tight and the average delivery time is behind the DD. MIL with dispatching rules FIFO and EDD show decreases, meaning delays exist among others releasing rules, which are -58.61 and -44.17 time units respectively (see Table 9). IMM mean lateness was -62.70 and -60.24 time units for dispatching rules FIFO and EDD, respectively.

		FIFO			
		7.6	15	38.4	79.3
TA	BIL	-55.9121304	72.88139	488.5696	1293.568
	FIL	-67.5084872	75.54234	524.72	1306.964
	IMM	-62.708918	86.248274	530.266	1332.1
	MIL	-58.615112	83.448308	523.0302	1310.962
	WLCDD	-72.554676	93.666988	533.01674	1309.092
		EDD			
		7.6	15	38.4	79.3
	BIL	-71.388772	86.597476	512.0976	1282.036
	FIL	-62.50787	72.089372	540.0746	1323.218
	IMM	-60.243488	61.286664	510.6284	1321.844
	MIL	-44.177402	70.900282	514.153	1324.77
	WLCDD	-47.215748	89.878172	532.3668	1294.668

Table 9. Mean Lateness Under Total Accepting Orders.

When the K_{TWK} = 15, meaning deferment switches from negative to positive, which in turn means that 15 represents loose factor and average delivery time earlier than the assigned DD. For IMM, at K_{TWK} = 15, mean lateness values were 86.24 and 61.28 with dispatching rule FIFO and EDD. WLCDD showed the best results. For K_{TWK} = 38.4 and 79.3, which are very loose factors, mean lateness for all order releases and dispatching rules have larger earlier delivery times than expected.

Tables 10 and 11 show the results of using 5-10% order rejection proportions. All results show positive values, which an average order's delivery time is earlier than the DD. This reflects upon the importance of using the strike rate method to estimate the proportion of future orders and adding them to the total workload. In the case of considering all orders as future jobs and assigning them a DD, meaning all confirmed and unconfirmed orders are considered as future orders, it is going to reduce the performance of the delivery date. When some orders are rejected while they were all considered accepted, a large portion of orders are going to be delivered earlier or need to reconsider their DD and RD, which is going to produce unbalance in scheduling and capacity management.

		FIFO			
		7.6	15	38.4	79.3
5%	BIL	62.3817606	209.58806	653.114	1439.772
	FIL	75.366512	203.5922	657.2332	1459.87
	IMM	74.477804	212.30292	661.1434	1454
	MIL	65.647459	207.0948	647.9724	1436.746
	WLCDD	69.33254	206.1217	655.8152	1449.948
		EDD			
		7.6	15	38.4	79.3
	BIL	55.48765	205.68668	665.6264	1451.69
	FIL	69.934628	200.65868	661.697	1447.112
	IMM	63.434158	200.33786	666.539	1452.864
	MIL	62.13	206.63366	655.461	1452.496
	WLCDD	57.648008	206.71808	647.6714	1454.842

Table 10. Mean Lateness with 5% Order Rejection Probability.

The company should consider rejecting some orders to reduce the pressure on the production system and improve DD or assign longer DD to give more time to process previous orders.

		FIFO			
		7.6	15	38.4	79.3
10%%	BIL	95.82844	240.7306	692.2188	1475.062
	FIL	94.312204	237.6292	689.257	1478.692
	IMM	96.76748	241.2226	689.9654	1480.612
	MIL	96.9881	242.512	688.9998	1480.794
	WLCDD	98.7512	239.2528	689.9494	1480.292
		EDD			
		7.6	15	38.4	79.3
	BIL	93.66736	242.4452	692.6212	1483.422
	FIL	98.9122	241.0322	690.4062	1477.28
	IMM	98.16928	239.517	690.8212	1475.064
	MIL	98.11382	238.8058	691.9156	1480.804
	WLCDD	99.2247	240.8878	689.7884	1479.6

Table 11. Mean Lateness with 10% Order Rejection Probability.

Percentages of tardy orders used to measure the performance of applying different order release rules. Table 12 shows the results of using TA order entry and the five different releasing rules with FIFO and EDD priority dispatching rules. WLCDD rule, which ranks orders according to the routing length and RD, shows unexpected performance. The WLCDD method combines two rules: first, in the pre-shop pool, orders are sorted according to routing length; second, if the RD becomes close, direct release is considered for the order despite route length.

		FIFO			
		7.6	15	38.4	79.3
TA	BIL	60%	24%	0%	0%
	FIL	66%	23%	0%	0%
	IMM	67%	27%	1%	0%
	MIL	56%	23%	0%	0%
	WLCDD	15%	12%	7%	0%
		EDD			
		7.6	15	38.4	79.3
	BIL	71%	20%	0%	0%
	FIL	59%	22%	0%	0%
	IMM	66%	30%	0%	0%
	MIL	64%	25%	0%	0%
	WLCDD	14%	11%	6%	2%

Table 12. Percentage of Tardy Orders Under TA.

Because of the destabilization in work centers utilization and bottlenecking existing in work centers 1 and 3, the estimated throughput time for orders with long routing is higher than actual throughput time. The utilization in work centers 1 and 3 is above 90% (see Appendix C), which means that the waiting time in front of these work centers is longer than other work centers. The waiting time in front of work center 1 and 3 are about 5-7 times units for each one where the average total waiting time in the shop floor is around 24-times units. In other words, because of the higher utilization at work centers 1 and 3, the waiting time in front of these work centers is equal to 50% of the entire shop floor waiting time. Therefore, the DD allowance factor planned according to the bottleneck work centers on the shop floor to ensure that all orders with short routing meet the DD. This explains the reason of having positive mean lateness at K_{TWK} = 15 which leads to an earlier delivery time than planned and higher P_{tardy} around 25%, see

Appendix B for the estimated lead time, actual throughput time, queue in the floor shop, and queue in the pre-shop pool.

Most of the WLC observed simulations assumed equal and fixed work centers, which is a practically unrealistic for Y company. The suggestion here is to use different DD allowances for each route to ensure meeting the DD for short routing orders and reducing the DD estimations.

Table 13 shows the percentages of tardy orders when 5% of orders are rejected. All percentages of tardy orders decreased about 30-40% and got closer to 0% at K_{TWK} = 38.4 and 79.3.

		FIFO			
		7.6	15	38.4	79.3
5%	BIL	14%	0%	0%	0%
	FIL	6%	0%	0%	0%
	IMM	11%	2%	0%	0%
	MIL	10%	1%	0%	0%
	WLCDD	7%	4%	0%	0%
		EDD			
		7.6	15	38.4	79.3
	BIL	17%	2%	0%	0%
	FIL	8%	0%	0%	0%
	IMM	11%	2%	0%	0%
	MIL	12%	0%	0%	0%
	WLCDD	8%	8%	1%	0%

Table 13. Percentages of Tardy Orders with 5% Order Rejection Probability.

