ANALYSIS OF POLCA AND GPOLCA MATERIAL CONTROL STRATEGIES

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Bachelor of Mechanical Engineering

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Pune, Maharashtra

2010

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2013

ANALYSIS OF POLCA AND GPOLCA MATERIAL CONTROL STRATEGIES

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Date of Degree: MAY, 2013

Title of Study: ANALYSIS OF POLCA AND GPOLCA MATERIAL CONTROL STRATEGIES

Major Field: INDUSTRIAL ENGINEERING AND MANAGEMENT

Scope and method of study: This research sheds new light on the performance of two relatively new material control strategies, known as Paired-cell Overlapping Loops of Cards with Authorization (POLCA) and Generic-POLCA (GPOLCA). POLCA and GPOLCA are designed for use in high variety/low volume manufacturing environments and were introduced in 1998 and 2006 respectively. So far, very few studies have been published comparing the performance of these two material control strategies and these have not considered practical shop floor conditions, which exist in a high variety manufacturing environment. The focus of this study was on analyzing the performance of POLCA and GPOLCA material control strategies for different manufacturing settings using simulation and design of experiments approach. Statistical analysis of the simulation results was used to compare the two strategies and provide new insight into their performance.

Findings and Conclusions: A new method of calculating the number of GPOLCA cards was developed instead of the previous method of random search for finding out number of cards. Also, a heuristic approach for setting up the POLCA and GPOLCA material control strategies was introduced and it was shown to be good alternative to the current iterative method of setting up these two strategies. Our study supports and confirms the previous comparison studies, which say that GPOLCA requires less WIP on the shop floor compared to POLCA to achieve the same throughput. At the same time, we have some new findings, which reveal that GPOLCA requires a higher total inventory and longer response time as compared to POLCA to achieve the same service level. Moreover, because of the incorrect prioritization of the orders, GPOLCA increases the average tardiness and total inventory of a product that needs a higher number of operations on the shop floor. Thus this research has uncovered a drawback of the GPOLCA material control strategy and showed the importance of proper prioritization of the orders in a high variety manufacturing environment.

ADVISOR'S APPROVAL: Dr. Manjunath Kamath

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The field of material planning and control is an important area within supply chain management and can provide competitive edge to a company by improving and streamlining its operations. Material planning and control strategies are mainly categorized as push, pull and push-pull (hybrid) strategies (Karmarkar, 1991; Krishnamurthy et al., 2004). These strategies are differentiated on the basis of how the production orders are released to the shop floor (Krishnamurthy et al., 2004). Push strategy mainly emphasizes the use of MRP, which releases production orders on the basis of forecasted demand (Orlicky et al., 1994). Orders are released to the shop floor by offsetting the manufacturing lead time of the order from the due date. In contrast, pull strategy uses inventory replenishment signals and it releases production orders based on actual requirement. Replenishment signal notifies the upstream workstation about the requirement of material at a downstream work station. In the hybrid strategy, a combination of both is used; a signal for replenishment is blended with the forecasted demand to maintain a steady rate of production.

In a customer-driven market environment, a company has to track customer demand and plan accordingly. Companies take different competitive stances such as guaranteeing a high-level of on-time deliveries to the customer, low price for bulk ordering, etc. to increase their customer base. These stances define competitive characteristics of the company by which they can win customer orders over their competitors. Competitive characteristics differentiate a company and provide an edge over its competitors, hence called as an order winner. According to The Association for Operations Management (APICS), order winner is defined as

"Those competitive characteristics that causes a firm's customer to choose that firm's goods and services over those of its competitors" (Blackstone, 2008)

The selection of a proper material control strategy plays a vital role in streamlining the operation on the shop floor. The type of material control strategy to be used is dependent on the company's manufacturing environment and balance of these two creates the order winning strategy (Vollmann et al., 1997).

A manufacturing environment can be classified into four main groups (Arnold et al., 2012).

1. Make-To-Stock (MTS): In this manufacturing environment a company manufactures the products and stores them as finished goods. A customer order is satisfied using the finished goods inventory. In this type of environment, the company produces a limited volume-variety mix and takes advantage of stable production by standardizing and automating production processes. The main characteristics of MTS are that the production rate is stable and the processes are standard and properly defined. Kanban material control strategy which is defined under lean manufacturing is mainly used in such environments.
2. Assemble-To-Order (ATO): In this manufacturing environment a company assembles the final order from the available raw materials and components. Here, the volume-variety mix is still limited. Again in this case the manufacturing rate of components and subassemblies stays reasonably constant but final assembly schedule changes according to the demand. Though the assembly schedule varies with demand, the level of subcomponent inventory and raw materials could be maintained by using the replenishment signal provided by a card control strategy such as Kanaban.
3. Make-To-Order (MTO): In this manufacturing environment, production starts after an order is received. Production rate and process routing vary according to the order. High variety/ low

volume products are mainly manufactured in a Make-To-Order environment where, small lead time proves as an order winning factor. In MTO, it is difficult to achieve standardization of order processing and it leads to new challenges. POLCA and GPOLCA are example of material control strategies which can be used in high variety manufacturing environments (Fernandes et al., 2006). This thesis research is more focused on the MTO type manufacturing environment.

4. Engineer-To-Order (ETO): In this type of environment, product design starts after getting the product specification and requirement. It is quite difficult to predict the production rate because every activity is dependent on the requirement of the customer. As in the case with MTO, this environment also has its own challenges in material control as most of the parts in this environment are non-standard.

The process of manufacturing the product at a constant rate is called as ‘level production’. In an MTS environment, it is easy to maintain level production and in an ATO environment it is again possible to achieve level production after some modification to planning. In level production, pull strategies are preferred over the push strategy because the initiation and transition of the replenishment signal is easily possible throughout the supply chain and we can successfully apply the Just in Time (JIT) principles in the same. Moreover, material control strategies such as Kanban are mainly designed for this type of production environment (Chang et al., 1994; Esparrago, 1988; Hollingsworth, 2011).

The 21st century market is highly dynamic and customer-driven because of explosive growth in e-business, advances in CAD/CAM, and other IS/IT innovations. In this market, customer demand can be satisfied by MTO and ETO environments. But in an MTO environment, order specification varies considerably and it requires different routings through the factory, thus making it difficult to achieve level production (Suri, 2003). In order to respond to this ever-changing and highly dynamic market, the Quick Response Manufacturing (QRM) approach was developed. QRM is a companywide approach to reduce lead times (Suri, 1998). In the 21st

century market, ‘time to respond’ plays a very crucial role in winning an order (Suri, 2003). QRM emphasizes lead time reduction unlike lean, which mainly focuses on standardizing the process and product, and reduction of waste (Suri, 2010).

Paired-cell Overlapping Loops of Cards with Authorization (POLCA) is a material control strategy which was introduced by Suri (1998) and is based on the QRM principle. POLCA uses the card signal on the shop floor for material control just like Kanban but *the main difference between Kanban and POLCA is that Kanban works as an inventory replenishment signal while POLCA is a capacity signal* (Krishnamurthy et al., 2009). The POLCA card attached to an order is a signal of available capacity at the downstream cell. Here, we can note one more difference between Kanban and POLCA; Kanban card is mainly associated with the “moving” part of the shop floor like WIP, while POLCA is mainly associated with the “stationary” part of the shop floor like machines and resources.