Table 14 shows the results of rejecting 10% of orders on percentages of tardy orders.

		FIFO			
		7.6	15	38.4	79.3
10%	BIL	1%	0%	0%	0%
	FIL	1%	0%	0%	0%
	IMM	2%	0%	0%	0%
	MIL	2%	0%	0%	0%
	WLCDD	2%	0%	0%	0%
		EDD			
		7.6	15	38.4	79.3
	BIL	2%	0%	0%	0%
	FIL	0%	0%	0%	0%
	IMM	1%	0%	0%	0%
	MIL	0%	0%	0%	0%
	WLCDD	2%	0%	0%	0%

Table 14. Percentages of Tardy Orders with 5% Order Rejection Probability.

Overall the WLCDD releasing rule performed much better than the other rules under the EDD priority dispatching rule.

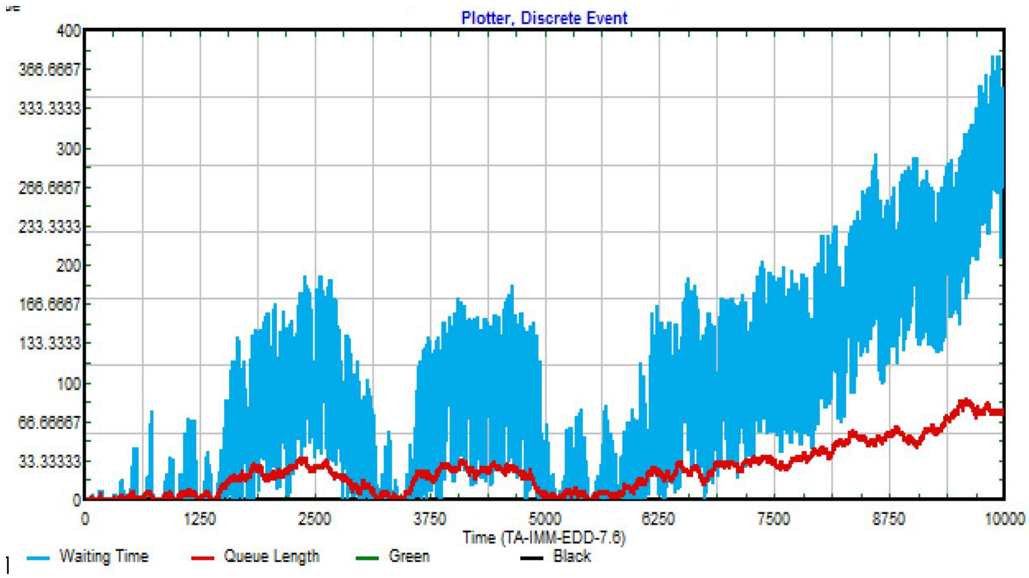

Figure 11. Waiting Time and Queue Length at Dispatching (TA-IMM-EDD-7.6).

Figure 11 shows the waiting time and queue length of the dispatching pool with an IMM order release rule at K_{TWK} = 7.6, which shows the fluctuation of queue length arriving at the maximum of 75 orders in queue. At EED priority dispatching, the average wait time was 41.66-time units and the maximum about 380-time units (see Appendix B). The maximum queue length of the WLCDD releasing rule has a close value to EDD rules; however, WLCDD kept orders in the pool at an average of 53.5-time units and the maximum at about 1000 times unit (see Figure 12) which was longer than IMM. This allows WLCDD to reduce waiting time on the shop floor after releasing to 15.6-time units, whereas average waiting time at dispatching was 21.5 time units. At tightened DD allowance of 7.6, WLCDD shows better efficiency in reducing P_{tardy} to 14% while IMM shows 66%.

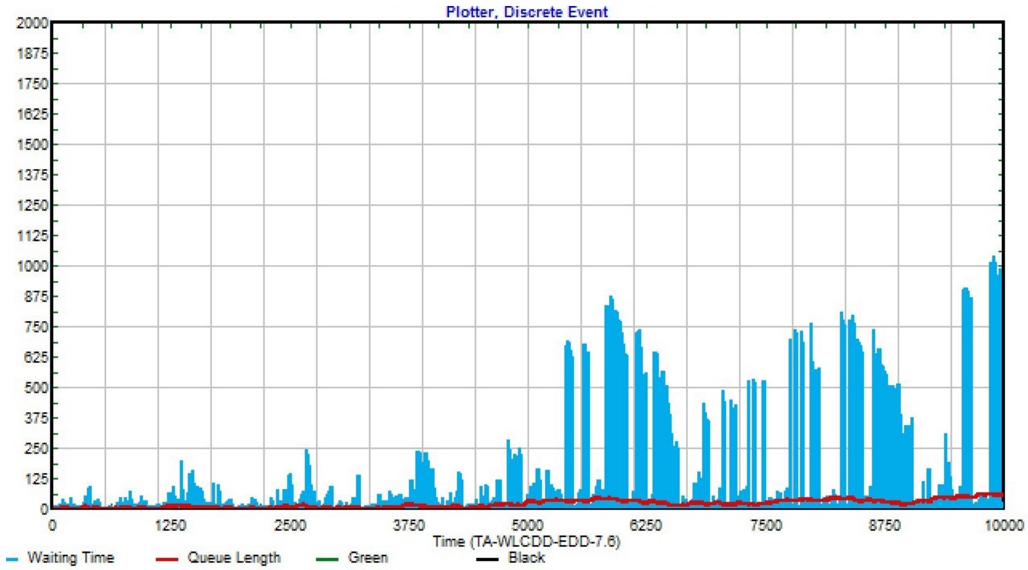

Figure 12. Waiting Time and Queue Length at OR Pool (TA-WLCDD-EDD-7.6).

At K_{TWK} = 15, the DD becomes a little loose; therefore, longer DD were assigned for confirmed orders, which provided more flexibility in meeting the DD. Figure 13 shows the performance of wait time and queue length at dispatching pool for IMM releasing rule. The average waiting time at the dispatching pool increased to 47.5 times units and 275 times units at maximum while queue length decreased. In contrast, Figure 14 depicts the WLCDD releasing rule, where the average waiting time in the dispatching pool dropped to 47.2-time units, but the maximum waiting time increased to 2250-time units, which means due to the increase of the DD, the orders were kept in dispatching pool for a longer time. Also, for both 7.6 and 15, the two releasing rules maintained steady waiting times on the shop floor.

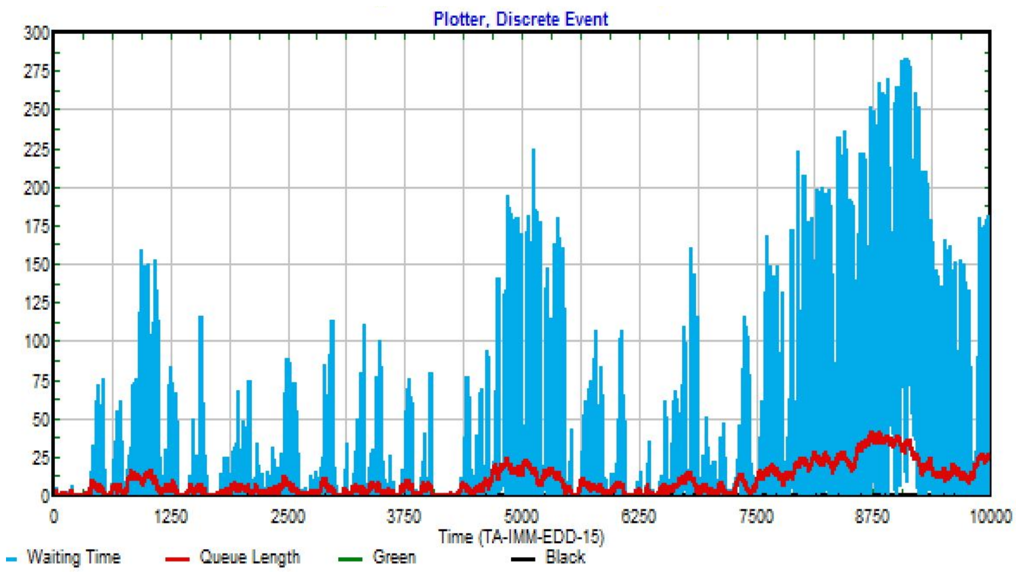

Figure 13. Waiting Time and Queue Length at Dispatching (TA-IMM-EDD-15).

Additionally, the P_{tardy} for IMM at K_{TWK}=15, decreased to 30% while WLCDD decreased to 11%. The other releasing rules showed better P_{tardy} reductions corresponding to the increase in K_{TWK} value.

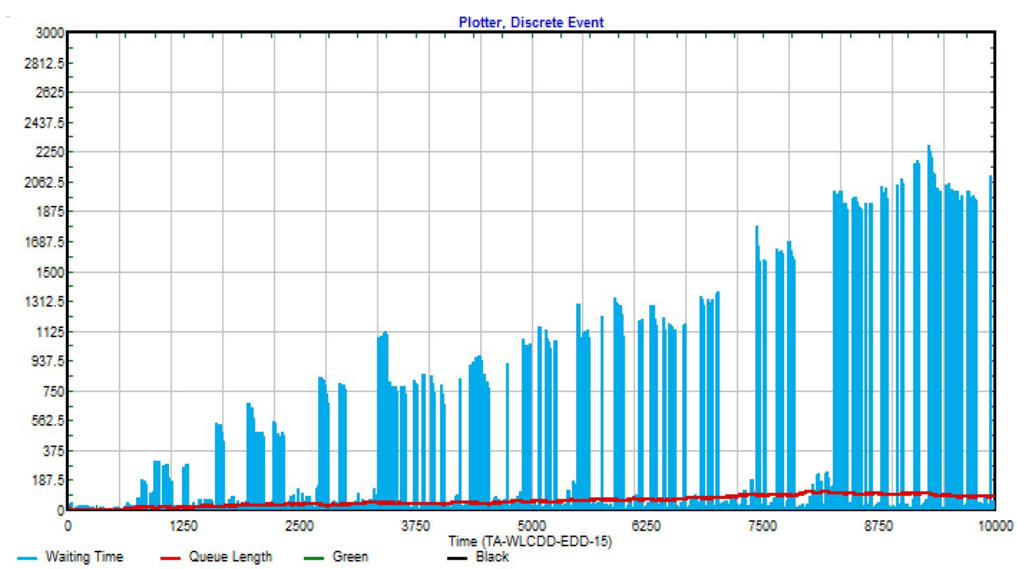

Figure 14. Waiting Time and Queue Length at OR Pool (TA-WLCDD-EDD-15).

Figures11-14 show increasing in queue length and waiting time because order release rule controls releasing mechanism, so some order might wait longer time than other orders. This increasing does not mean that the system not stable because the goals are to stable the production load in the floor shop and meet DD.

Over all, the simulation showed a promising result towards implementation even though previous research reported higher performance during implementation.

- Simulation Assumption and Limitation

There are a couple of assumptions and limitations of the simulation that must be identified:

- The distributions used to run the model resemble the one used in Thürer (2012a) with increasing the number of work centers to 8.
- An adjustment was applied to order generation distribution by increasing the mean to 3.7 while it was 2.27 in the previous model due to the increased process times for the extra two work centers.
- The human labor factor and the applicability of relocating machine operators was not taken into account during the simulation.
- Simple order releasing rules that neglected the current load on the shop floor at the time of releasing may have corrupted the final data.
- The time required for order confirmation was not calculated.
- The preparation stage included the time required to design, buy, and prepare material and tools, which is highly variant in reality.

Chapter 5 – Suggestion for Additional Work

In the study, the simulation results found that WLCDD releasing rules performed much better than the other rules that were measured. However, different rules that were not measured for, such DBR or constant work-in-process, may improve the performance more than WLCDD. Further research is needed to measure the effectiveness of different releasing rules.

Additionally, the planning factor, which is used to estimate the DD, was selected based on the percentages of late orders. A suggestion for further research is to optimize the planning factor in order to minimize the lateness time and percentage of tardy orders.

Also, realism within the simulated model needs to be adjusted to accommodate for availability and utilizations of operators, order confirmation time and design time, applicability of balancing the workload between work centers, and material availability. Also, the simulation should account for the possibility of type I errors, which requires fixing a product or re-producing it even though the chance of this happening is low.

Overall, further investigation on WLC implementation is needed. Reports examining successful implementations of WLC are critical to compiling a detailed and effective implementation strategy to overcome implementation uncertainties.