Considerable research has been done on different types of material control strategies. Initially research was focused on pull-control strategies such as Kanban and its variations (Aggarwal, 1985; Muris et al., 2010). After realizing the limitations of a pure pull strategy, research was conducted on the development of hybrid strategies (Olhager et al., 1990). Qualitative and quantitative studies have been done for the comparison of the different material control strategies (Geraghty et al., 2004; Krishnamurthy et al., 2004; Peters et al., 2001). Krishnamurthy et al. (2004) developed a simulation model to compare the performance of MRP and Kanban for flexible manufacturing systems. After realizing the power of lead time reduction in gaining competitive advantage, Suri (1998) developed a new material control strategy called POLCA. Very few research studies have been done on POLCA in the last decade. Initial research covered the part about planning and implementation of POLCA (Krishnamurthy et al., 2009). Later, Reiezebos (2010) focused on the design of POLCA material control system. Research was also conducted on increasing the effectiveness of POLCA strategy and it resulted in two modified

POLCA strategies called the Load-Based POLCA (LB-POLCA) (Vandaele et al., 2008) and Generic POLCA (GPOLCA) (Fernandes et al., 2006). After that, very little additional research has been published on these variations of the POLCA strategy. Additional research is needed to better understand the performance of the new variants of POLCA, so that proper guidelines can be developed to facilitate their implementation. This research focused on the performance of POLCA and GPOLCA strategies under practical manufacturing environmental settings.

The rest of this thesis document is organized as follows. In Chapter 2, an overview of previous research studies about POLCA and GPOLCA material control strategies is provided. Chapter 3 describes the problem statement and the need for this research. Chapter 4 outlines the research approach and describes the manufacturing environment. Chapter 5 describes the different experimental parameters chosen and their levels selected for this research. Chapter 6 explains the execution of the simulation model and the procedure developed to define the POLCA and GPOLCA systems. Chapter 7 mainly focuses on the results obtained and their statistical analysis followed by Chapter 8 which talks about the main findings of the research work conducted. Finally Chapter 9 summarizes the work conducted and presents some directions for future research.

CHAPTER II

REVIEW OF LITERATURE

This chapter presents a review of literature on the different material control strategies that are relevant to this research. Section 2.1 deals with the concept of QRM and explains how QRM is different from and better than lean when it comes to high variety/ low volume manufacturing environments. Section 2.2 deals with the POLCA material control strategy. A brief discussion of POLCA is provided to give an idea about the operational aspects of POLCA. Section 2.3 presents the GPOLCA material control strategy and explains how it is different from POLCA.

2.1 Quick Response Manufacturing

Depending on its manufacturing environment a company chooses a material control strategy to handle its volume-variety mix. The two most common types of volume-variety mix that can be observed on the shop floor are the following.

1. High volume-low variety mix
2. Low volume-high variety mix

In high volume-low variety mix, a company mainly focuses on a limited number of product types, which require the same set of manufacturing processes. As the company manufactures a limited variety of products, elimination of waste is possible by standardizing the processes and this represents the lean philosophy. Lean manufacturing is focused on standardization; it includes products as well as processes. Level scheduling, takt time and the use of existing components in a new product are all generated from the concept of standardization. However, in the 21st century market, many companies are using low volume-high variety mix as a competitive strategy. They are attracting customers by offering multiple options in one product. In such an environment, standardization could be difficult because customers may have different requirements. This is where QRM comes into the picture. Quick response manufacturing focuses on reducing time to respond to a customer in highly dynamic environments. Roots of this strategy can be found in the Japanese enterprises in 1980s. Previously this was documented as time-based competition which is also known by the familiar acronym TBC. In time-based competition, production speed is used as a way to gain competitive advantage (Suri, 1998). QRM uses lead time reduction as a tool to reduce non-value adding aspects thereby, reducing the overall cost and time for the customer (Suri, 1998).

From a customer's perspective, QRM can be defined as the rapid designing and manufacturing of a customized product based on customer's need (Suri, 2010). One way of achieving this is by creating small process-oriented cells in the manufacturing plant which will focus on the different production processes (Krishnamurthy et al., 2009). This strategy will reduce the transportation and handling time on the shop floor and thereby reduce the overall lead time. There are many other ways by which we can expedite the customer orders through the factory, such as faster order processing, having fewer levels in the product hierarchy, cross-functional teams for product development, etc.

2.2 POLCA Material Control Strategy

As explained earlier, the QRM philosophy is used to gain competitive advantage in a low volume-high variety manufacturing environment. Traditional pull control strategies such as Kanban and CONWIP (Germs et al., 2010) have their own disadvantages when it comes to a low volume -high variety production setting. *If we implement Kanban in high variety environment then we would end up with very high WIP at every stage*. To explain this concept we will refer the reader to Figure 2.1; we can see that *number of side stack bins increases drastically at every* *subsequent downstream operation in a high variety environment.*

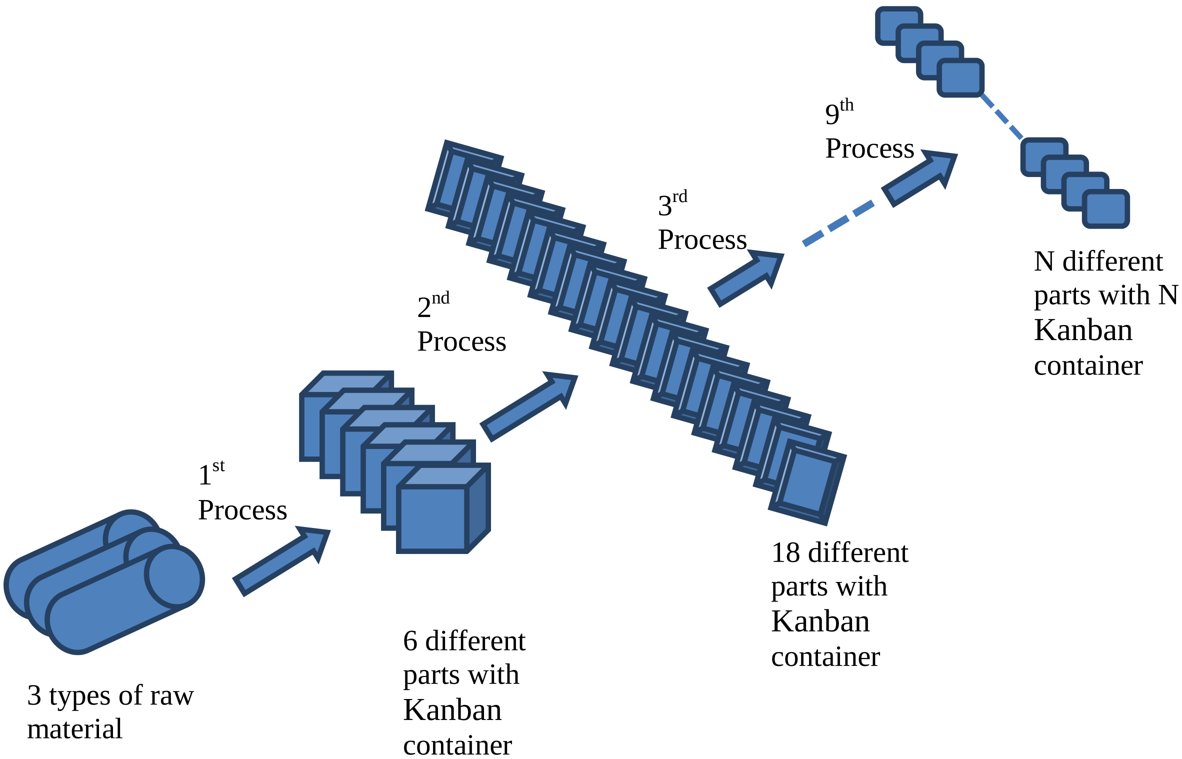

Figure 2.1: Material control using Kanban (Suri, 2003)

To address this issue Suri (1998) introduced a new material control strategy called the Paired-cell Overlapping Loop of Cards with Authorization (POLCA). It mainly focuses on the execution part of the QRM philosophy. The basic principle in this strategy is that it uses the card as an available capacity signal between two cells unlike Kanban, in which a card indicates an inventory replenishment signal. Along with that, POLCA uses high level MRP (HL/MRP) package for order release authorization to shop floor. HL/MRP uses the same logic of regular MRP but works on a cellular level and not at the work center level. The detailed explanation of the POLCA strategy is presented in the following Section.

2.2.1 Working mechanism of POLCA material control strategy

A POLCA card represents the available capacity between two cells and every POLCA card is assigned to a pair of cells and it strictly travels between assigned cells. The workflow on the shop floor is controlled by the combination of release authorization and POLCA card. HL/MRP system is the release authorization system, used in the POLCA material control strategy. It is similar to the regular MRP system but it authorizes the start time for an order based on the routing through different cells. More specifically, it does not work at the operation level but at a higher level. HL/MRP considers every cell as a black box and plans the material flow only across the cells (Krishnamurthy et al., 2009)

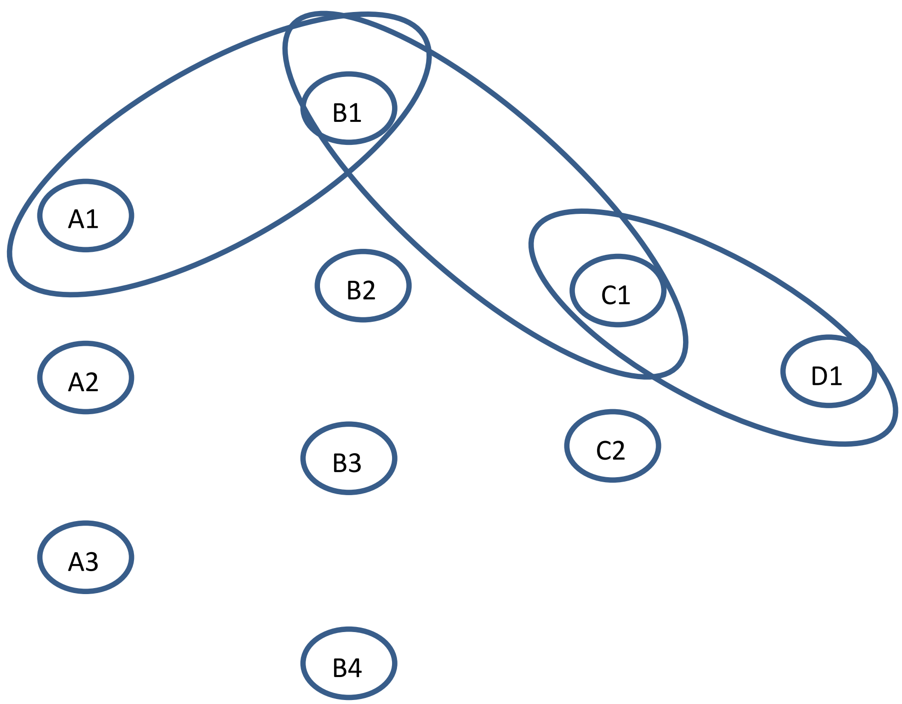

Figure 2.2: POLCA card flow for a particular order

Let us consider Figure 2.2 that shows the POLCA card flow for a particular order flowing through a factory with multiple cells as shown in Figure 2.2. Consider a particular order that is flows through the factory using the route A1-B1-C1-D1.

In the POLCA strategy, HL/MRP will first decide the release date for that particular order by using the back scheduling concept of the MRP logic. The release time indicates the time at which the first cell in the route can start. However, work cell cannot start until the required POLCA card is available.

Before starting the first operation on machine A1, an order needs to seize an A1/B1 POLCA card which is the assigned card for that pair of cells. After finishing the work on A1, the order will wait for the next required card, which is, card B1/C1. A point worth mentioning here is that, A1/B1 card is still with the order and the attachment of the new POLCA card B1/C1 creates the overlapping of POLCA loops. Once B1 completes its work on the order, the A1/B1 POLCA card is detached from the order before transferring it to C1. This process continues till all the processing on the route is completed.

On the shop floor, a POLCA card is transferred only between cells and it gives the freedom to choose any material control strategy within a cell. HL/MRP calculates the release time of a particular order and a cell cannot start working on that order until it has the POLCA card which is transferred between two cells. Hence, POLCA properly handles the volume-variety product mix, by combining the best features of push and pull strategies.

Recently researches have proposed modifications to POLCA to improve implementation effectiveness (Fernandes et al., 2006; Vandaele et al., 2008). Out of those, Fernandes and Carlo-Silva (2006) proposed the concept of Generic POLCA (GPOLCA). According to their simulation study, GPOLCA can provide the same throughput as POLCA with less WIP. In the following Section we will briefly discuss the GPOLCA strategy.

2.3 GPOLCA Material Control Strategy

GPOLCA has adopted the same order handling mechanism as that of POLCA. The order released to the shop floor uses a combination of release dates from a HL/MRP system and available capacity signal (GPOLCA cards) (Fernandes et al., 2006). HL/ MRP package calculates the earliest processing start date for an order. After that, we need to *make sure that all the GPOLCA cards between the cells in the job's route are available and then the job gets started*. In other words, capacity on all the required cells is reserved and the job is "pushed" through the supply-production chain (Fernandes et al., 2006). The detailed explanation of the GPOLCA strategy is presented in the following Section.

2.2.2 Working mechanism of GPOLCA material control strategy

As I said earlier, the GPOLCA strategy has adopted the same order release mechanism as that of POLCA. HL/MRP is used to create the authorization time for an order to enter the system. But an order cannot start processing on the first cell till all the cards for the entire route are available. Hence, first capacity is reserved on all the required cells before the processing of the order can begin on the first cell. Let us consider the previous example shown in Figure 2.3.

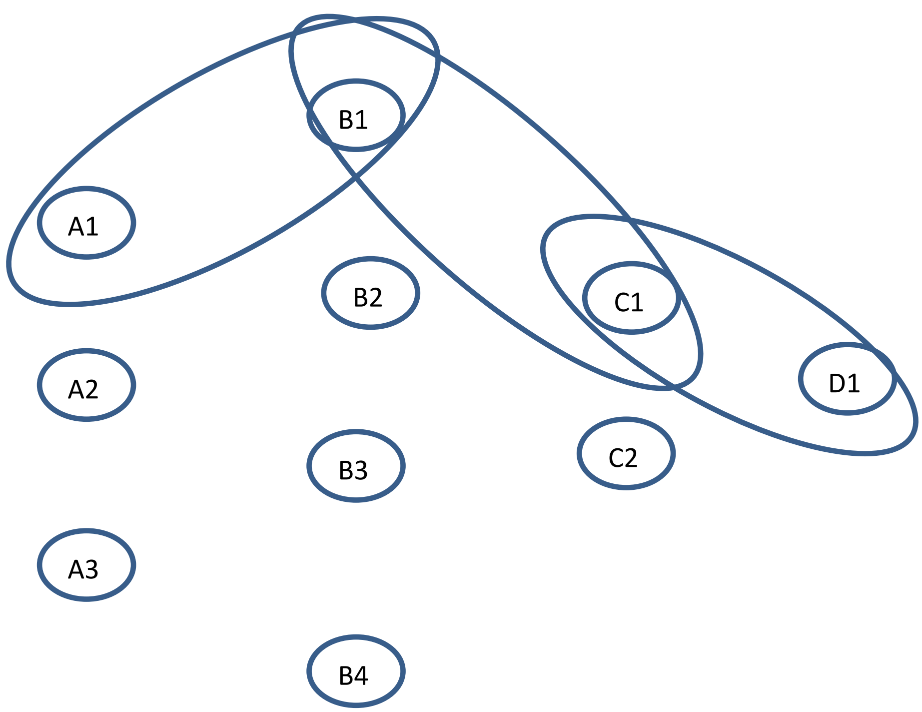

Figure 2.3: GPOLCA card flow for a particular order

Consider a particular order that is flowing through the factory using the A1-B1-C1-D1 route. Initially, HL/MRP will calculate the order release time on the shop floor in a manner similar to the POLCA material control strategy. But the order cannot start processing on Cell A1, till cards A1/B1, B1/C1 and C1/D1 are available. The order will first seize all the required cards and then start its processing on Cell A1. After the order is processed on Cells A1 and B1, A1/B1 card is released. Similar steps get repeated in next loops.