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Appendices

Appendix A: Simulation Model

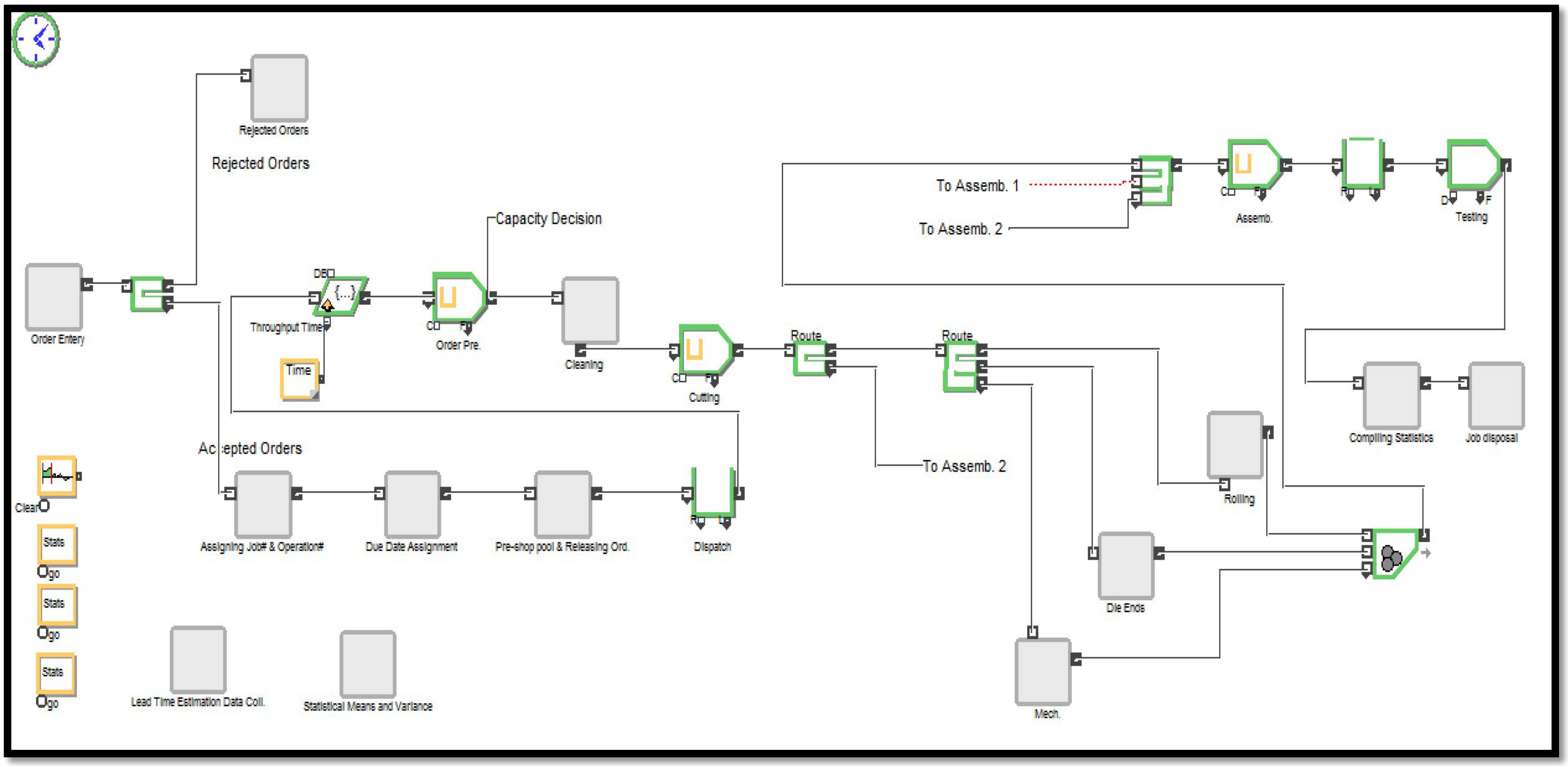

Figure 15- ExtendSim Summarized Model.