In summary, the HL/MRP first creates the release authorization, then order waits for all cards and once those are available, the order is pushed through the production network without any obstacle (Fernandes et al., 2006).

To demonstrate the effectiveness of GPOLCA over POLCA and MRP, Fernandes and Carlo-Silva (2006) used a three-tier manufacturing model introduced by Krishnamurthy (2004) and concluded that for a desired throughput, GPOLCA needed less WIP as compared to POLCA and MRP. Since then no research has been published on the performance of GPOLCA. In the experimental setup, the researchers considered only a single route for all job types.

In this thesis effort, the focus is on gaining additional insight into the design and performance analysis of the POLCA and GPOLCA strategies under more practical manufacturing settings such as systems with multiple products, overlapped routings and medium to high variability in processing times and inters arrival times of orders.

CHAPTER III

PROBLEM DESCRIPTION AND ITS SETTING

This chapter first discusses the problem addressed by this thesis research and then presents the research objectives. Section 3.1 presents some of the drawbacks of GPOLCA material control strategy which formed the basis for the research problem. Section 3.2 describes the research objectives and Section 3.3 describes the key performance measures that were used in this study.

3.1 Problem Formulation

POLCA and GPOLCA are material control strategies that are based on the QRM philosophy. QRM is mainly used in high variety manufacturing environments to reduce the order completion lead time. High variety-low volume manufacturing industries mainly operate in MTO or ATO environments and many different job routings on the shop floor are possible. When multiple routes overlap, the chosen material control strategy has the job of prioritizing the different order as they flow through the shared cells in the overlapping portion of the routes.

Different strategies differ on the way they prioritize the orders and this way affects the overall system performance. POLCA and GPOLCA strategies both work on the same basic principle, but differ in their operating mechanisms. In the POLCA strategy, we make sure that capacity is available on the immediate downstream cell and then start processing the order. If the downstream cell is blocked or running behind schedule then we could start working on other orders, which require some other cells for their next operations. This way we can avoid inventory buildup in front of any particular cell.

Now, in case of the GPOLCA strategy we first reserve the capacity on all the required cells and then start processing the order in the first cell.

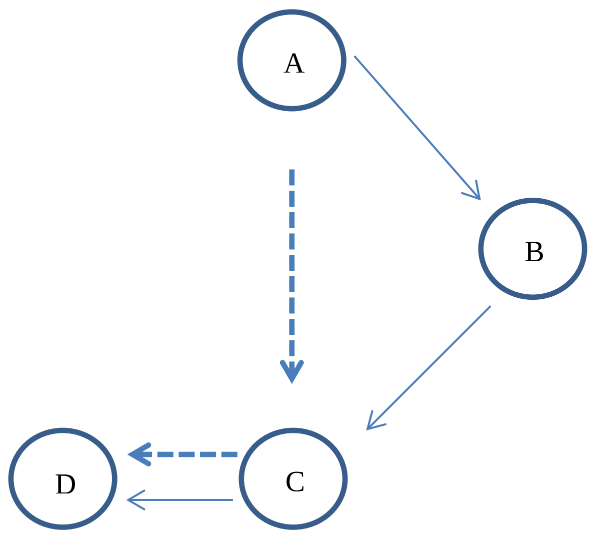

Figure 3.1: Multiple overlapping routings example

Consider the case of overlapping of routings, as we know this condition usually occurs in an MTO environment. Figure 3.1 shows two different routings; route A-B-C-D and route A-C-D respectively. An overlapping of routes occurs after Cell C, that is, on route C-D thus creating the mandatory situation for all the orders to pass through Cell C and Cell D. If any upstream cell runs behind schedule then it ultimately disrupts the supply of the critical cell that is Cell C, but the disturbance in the supply could be compensated by the orders present in the input buffer of Cell C. In Figure 3.1, if we assume that Cell B is running behind schedule then we can use the content from input buffer of Cell C, to keep Cell C running. At the same time feeding work to Cell B from Cell A will only increase the work-in-process and would not do anything to alleviate the problem at Cell B. In such cases if we use POLCA to control the material flow, then we could process different orders on Cell A by sending a capacity signal in the form of POLCA cards to process orders that do not require Cell B for their next operation and can balance the flow of work to Cell C, the critical cell. In case of GPOLCA material control strategy, we seize all the required cards together at the first operation. It is possible that, an order which is currently on Cell B has all the cards required for downstream work i.e. card B/C and card C/D. Hence, we cannot start processing an order on Cell A which goes through route C-D because all the C/D cards are currently at Cell B. This could slow down the flow of work to the critical cell and could negatively impact the performance of the system.

Fernandes and Carlo-Silva (2006) studied the performance of POLCA and GPOLCA for a three-stage manufacturing line producing different products. All products follow the same routes, and hence the dynamics created by different overlapping routes could not be captured by their study. In this research we reexamined the performance of the POLCA and GPOLCA material control strategies using a simulated manufacturing environment with a richer set of product routings.

In addition, this study also addressed the design aspect of the POLCA and GPOLCA strategies pertaining to the calculation of the number of cards. Currently, a mathematical approach is used to calculate the preliminary number of POLCA cards followed by adjustments (addition or removal of cards) during the initial operation of the actual system. Also, a mathematical approach for calculating the initial number of GPOLCA cards is not available in the literature and the current literature only suggests a random iterative method for finalizing the number of cards in a GPOLCA system. Hence, this study developed an approach that begins with an initial analytical calculation and then shows how the number of POLCA/GPOLCA cards can be adjusted using a simulated environment.

3.2 Research Objectives

The objectives of this research are as follows:

I. To develop a heuristic approach that can be implemented within a simulated environment to refine the POLCA/ GPOLCA card calculations.

II. To analyze in depth the performance of POLCA and GPOLCA strategies in the presence of multiple overlapping routings.

III. To develop a better understanding of the advantages and disadvantages of the GPOLCA strategy compared to the POLCA strategy.

3.3 Performance Measures

3.3.1 Flow time

APICS defines flow time as “The time between release of a job to a work center or shop until the job is finished.” Average flow time is considered to be an important measure of effectiveness in QRM. Less flow time on the shop floor indicates that the order is going through the system quickly and system is very responsive to the customer’s demand. Moreover, we could also detect the bottleneck on the shop floor by analyzing the change in the flow time. Continuous increase in flow time is an indication of the creation of a bottleneck (Vollmann et al., 1997). The flow time should be kept as small as possible in order to maintain the flexibility and responsiveness of the system.

3.3.2 Work in process (WIP)

In a simulated shop floor, work in process is calculated as the summation of the entities present in the output buffer, input buffer and processing stage of all the work stations. Furthermore, a high WIP value is a strong indication of high machine utilization and, beyond a certain limit; it can result in the overcrowding of the shop floor. The resulting scenario can cause longer lead times, and thus hurt the shop-floor responsiveness to the customer order. Nowadays, companies are focusing on holding the minimum WIP, because it takes less investment and avoids losses.

3.3.3 Throughput

Throughput can be defined as, “Number of final products produced per unit time” (Weeda, 1992). Throughput is considered a very important measure in many industries. According to the “Theory of Constraints”, throughput can be considered a drumbeat which can be used to set the pace of the factory (Goldratt et al., 2004). Every effort in lead time reduction can be traced to increase in throughput. It can be considered a base measure for the future analysis. In this research, we took throughput as a key parameter of the system and calculated the WIP required achieving that throughput.

3.3.4 Due date performance

Due date performance is related to the on-time completion of orders. A related metric is the ratio of number of orders completed on time to the total number of completed orders. In some industries it is also known as on-time performance. It is one of the important measures for companies that focus on providing good customer service.