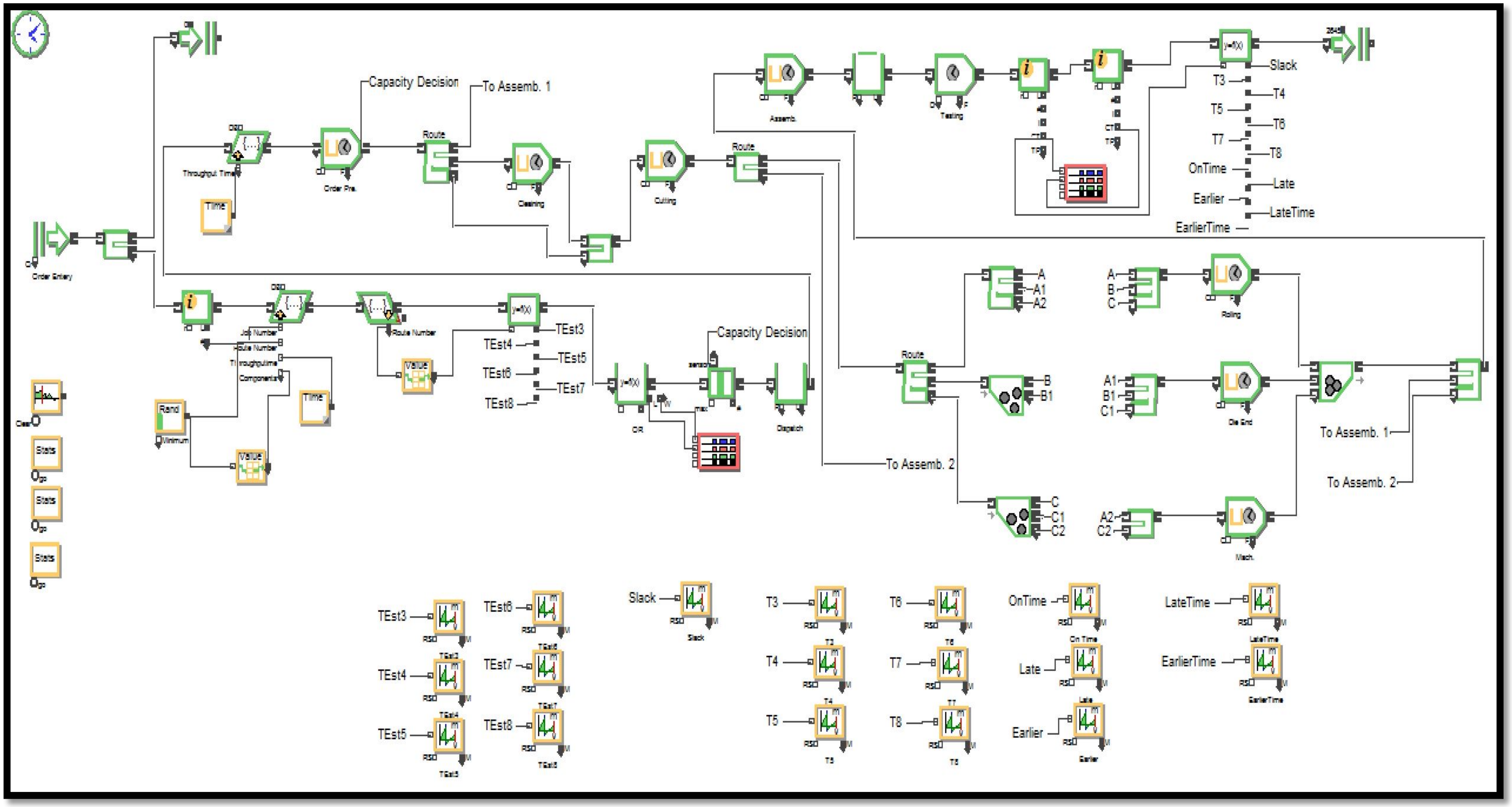

Figure 16- ExtendSim Model.

Appendix B: Lead Time Estimated and Queues Data Tables

	ORR	DR	K_{TWK}	Lest.	SDest	T	SD	Q in SF	Q in OR
TA	BIL	FIFO	7.6	146.51	1.80	202.38	71.61	16.73	165.11
	FIL	FIFO	7.6	146.53	1.79	214.07	69.87	16.73	176.83
	IMM	FIFO	7.6	146.52	1.79	209.15	65.34	24.10	164.29
	MIL	FIFO	7.6	146.51	1.78	205.12	62.86	16.91	167.64
	WLCDD	FIFO	7.6	146.53	1.78	247.53	96.49	17.46	180.90
	ORR	DR	K_{TWK}	Lest.	SDest	T	SD	Q in SF	Q in OR
TA	BIL	FIFO	15	289.19	3.53	216.28	66.14	16.89	178.56
	FIL	FIFO	15	289.20	3.51	213.62	70.11	16.89	176.15
	IMM	FIFO	15	289.18	3.53	202.98	66.02	23.98	158.28
	MIL	FIFO	15	289.17	3.51	205.80	70.63	16.66	169.06
	WLCDD	FIFO	15	289.19	3.52	216.58	82.03	17.82	155.70
	ORR	DR	K_{TWK}	Lest.	SDest	T	SD	Q in SF	Q in OR
TA	BIL	FIFO	38.4	740.33	9.08	251.23	84.88	17.02	213.21
	FIL	FIFO	38.4	740.38	8.96	215.32	68.47	16.90	177.71
	IMM	FIFO	38.4	740.30	9.07	210.98	67.12	24.17	166.01
	MIL	FIFO	38.4	740.28	8.93	216.97	71.87	16.83	179.50
	WLCDD	FIFO	38.4	689.36	36.91	291.79	75.84	17.30	177.71
	ORR	DR	K_{TWK}	Lest.	SDest	T	SD	Q in SF	Q in OR
TA	BIL	FIFO	79.3	5.71	81.18	232.55	71.37	3.42	190.88
	FIL	FIFO	79.3	1528.82	18.48	217.80	74.59	17.04	176.53
	IMM	FIFO	79.3	1528.74	18.50	198.96	60.42	24.34	153.55
	MIL	FIFO	79.3	1528.82	18.58	211.95	77.67	17.17	170.51
	WLCDD	FIFO	79.3	1528.87	18.55	233.59	88.75	17.51	168.33

Table 15. Output Data Under Total Order acceptance.

	ORR	DR	K_{TWK}	Lest.	SDest	T	SD	Q in SF	Q in OR
5%	BIL	FIFO	7.6	146.53	1.81	84.24	39.29	14.88	49.75
	FIL	FIFO	7.6	146.53	1.78	71.10	34.04	14.56	37.32
	IMM	FIFO	7.6	146.53	1.79	72.21	34.12	20.91	31.33
	MIL	FIFO	7.6	146.51	1.79	80.69	36.12	14.94	46.10
	WLCDD	FIFO	7.6	146.52	1.79	77.23	43.04	15.20	42.74
	ORR	DR	K_{TWK}	Lest.	SDest	T	SD	Q in SF	Q in OR
5%	BIL	FIFO	15	289.17	3.55	79.54	38.64	15.18	44.73
	FIL	FIFO	15	289.22	3.55	85.47	43.35	14.96	51.02
	IMM	FIFO	15	289.16	3.52	76.49	36.68	20.72	36.14
	MIL	FIFO	15	289.18	3.53	81.95	39.47	14.88	47.54
	WLCDD	FIFO	15	289.18	3.52	84.31	49.49	15.62	47.96
	ORR	DR	K_{TWK}	Lest.	SDest	T	SD	Q in SF	Q in OR
5%	BIL	FIFO	38.4	740.32	9.10	86.17	45.22	15.39	51.04
	FIL	FIFO	38.4	740.35	9.06	82.39	42.15	14.86	48.27
	IMM	FIFO	38.4	740.30	9.07	79.49	36.29	21.42	38.10
	MIL	FIFO	38.4	740.26	8.96	91.93	42.85	15.48	56.65
	WLCDD	FIFO	38.4	740.38	9.01	85.42	47.52	15.63	49.73
	ORR	DR	K_{TWK}	Lest.	SDest	T	SD	Q in SF	Q in OR
5%	BIL	FIFO	79.3	1528.69	18.91	89.06	45.85	15.16	54.27
	FIL	FIFO	79.3	1528.99	18.60	73.71	41.41	15.39	39.46
	IMM	FIFO	79.3	1528.82	18.73	77.31	33.60	21.20	36.03
	MIL	FIFO	79.3	1528.82	18.64	89.81	45.75	15.59	54.11
	WLCDD	FIFO	79.3	1528.92	18.64	79.20	45.85	15.51	44.44

Table 16. Output Data Under 5% Order Rejection.