CHAPTER IV

RESEARCH APPROACH

This chapter briefly describes the approach that was used for this thesis research. Section 4.1 outlines the research approach. Section 4.2 describes the configuration of the manufacturing system and Section 4.3 describes the simulation tool that was used to simulate the manufacturing system configurations.

4.1 Research Outline

The major steps that were followed in this research are briefly explained in this Section.

4.1.1. Development of simulation models using Simio

This task included the development of simulation models for depicting the behavior and properties of shop floor model under POLCA and GPOLCA strategies.

4.1.2. Determining experimental factors

This task used previous research studies of Krishnamurthy et al. (2004), and Fernandes and Carlo-Silva (2006) to set the different input parameters and their levels. Preliminary simulation runs were conducted to calculate the warm-up period and simulation run length (Refer Appendix D for more details). Preliminary runs were also used in determining initial estimates of the flow time on the shop floor and across different cells. The quantitative method described in Suri (1998) was used to compute the initial number of POLCA cards (Refer Appendix A for details). The final number of cards to achieve a desired service level was determined using a new procedure developed in this study. Details of this procedure are presented in Section 6.1. Currently there

there is no method available in the literature for calculating the number of GPOLCA cards. Hence, Little's law was used in calculating the initial number of GPOLCA cards. Further details of the procedure developed to calculate the final set of GPOLCA cards are contained in Section 6.2.

4.1.3. Conducting the simulation experiments

In this step the manufacturing model for different parameter settings simulated. A design of experiments approach was used to identify the various configurations to be simulated. The output of the simulation experiments was analyzed graphically and through appropriate statistical analysis.

4.1.4. Documenting findings and identifying areas for future research

First the analysis of the experimental results was used to evaluate the POLCA and GPOLCA strategies and compare their performances. Then the findings were documented and areas for future research were identified.

4.2 Manufacturing System

For this thesis research, a five-stage manufacturing system was used instead of three-stage system used by Krishnamurthy (2004), and Fernandes and Carlo-Silva (2006). The five-stage model allowed us to incorporate overlapping routings, while keeping the overall system size similar to that of the previous studies.

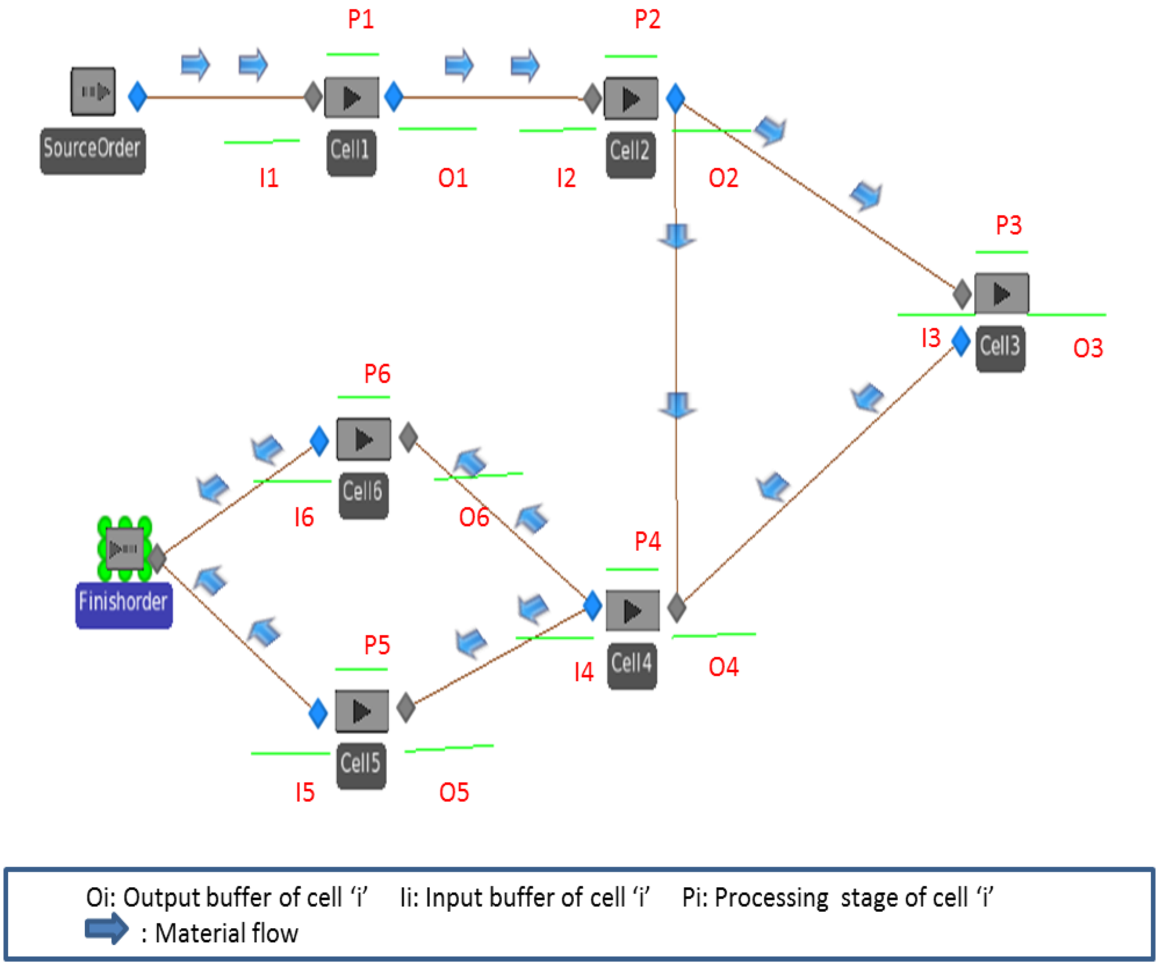

Figure 4.1: Illustration of the Five-Stage Manufacturing System

Figure 4.1 shows the manufacturing system for the MTO manufacturing environment. Different orders were generated according to the system's random demand process and they flow through the shop floor following the route determined by the product type. In MRP, POLCA and GPOLCA systems planning is very important, and the production planner plays an important role in maintaining the proper control of the material's flow on the shop floor. We assumed that the planned material flow created a uniform load on every cell. A bottleneck was not considered in this research because our focus was not to solve the problems associated with bottlenecks but to study the behavior of different material control strategies in the presence of overlapping routings and varying product mix.

In Figure 4.1, SourceOrder indicates the order generation point, where the orders of different product types are generated. Four types of order were generated from the source and those were for product type A, B, C and D. Any order at the source indicated that the order was a firm order and the time of generation was the release date in the MRP or HL/MRP system. The release authorizations of the orders on subsequent cells were also handled by the HL/ MRP. Every order has a specific due date which is assigned based on the product's route and lead time required across different cells. For modeling the order arrival and due date setting, Krishnamurthy (2004) have assumed that the mean time between the delivery dates of orders is $1/D_i$, where 'i' indicates the product type (i = A, B, C and D). Similar logic was used in this research as well because this assumption helped us to set the demand rate to D_i for product type i. Product variety is modeled using the four product types and each type of product has a different demand rate, different routing, and different processing times on a cell.

MRP and HL/ MRP system back calculates authorization time for an order on every cell by considering the due date, average lead time and safety lead time of different cells. As mentioned before, authorization time is the time when a cell could start processing the order if capacity is available. In the simulation model, the generation of orders at the source indicates that MRP or HL/ MRP system has scheduled the order to be released to the shop floor. In a POLCA or GPOLCA system the order will wait at the source for the next available card for the first cell. Early completion of an order was considered acceptable and hence finish goods in the Figure 4.1 indicate that the order is completed and waiting for the due date. Items in finished goods were not counted towards the work-in-process inventory. We assumed that the every cell consisted of a single machine with an input buffer, output buffer and processing stage. Orders wait in output buffer for either the next authorization time or for the next required card to become available.

As mentioned before, different types of products need different operations and hence have different routing sequences on the shop floor. There are four different product types, namely Product A, Product B, Product C and Product D. Table 4.1 documents the routing sequence of different product types on the shop floor.

Product Type	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
Product A	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5
Product B	Cell 1	Cell 2	Cell 3	Cell 4	Cell 6
Product C	Cell 1	Cell 2	Cell 4	Cell 5	-
Product D	Cell 1	Cell 2	Cell 4	Cell 6	-

Table 4.1: Product routings

The POLCA and GPOLCA cards are the capacity signals between any two successive cells in a product routing. Depending on the routing sequence, an order would seize different POLCA (GPOLCA) cards.

4.2.1 Description of the POLCA system

Every order had a due date which was assigned while releasing the order. The authorization time at every cell was pre-calculated by offsetting the lead time across different cells from the due date. In the POLCA system, once released, an order needs the POLCA card C1/C2 before moving into the input buffer of Cell 1. POLCA card C1/C2 is associated with Cell 1 and Cell 2 and indicates that capacity is available in the loop C1-C2. After completing the operation in Cell 1 order shifts to output buffer and waits for next authorization which was calculated by the HL/MRP system. Once it is authorized for the next operation it seizes the next required POLCA card. Depending on the product type, the order seizes either card C2/C3 or card C2/C4 and moves to the input buffer of Cell 2. Product A has a routing sequence from Cell 2 to Cell 3 hence it seizes the card C2/C3 and shifts to input buffer of Cell 2. After completing the operation in Cell 2 the order releases the card C1/C2 and makes the capacity available in loop C1-C2 for the next queued order. Thereafter this order waits in output buffer for next authorization and next required

POLCA card. The process continuous till all the operations get completed and job is reported as a finished good. All product types use the same logic while moving on the shop floor but they seize different cards as per their routing. We have developed a new method for setting up the POLCA system in this research. A thorough description of this new method is provided in Section 6.1.

4.2.2 Description of the GPOLCA system

In the GPOLCA system, every order released on the shop floor needs to reserve the capacity in all the required cells before starting its processing on the first cell. It seizes all required cards together and then shifts to the input buffer of first cell.

Let us consider an order for Product A which is authorized to be worked by on Cell 1. It requires processing in Cell 1, Cell 2, Cell 3, Cell 4, and Cell 5 respectively. Hence, it first seizes GPOLCA cards C1/C2, C2/C3, C3/C4 and C4/C5, and then transfers to input buffer of Cell 1. After completing the operation in Cell 1 and Cell 2 it releases the GPOLCA card C1/C2 because in the GPOLCA system an order releases a card after completion of processing in both cells of a loop. After completing the operation in any cell the order does not wait for the next required card. Hence, we can say that once order is released it gets pushed through the “supply-production” network in the GPOLCA system.

4.3 Simulation tool

The simulation was performed using a discrete event simulation tool called Simio. The advantage of using Simio is that it provides advanced built-in intelligent objects which make simulation model development easier. One can easily build the model in Simio by combining the objects which represent real components. The model was traced by using the ‘model trace’ option. It provided a detailed description of every step, which was useful for the verification of the model ("About Simio," 2012).

4.4 Simio Components

The modeling components of Simio used in the development of our manufacturing system model are presented next.

4.4.1 Source

The source is any object which can generate discrete entities. We have used the source for generation of product orders. The different parameters associated with source are entity arrival rate, type of order, etc.

4.4.2 Entity

Entity is the object which flows in the system and gives the dynamic nature to the model. In this research these entities were used to represent different orders which flow through the shop floor. Every entity had its own property, e.g. time spent in the system, waiting time at different work cells, etc. These entities were generated by the source and then processed by different cells.

4.4.3 Server

The function of the server is to perform a process on an entity. In our research the server object represented a manufacturing cell. Different queues are associated to the server and these are output buffer, input buffer and processing stage. The entity in the input buffer indicates that the work cell is busy and orders are waiting in the queue. Entity in the processing stage represents the order being processed in the work cell. Whereas output buffer indicates the orders which were processed by the cell but waiting for the next authorization or card. Properties of the server such as average processing time and processing time distribution are explained in the next chapter.

4.4.4 Sink

The sink destroys the entity and generates a trigger to store values associated with every entity such as flow time. We used it to transfer the completed orders and after that to record the time-based values of every order.

4.5 Assumptions

We used previous simulation studies by Fernandes and Carlo-Silva (2006) and Krishnamurthy (2004) for determining the experimental factors. Hence, some assumptions were made and those are summarised below.

A. Every cell contains a single machine.
B. Setup time was not modeled explicitly and was considered to be a part of processing time.
C. The flow of material was unidirectional and quality issues are not considered.
D. Job dispatching rule for POLCA and GPOLCA is first come first served (FCFS).
E. Every job represents one order and order processing can start immediately after it released for processing if the required cards are available.
F. POLCA/GPOLCA cards were available to reuse immediately after the completion of operation on second cell of loop; hence transfer time for cards was not considered.

CHAPTER V

EXPERIMENTAL PARAMETERS

This Section provides additional details regarding the experimental system. Section 5.1 gives in-depth information about the demand pattern of different product types and load distribution on every work cell. Section 5.2 describes the routing sequence and average processing time required for every product type on different cells and Section 5.3 describes the experimental design and metrics used for the analysis and comparison of the POLCA and GPOLCA systems.

5.1 Demand Pattern and System Load

Load is defined as the long run utilization of the cell. The set load (L) on a cell is the combined effect of demand rate of different product types and processing time of different product types on the cell. In our research, we considered two different types of loads on every cell which were 75% and 85% of the cell capacity. Hence, 75% load setting will set the utilization level of every cell to 75% of the cell's capacity.

The total average demand rate (Q) was set at 1 order every 5 time units which is 0.2 orders/time unit. The average total demand was constant but the demand for every product type varied in different experimental settings. Some of the scenarios studied had created equal demand for all products, hence generating equal material flow through all the routes which is known as the uniform demand pattern. Some of the scenarios had created unequal demand for different product types, wherein some routes had high material flow as compared to the others; this is known as the uneven demand pattern. This point is well illustrated in the following example.

Order Type (i)	**Demand Rate (Q_i = Units of 'i' per time unit)**
A	0.08
B	0.05
C	0.03
D	0.04
Total Demand	**0.2**

Table 5.1: Example demand rates for different product types

In the scenario shown in Table 5.1, Product A and Product B had higher demand rates compared to the other products. This creates more material flow from Cell 2 to Cell 3 as compared to flow from Cell 3 to Cell 4. For the order inter-arrival time distribution, we assumed that for every product type it was either exponential or Erlang to model high and low variability respectively.

5.2 Processing Time

Setting the average processing time S_{ij} for product type 'i' on cell 'j' had to done carefully. S_{ij} had to chosen in such a way that the overall utilization of Cell j was the set load L_j. This was accomplished by the use of processing time factors as explained next.

Product/Cell	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Product A	1	1	1	1	1	0
Product B	2	1	3	2	0	1
Product C	3	1	0	1	0.3	0
Product D	4	1	0	0.5	0	2

Table 5.2: Processing time factors[1]

Table 5.2 shows the processing time factors K_{ij} (i = A, B, C, D and j = 1, 2,…, 6) that were used to set average processing times. If Product A takes an average of 'X' time units on Cell 1, then Product B would require an average of '2X' time units to process on the same cell. Similarly, Products C and D require 3X and 4X time units respectively. The same logic was used in defining average processing times for Cell 2 to Cell5. In case of Cell 6, if Product B takes average of 'X' time units on Cell 6, then Product D would require an average of '2X' time units to process on Cell6.

S_{ij} have to satisfy the following set of linear equations.

$$L_j = \left(\sum_i \frac{Q_i}{Q} * S_{Aj} * K_{ij}\right) * Q \quad \text{Where } j = 1, 2, 3, 4, 5 \qquad (5.1)$$

And

$$L_j = \left(\sum_i \frac{Q_i}{Q} * S_{Bj} * K_{ij}\right) * Q \quad \text{Where } j = 6$$

(5.2)

$L_j = Set\ load\ on\ Cell\ j$

[1] '0' in the table indicates that the product type was not routed through that Cell.