	ORR	DR	KTWK	Lest.	SDest	T	SD	Q in SF	Q in OR
10%	BIL	FIFO	7.6	146.52	1.81	50.63	24.75	12.70	19.25
	FIL	FIFO	7.6	146.54	1.77	52.10	24.92	12.92	20.66
	IMM	FIFO	7.6	146.52	1.79	49.72	23.41	17.92	12.91
	MIL	FIFO	7.6	146.51	1.78	49.65	24.31	12.55	18.88
	WLCDD	FIFO	7.6	146.53	1.80	47.89	26.07	12.76	16.97
	ORR	DR	KTWK	Lest.	SDest	T	SD	Q in SF	Q in OR
10%	BIL	FIFO	15	289.17	3.56	48.56	24.14	12.53	17.73
	FIL	FIFO	15	289.20	3.50	51.25	26.52	12.71	20.16
	IMM	FIFO	15	289.16	3.51	47.93	21.83	17.89	11.19
	MIL	FIFO	15	289.19	3.55	46.73	22.14	12.39	16.29
	WLCDD	FIFO	15	289.21	3.54	50.06	28.28	12.92	19.09
	ORR	DR	KTWK	Lest.	SDest	T	SD	Q in SF	Q in OR
10%	BIL	FIFO	38.4	740.32	9.03	48.74	26.04	12.77	17.86
	FIL	FIFO	38.4	740.31	8.88	50.25	26.44	12.73	19.08
	IMM	FIFO	38.4	740.30	9.00	50.34	23.91	17.78	13.67
	MIL	FIFO	38.4	740.35	9.03	50.51	27.10	12.97	19.22
	WLCDD	FIFO	38.4	740.35	8.98	50.16	28.38	12.83	18.66
	ORR	DR	KTWK	Lest.	SDest	T	SD	Q in SF	Q in OR
10%	BIL	FIFO	79.3	1528.76	18.62	53.64	29.71	102.15	21.90
	FIL	FIFO	79.3	1528.95	18.64	49.11	26.52	12.77	18.16
	IMM	FIFO	79.3	1528.80	18.66	49.68	23.00	17.85	12.82
	MIL	FIFO	79.3	1528.80	18.78	50.08	28.12	12.81	19.16
	WLCDD	FIFO	79.3	1528.83	18.48	48.51	26.92	12.60	17.79

Table 17. Output Data Under 10% Order Rejection.

	ORR	DR	KTW K	Lest.	SDest	T	SD	Q in SF	Q in OR
TA	BIL	EDD	7.6	144.59	1.77	215.99	65.82	16.85	178.65
	FIL	EDD	7.6	146.53	1.78	209.02	69.52	17.00	171.78
	IMM	EDD	7.6	146.51	1.79	206.75	62.14	24.16	161.81
	MIL	EDD	7.6	146.52	1.78	65.92	65.92	16.84	153.26
	WLCDD	EDD	7.6	146.52	1.78	210.87	84.97	17.57	155.92
	ORR	DR	KTW K	Lest.	SDest	T	SD	Q in SF	Q in OR
TA	BIL	EDD	15	289.17	3.53	202.53	70.29	16.85	165.42
	FIL	EDD	15	289.20	3.54	217.13	71.76	17.18	179.79
	IMM	EDD	15	289.16	3.52	227.81	78.38	24.41	183.04
	MIL	EDD	15	289.17	3.54	218.18	70.62	16.88	181.05
	WLCDD	EDD	15	289.20	3.56	223.40	85.23	17.41	159.48
	ORR	DR	KTW K	Lest.	SDest	T	SD	Q in SF	Q in OR
TA	BIL	EDD	38.4	740.30	9.02	227.44	77.27	16.93	188.95
	FIL	EDD	38.4	740.42	9.03	199.26	74.73	16.80	161.18
	IMM	EDD	38.4	740.34	9.00	229.15	64.73	24.02	183.50
	MIL	EDD	38.4	740.30	9.03	224.90	73.82	16.98	185.97
	WLCDD	EDD	38.4	740.32	8.95	223.73	82.59	17.58	164.79
	ORR	DR	KTW K	Lest.	SDest	T	SD	Q in SF	Q in OR
TA	BIL	EDD	79.3	1528.65	18.62	241.87	81.25	17.13	201.12
	FIL	EDD	79.3	1529.01	18.58	200.15	76.36	17.17	159.01
	IMM	EDD	79.3	1528.72	18.65	203.11	77.17	24.48	154.50
	MIL	EDD	79.3	1528.8	18.61	199.11	75.00	17.38	157.66
	WLCDD	EDD	79.3	1528.8	18.52	248.46	93.28	17.63	179.87

Table 18. Output Data Under Total Order Acceptance.

	ORR	DR	KTWK	Lest.	SDest	T	SD	Q in SF	Q in OR
5%	BIL	EDD	7.6	144.58	1.76	89.00	39.04	15.04	53.97
	FIL	EDD	7.6	146.52	1.78	76.55	35.05	14.99	42.05
	IMM	EDD	7.6	146.52	1.78	83.16	39.37	21.58	41.66
	MIL	EDD	7.6	146.51	1.79	84.43	37.86	15.09	49.30
	WLCDD	EDD	7.6	146.52	1.79	88.94	46.23	15.62	53.56
	ORR	DR	KTWK	Lest.	SDest	T	SD	Q in SF	Q in OR
5%	BIL	EDD	15	289.19	3.51	83.53	41.74	15.13	48.88
	FIL	EDD	15	289.21	3.51	88.67	41.79	15.51	53.45
	IMM	EDD	15	289.16	3.52	88.99	40.19	21.36	47.54
	MIL	EDD	15	289.18	3.51	82.62	43.09	14.83	48.68
	WLCDD	EDD	15	289.21	3.52	82.58	43.35	15.68	47.23
	ORR	DR	KTWK	Lest.	SDest	T	SD	Q in SF	Q in OR
5%	BIL	EDD	38.4	740.31	9.00	73.42	40.29	15.12	38.99
	FIL	EDD	38.4	740.34	9.02	78.26	40.51	15.30	43.88
	IMM	EDD	38.4	740.26	8.94	72.42	37.90	21.27	31.27
	MIL	EDD	38.4	740.30	9.02	84.80	43.63	15.28	49.71
	WLCDD	EDD	38.4	740.37	9.01	92.51	51.71	15.61	55.86
	ORR	DR	KTWK	Lest.	SDest	T	SD	Q in SF	Q in OR
5%	BIL	EDD	79.3	1528.80	18.75	76.14	41.94	15.35	41.32
	FIL	EDD	79.3	1528.91	18.65	82.12	44.76	15.53	46.61
	IMM	EDD	79.3	1528.68	18.59	77.70	41.25	21.46	36.53
	MIL	EDD	79.3	1528.73	18.67	78.50	43.86	15.64	43.62
	WLCDD	EDD	79.3	1528.88	18.49	75.75	43.53	15.14	41.68

Table 19. Output Data Under 5% Order Rejection.