$Q = Total\ demand\ rate$

$Q_i = Demand\ rate\ for\ product\ type\ i\ where\ i = A, B, C, D$

$S_{Aj} = Average\ processing\ time\ of\ product\ A\ on\ Cell\ j$

$S_{Bj} = Average\ processing\ time\ of\ product\ B\ on\ Cell\ j$

$K_{ij} = Multiplication\ factor\ for\ product\ i\ on\ Cell\ j$

For setting the processing time variability, we assumed that processing time was either exponentially distributed or Erlang distributed to model high and low variability respectively.

5.3 Due Date

While setting due dates, we considered the average flow time of every type of product and added some safety lead time to it in order to assign a due date to every order. In our experiment, three safety lead times were used and those are 20%, 40% and 60% of the flow time respectively.

Due date was calculated by the following equation,

Due Date = Order release time + Average flow time + Safety lead time

5.4 Design of Experiments

To consider wide range of scenarios, we ran the experiments for different input settings. Initial warm up phase and run length were calculated by using Welches method (Details are provided in Appendix B). Table 5.3 lists the level of variability and type of distribution used in this research.

Distribution Type	**Squared Coefficient of Variation (SCV)**
4 – Stage Erlang Distribution	0.25
Exponential Distribution	1

Table 5.3: Distribution types

Different input parameters and their levels are given in Table 5.4. A total of 48 different scenarios were studied for each type of material control strategy (Please refer Table C.1 in Appendix C for details).

Parameter	Levels
Cell Load	2
Inter-arrival Time Variability	2
Product Mix	2
Processing Time Variability	2
Safety Lead Time	3

Table 5.4: Input parameters for experiments

CHAPTER VI

POLCA AND GPOLCA SIMULATION MODELS

This chapter provides detailed information about the procedure that was developed and used to set up the POLCA and GPOLCA systems. Section 6.1 describes the development of POLCA simulation and Section 6.2 describes the development of GPOLCA simulation.

6.1 POLCA Simulation Model

Initially, the POLCA simulation run was carried out using the following steps.

1. The simulation model was run without POLCA cards to obtain lead time estimates across every cell.
2. These lead times were used to calculate the number of POLCA cards required in every loop by using Little's law and 10 % safety cards were added as per recommendation in the literature (Suri, 2010).
3. The simulation model was run with the POLCA cards for different due date settings.

While running the simulation using the above method, we came across a new problem of deciding the appropriate number of POLCA cards in every loop. As per Suri (2010), finalizing the POLCA cards is an iterative method and it changes based on the shop floor load and other existing parameters. In our initial simulation run, we tried this approach of iterative search for 25 iterations, but finding out the proper termination point proved to be difficult. The problem of finding right number of cards in all the loops to achieve the required throughput rates is a challenging problem because of the stochastic nature of the problem. Hence, we developed a new heuristic approach for setting up the POLCA system, which we believe will be useful in future research on the POLCA material control strategy.

6.1.1 Development of the simulated POLCA system

In our research, we introduced a new heuristic approach for setting up the POLCA system which uses feedback from the actual (simulated in our case) system and uses that to calculate the new number POLCA of cards in every loop and release dates for every cell. The process of creating the POLCA system is presented in the reminder of this section.

Defining the POLCA system:

1. Make an initial run where orders arrive and are pushed through the system. Record the lead times across different cells.
2. Use forward scheduling method to setup H/L MRP and decide the release time for every cell.
3. Run the model with active HL/MRP and calculate new lead times across different cells and the waiting time for authorization at the output buffer of each cell.
4. Use newly calculated lead times and waiting times to calculate the number of POLCA cards and add 10% more cards.
5. Use the newly calculated number of POLCA cards in every loop and run the system to analyze its performance.
6. Use the new lead time and waiting time estimates to reset the HL/MRP parameters.
7. Now we have the newly calculated release dates and number of POLCA cards. Run the system and calculate the average flow time for every order using this new data. Flow time includes every part of the time spent by an order on the shop floor. It even includes the time spent waiting for cards to be available and waiting in queue for a cell.

8. To the newly calculated flow time, add safety lead time to assign due dates to every order.
9. Run the system for assigned due dates and analyze the performance.

6.1.2 Example of the heuristic approach

We studied different configurations in our research and we have presented one of those to better understand the heuristic approach that was developed to set up POLCA system.

Details of the configuration are as follows.

a) Cell Load : 85%
b) Processing time variability and inter-arrival time variability: High (CoV = 1)
c) Arrival rates for different products

Product Type	Arrival Rate
A	0.08
B	0.05
C	0.03
D	0.04

Table 6.1: Arrival rate of different product types

After every step of the heuristic approach we had collected some of the important metrics, those are presented in the reminder of this section.

1. Orders generated were released immediately on the shop floor to calculate the initial lead time across different cells. These lead times were used to set up the HL/MRP system by using forward scheduling.
2. Simulation results obtained after running the HL/MRP system are as follows.

Lead time[2] across cell	**Value**
Cell 1	48.61
Cell 2	39.61
Cell 3	68.21
Cell 4	41.59
Cell 5	61.1
Cell 6	64.32
WIP	47.38
Average Flow Time	236.634

Table 6.2: Lead time obtained after implementing HL/MRP

Performance Measure	**Value**
WIP	47.38
Average Flow Time	236.634

Figure 6.3: Results obtained after implementing HL/MRP

3. We used these new lead times to calculate the number of POLCA cards in every loop by using the Little's law.

[2] Lead time includes the waiting for authorization.

Card Type	Calculated number of cards	Total number of cards after adding 10%	Actual Cards
Card 12	17.65	19.41	20
Card 23	14.02	15.42	16
Card 34	14.28	15.70	16
Card 24	5.69	6.25	7
Card 45	11.30	12.43	13
Card 46	9.53	10.49	11

Table 6.4: Calculated number of POLCA cards for every loop

4. Results obtained after implementing card control system

Performance Measure	Value
WIP	45.68
Average Flow Time	228.18

Table 6.5: Results obtained after implementing POLCA card control system

5. We adjusted the release time after implementing the card control system in order to avoid any unnecessary planning delay. Results obtained after the final setting are presented in Table 6.6.

Parameters	Value
WIP	43.199
Average Flow Time	216.326

Table 6.6: Results obtained after finalizing POLCA system

The heuristic helps us to decide the proper termination point for finalizing the number of POLCA cards in every cell loop. In Table 6.7 we have presented the results of different iterations in the existing method of setting up the POLCA system and results of the heuristic approach. We can see that the heuristic approach allows us to reach the required setting without any open ended iteration and termination issues (Refer Table A.4 for results of all ten iterations).

Performance Measure	Existing Method			Heuristic approach
	1st iteration	5th iteration	10th iteration	
WIP	66.02	44.99	43.15	43.19
Flow Time	330.17	225.19	215.86	216.326

Table 6.7: Comparison of heuristic method with existing method of setting up a POLCA system

6.2 GPOLCA Simulation Model

In this Section, the first part describes the method of calculating the number of GPOLCA cards for every loop because in any of the previous literature, no specific method is mentioned for calculating the number of GPOLCA cards. The method used in the previous literature (Fernandes et al., 2006) was only based on the iterative search. In this research, we have developed an analytical approach for calculating the initial number of GPOLCA cards. It uses the same logic as that of POLCA but works at the product routing level unlike POLCA which works at the loop level. The process of calculating the number of GPOLCA cards is given in the following sub-Section. After that, in Sub-Section 6.2.2 the approach for setting up the simulated GPOLCA system is described.