	ORR	DR	KTW K	Lest.	SDest	T	SD	Q in SF	Q in OR
10%	BIL	EDD	7.6	144.59	1.76	50.90	23.70	12.55	19.90
	FIL	EDD	7.6	146.52	1.77	47.36	21.58	12.50	16.41
	IMM	EDD	7.6	146.52	1.80	48.22	23.46	17.68	11.92
	MIL	EDD	7.6	146.52	1.79	48.29	22.48	12.37	17.47
	WLCDD	EDD	7.6	146.52	1.78	47.39	25.90	12.51	17.01
	ORR	DR	KTW K	Lest.	SDest	T	SD	Q in SF	Q in OR
10%	BIL	EDD	15	289.18	3.53	46.94	23.14	12.66	16.24
	FIL	EDD	15	289.20	3.56	48.02	24.65	12.43	17.45
	IMM	EDD	15	289.20	3.55	49.86	26.03	18.02	13.29
	MIL	EDD	15	289.19	3.55	50.44	25.50	12.87	19.09
	WLCDD	EDD	15	289.19	3.50	48.25	26.49	12.66	17.46
	ORR	DR	KTW K	Lest.	SDest	T	SD	Q in SF	Q in OR
10%	BIL	EDD	38.4	740.30	9.04	47.63	24.75	12.53	16.87
	FIL	EDD	38.4	740.34	8.96	50.07	26.88	12.94	18.93
	IMM	EDD	38.4	740.29	9.05	50.65	27.14	18.11	14.13
	MIL	EDD	38.4	740.30	9.05	49.26	25.94	12.70	18.36
	WLCDD	EDD	38.4	740.34	9.01	50.17	27.16	12.97	19.09
	ORR	DR	KTW K	Lest.	SDest	T	SD	Q in SF	Q in OR
10%	BIL	EDD	79.3	1528.80	18.79	48.49	26.40	12.92	17.56
	FIL	EDD	79.3	1528.77	18.47	49.93	27.58	12.84	18.95
	IMM	EDD	79.3	1528.78	18.61	49.66	25.63	18.33	12.71
	MIL	EDD	79.3	1528.77	18.69	48.89	27.30	12.76	18.01
	WLCDD	EDD	79.3	1528.90	18.70	48.36	27.09	12.73	17.70

Table 20. Output Data under 10% Order rejection.

Appendix C: Work Centers' Utilizations

FIFO	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
TA	Assembly	7.6	97%	97%	97%	97%	97%
	Cleaning	7.6	70%	69%	70%	70%	68%
	Cutting	7.6	86%	85%	86%	86%	84%
	Die End	7.6	37%	37%	37%	37%	35%
	Mach.	7.6	18%	18%	18%	18%	16%
	Order Pre.	7.6	99%	99%	99%	99%	99%
	Rolling	7.6	37%	37%	37%	37%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
TA	Assembly	15	97%	97%	97%	97%	97%
	Cleaning	15	69%	69%	69%	69%	68%
	Cutting	15	85%	85%	86%	85%	85%
	Die End	15	37%	37%	37%	37%	36%
	Mach.	15	18%	19%	18%	18%	17%
	Order Pre.	15	99%	99%	99%	99%	100%
	Rolling	15	37%	37%	37%	37%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
TA	Assembly	38.4	97%	97%	97%	97%	97%
	Cleaning	38.4	69%	68%	70%	69%	67%
	Cutting	38.4	84%	84%	86%	84%	84%
	Die End	38.4	36%	37%	37%	37%	36%
	Mach.	38.4	18%	18%	19%	18%	17%
	Order Pre.	38.4	99%	99%	99%	99%	99%
	Rolling	38.4	37%	37%	37%	36%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
TA	Assembly	79.3	97%	97%	97%	97%	97%
	Cleaning	79.3	68%	68%	70%	67%	68%
	Cutting	79.3	84%	84%	86%	84%	84%
	Die End	79.3	36%	36%	37%	36%	36%
	Mach.	79.3	18%	18%	18%	18%	17%
	Order Pre.	79.3	99%	99%	99%	99%	99%
	Rolling	79.3	36%	36%	37%	36%	36%

Table 21. WC Utilization Under Order Total Acceptance and FIFO DR.

FIFO	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
5%	Assembly	7.6	93%	92%	93%	93%	93%
	Cleaning	7.6	65%	64%	65%	65%	64%
	Cutting	7.6	80%	79%	80%	80%	79%
	Die End	7.6	36%	35%	36%	35%	36%
	Mach.	7.6	18%	18%	18%	18%	18%
	Order Pre.	7.6	94%	93%	93%	94%	94%
	Rolling	7.6	36%	35%	36%	36%	35%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
5%	Assembly	15	93%	93%	93%	93%	93%
	Cleaning	15	65%	64%	64%	64%	65%
	Cutting	15	80%	80%	80%	79%	80%
	Die End	15	35%	36%	35%	35%	35%
	Mach.	15	18%	18%	18%	18%	18%
	Order Pre.	15	94%	94%	94%	94%	94%
	Rolling	15	36%	35%	35%	36%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
5%	Assembly	38.4	93%	93%	93%	94%	93%
	Cleaning	38.4	64%	63%	65%	65%	65%
	Cutting	38.4	80%	79%	81%	81%	80%
	Die End	38.4	36%	35%	36%	36%	36%
	Mach.	38.4	18%	18%	18%	18%	18%
	Order Pre.	38.4	95%	94%	94%	95%	95%
	Rolling	38.4	36%	36%	36%	36%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
5%	Assembly	79.3	93%	93%	93%	93%	93%
	Cleaning	79.3	64%	65%	65%	64%	65%
	Cutting	79.3	80%	80%	81%	80%	80%
	Die End	79.3	36%	36%	36%	35%	36%
	Mach.	79.3	18%	18%	18%	18%	18%
	Order Pre.	79.3	94%	94%	94%	94%	94%
	Rolling	79.3	36%	36%	36%	35%	35%

Table 22. WC Utilization Under 5% Order Rejection and FIFO DR.

FIFO	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
10%	Assembly	7.6	88%	88%	88%	88%	88%
	Cleaning	7.6	60%	60%	60%	60%	59%
	Cutting	7.6	74%	74%	75%	74%	74%
	Die End	7.6	34%	34%	34%	34%	34%
	Mach.	7.6	17%	17%	17%	17%	17%
	Order Pre.	7.6	88%	88%	88%	88%	88%
	Rolling	7.6	34%	34%	34%	34%	34%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
10%	Assembly	15	87%	88%	88%	87%	88%
	Cleaning	15	59%	59%	60%	59%	59%
	Cutting	15	74%	74%	75%	73%	74%
	Die End	15	34%	34%	34%	34%	34%
	Mach.	15	17%	17%	17%	17%	17%
	Order Pre.	15	87%	88%	88%	87%	88%
	Rolling	15	34%	34%	34%	34%	34%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
10%	Assembly	38.4	88%	88%	88%	88%	88%
	Cleaning	38.4	59%	59%	60%	60%	59%
	Cutting	38.4	74%	74%	74%	74%	74%
	Die End	38.4	34%	34%	34%	34%	34%
	Mach.	38.4	17%	17%	17%	17%	17%
	Order Pre.	38.4	88%	88%	88%	88%	88%
	Rolling	38.4	34%	34%	34%	34%	34%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
10%	Assembly	79.3	88%	88%	88%	87%	87%
	Cleaning	79.3	60%	59%	60%	60%	59%
	Cutting	79.3	75%	74%	75%	74%	74%
	Die End	79.3	34%	34%	34%	34%	34%
	Mach.	79.3	17%	17%	17%	17%	17%
	Order Pre.	79.3	88%	88%	88%	87%	87%
	Rolling	79.3	34%	34%	34%	34%	34%

Table 23. WC Utilization Under 10% Order Rejection and FIFO DR.

EDD	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
TA	Assembly	7.6	97%	97%	97%	97%	97%
	Cleaning	7.6	70%	70%	69%	69%	68%
	Cutting	7.6	85%	86%	85%	85%	84%
	Die End	7.6	37%	37%	37%	37%	36%
	Mach.	7.6	18%	18%	18%	18%	17%
	Order Pre.	7.6	99%	99%	99%	99%	99%
	Rolling	7.6	37%	37%	37%	37%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
TA	Assembly	15	97%	97%	97%	97%	97%
	Cleaning	15	69%	70%	70%	69%	68%
	Cutting	15	85%	86%	86%	85%	84%
	Die End	15	37%	37%	37%	37%	35%
	Mach.	15	18%	18%	18%	18%	17%
	Order Pre.	15	99%	100%	99%	99%	99%
	Rolling	15	37%	37%	37%	37%	35%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
TA	Assembly	38.4	97%	96%	97%	97%	97%
	Cleaning	38.4	68%	68%	68%	68%	68%
	Cutting	38.4	84%	84%	84%	84%	84%
	Die End	38.4	37%	36%	37%	36%	36%
	Mach.	38.4	18%	18%	18%	18%	17%
	Order Pre.	38.4	99%	99%	99%	99%	99%
	Rolling	38.4	37%	36%	36%	36%	35%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
TA	Assembly	79.3	97%	97%	97%	97%	97%
	Cleaning	79.3	67%	68%	68%	68%	67%
	Cutting	79.3	84%	84%	84%	84%	84%
	Die End	79.3	36%	36%	36%	36%	35%
	Mach.	79.3	18%	18%	18%	18%	17%
	Order Pre.	79.3	99%	99%	99%	99%	100%
	Rolling	79.3	36%	36%	36%	36%	36%

Table 24. WC Utilization Under Order Total Acceptance and EDD DR.

EDD	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
5%	Assembly	7.6	94%	93%	93%	94%	94%
	Cleaning	7.6	65%	65%	65%	65%	65%
	Cutting	7.6	81%	80%	80%	81%	80%
	Die End	7.6	36%	36%	36%	36%	36%
	Mach.	7.6	18%	18%	18%	18%	18%
	Order Pre.	7.6	95%	94%	94%	95%	95%
	Rolling	7.6	36%	36%	36%	36%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
5%	Assembly	15	93%	94%	94%	93%	93%
	Cleaning	15	65%	66%	65%	64%	64%
	Cutting	15	80%	81%	80%	79%	80%
	Die End	15	36%	36%	36%	36%	36%
	Mach.	15	18%	18%	18%	18%	18%
	Order Pre.	15	94%	95%	94%	94%	95%
	Rolling	15	36%	36%	36%	36%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
5%	Assembly	38.4	93%	93%	93%	93%	94%
	Cleaning	38.4	64%	64%	64%	65%	64%
	Cutting	38.4	79%	80%	80%	80%	80%
	Die End	38.4	35%	36%	35%	36%	36%
	Mach.	38.4	18%	18%	17%	18%	17%
	Order Pre.	38.4	93%	94%	94%	94%	95%
	Rolling	38.4	35%	36%	35%	36%	36%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
5%	Assembly	79.3	93%	94%	93%	93%	93%
	Cleaning	79.3	64%	65%	64%	65%	64%
	Cutting	79.3	79%	80%	80%	80%	80%
	Die End	79.3	36%	36%	36%	36%	36%
	Mach.	79.3	18%	18%	18%	18%	18%
	Order Pre.	79.3	94%	95%	93%	94%	94%
	Rolling	79.3	35%	36%	36%	36%	36%

Table 25. WC Utilization Under 5% Order Rejection and EDD DR.

EDD	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
10%	Assembly	7.6	88%	87%	88%	88%	87%
	Cleaning	7.6	60%	59%	59%	59%	59%
	Cutting	7.6	74%	73%	74%	74%	74%
	Die End	7.6	34%	34%	34%	34%	34%
	Mach.	7.6	17%	17%	17%	17%	17%
	Order Pre.	7.6	88%	87%	88%	88%	87%
	Rolling	7.6	34%	33%	34%	34%	34%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
10%	Assembly	15	88%	87%	88%	88%	87%
	Cleaning	15	59%	59%	60%	60%	59%
	Cutting	15	73%	73%	74%	74%	73%
	Die End	15	34%	34%	34%	34%	34%
	Mach.	15	17%	17%	17%	17%	17%
	Order Pre.	15	87%	87%	88%	88%	87%
	Rolling	15	34%	34%	34%	34%	34%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
10%	Assembly	38.4	88%	88%	88%	88%	88%
	Cleaning	38.4	59%	60%	60%	59%	59%
	Cutting	38.4	73%	74%	74%	74%	74%
	Die End	38.4	34%	34%	34%	34%	34%
	Mach.	38.4	17%	17%	17%	17%	17%
	Order Pre.	38.4	87%	88%	88%	88%	88%
	Rolling	38.4	34%	34%	34%	34%	34%
	WC	KTWK	BIL	FIL	IMM	MIL	WLCDD
10%	Assembly	79.3	88%	88%	88%	87%	87%
	Cleaning	79.3	60%	59%	60%	59%	59%
	Cutting	79.3	74%	74%	75%	74%	73%
	Die End	79.3	34%	34%	34%	34%	34%
	Mach.	79.3	17%	17%	17%	17%	17%
	Order Pre.	79.3	88%	88%	88%	87%	87%
	Rolling	79.3	34%	34%	34%	34%	34%

Table 26. WC Utilization Under 10% Order Rejection and EDD DR.