6.2.1 Calculating the initial number of GPOLCA cards

In the GPOLCA material control strategy, all the required cards are seized at the first operation and released one by one after completing the last operation of every loop. So every order carries a GPOLCA card from the first operation of routing till the last operation of the card's loop. Hence, we used Little's law (Hopp et al., 1996) to calculate the number of GPOLCA cards at the routing level which controls the inventory in loops and thereby in the whole system.

The equation of calculating GPOLCA cards is given below

$$N_{M/N} = \left(\sum LT_i \times [NUM_{i,N}/P]\right) + \left(LT_N \times [NUM_{M,N}/P]\right) \quad (6.1)$$

$M = \text{First cell of the loop}$

$N = \text{Last cell of the loop}$

$N_{M/N} = \text{Number of GPOLCA card in loops } M - N$

$LT_i = \text{Estimated average lead time of Cell } 'i'$

$LT_N = \text{Estimated average lead time of Cell } 'N'$

$NUM_{i,N} = \text{Number of jobs travelling from Cell i to Cell N through loop } M - N$

$NUM_{M,N} = \text{Number of jobs travelling from Cell M to Cell N}$

$P = \text{Planning Period}$

6.2.2 Development of the simulated GPOLCA strategy

Based on the working principle of the GPOLCA material control strategy, an order seizes all the required cards at the first operation and releases them one by one after completing both the operations of a card's loop. Hence, no additional waiting delays occur after every operation for the next required card unlike in the POLCA material control strategy.

Defining the GPOLCA system:

1. Make an initial run where orders arrive and are pushed through the system. Record the lead times across different cells.

2. Use recorded lead times to calculate the number of GPOLCA cards as shown in equation 6.1.
3. Used the newly calculated number of GPOLCA cards to run the system and calculate average flow time for every order.
4. To the newly calculated flow time, add safety lead time to assign due dates to every order.
5. Run the system for the assigned due dates and analyze the performance.

The above approach follows the same principle as that of POLCA method. The heuristic approach that we have developed to define the POLCA and GPOLCA systems provides a consistent way to decide the number of cards in every loop and hence, provides a common basis for comparison.

CHAPTER VII

RESULTS AND DISCUSSION

This chapter presents an analysis of the experimental results and a discussion of the findings. The experimental results were analyzed using two different business analytics software: SAS and Minitab. In Section 7.1, present some terminology which has been used while presenting our results. Sections 7.2 and 7.3, present an analysis of the output results related to POLCA and GPOLCA systems respectively. These Sections are very important in developing proper insights about the operation of the POLCA and GPOLCA systems. We also verified our heuristic approach of setting up POLCA and GPOLCA systems in these two Sections. In Section 7.4, we compare the POLCA and GPOLCA material control strategies by using ANOVA procedures and present our findings.

7.1 Terminology

This Section presents the terminology that we have used while conducting the analysis of the experimental data.

1. **Overall service level:** It is defined as the ratio of the total number of orders delivered on time to the total number of orders completed. In some places, it is also referred to as due date performance.
2. **Work-in-process (WIP):** It is defined as the total number of orders on the shop floor. Any order is counted in WIP from the time it enters the input buffer of the first cell of its route till it completes the last operation.

3. **Finish goods inventory:** Any order completed before due date is counted as a part of the finish goods inventory.
4. **Total inventory (TI):** It is defined as the sum of work in process and finish goods inventory.
5. **Tardiness:** It is defined as the average delay in time units of any late order.
6. **Load:** Load is the scheduled or planned utilization of the total capacity.
7. **Inter arrival time variability:** It is defined as variability present in the time of generation of two successive orders.
8. **Product mix:** It is the type of the demand pattern of different types of orders. Uniform product mix indicates same demand rate for all the product types and uneven product mix indicates different demand rates for the product types.
9. **Processing time variability:** It is defined as the variability present in the processing time of orders for the same product such as two different orders of product A.
10. **Safety lead time:** Additional time considered while quoting the due dates in order to achieve a better service level.

All the results collected in the experiments are summarized in a tabular format and presented in Appendix C.

7.2 Analyzing the POLCA Material Control Strategy

In this Section we analyzed the behavior of POLCA material control strategy for different manufacturing settings.

7.2.1 Effect of different parameters on the POLCA strategy

This Section focuses on the performance of the POLCA strategy for different manufacturing settings. We traced the change in WIP for different input combinations. The Pareto chart shown in Figure 7.1 was used for analyzing the impact of different input parameters and their combinations on the POLCA material control strategy.

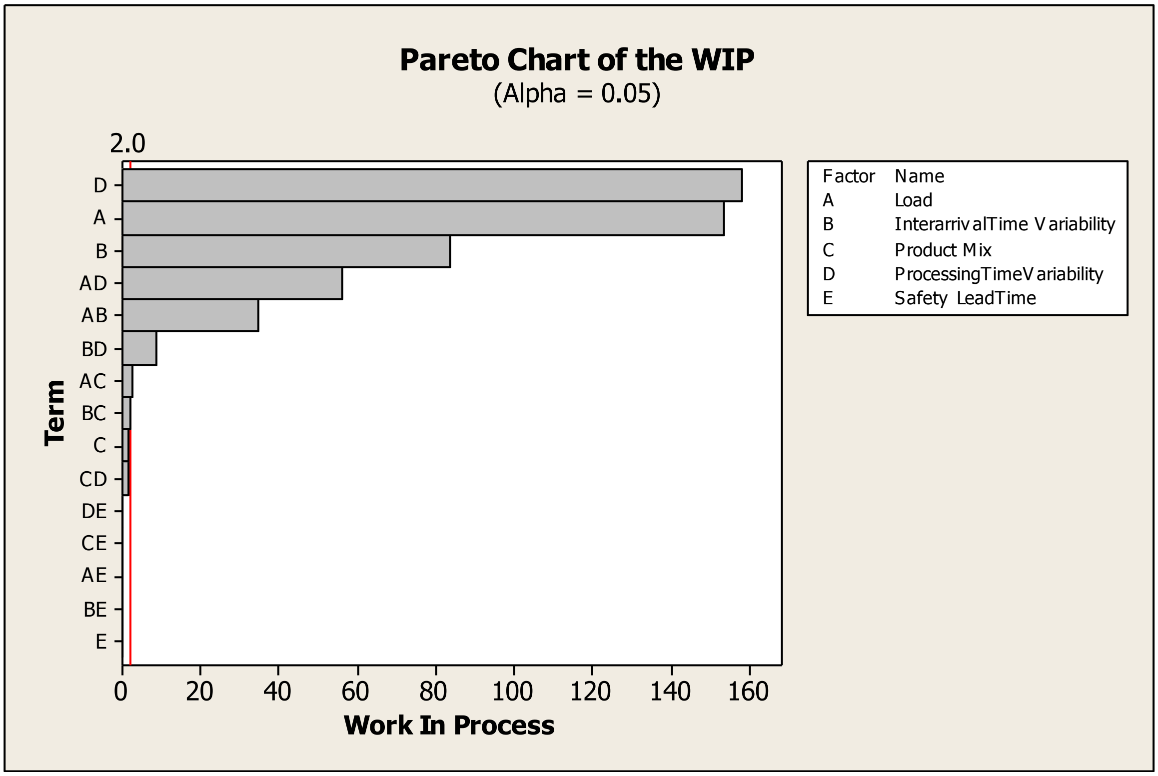

Figure 7.1: Effect of different input parameters on the WIP for the POLCA strategy

Factorial design function of the Minitab was used to analyze results. The red line in Figure 7.1 indicates the level of significance. In our study we have selected it as 0.05 to keep the confidence level at 95%. It means that any parameter which crosses the red line significantly affects the performance of POLCA system.

From Figure 7.1 we observed that all the parameters other than safety lead time and product mix affect the performance of the POLCA system, which means that they are significantly affecting the WIP on the shop floor. We are using the safety lead time as an extra time buffer at the end so it does not change WIP but it changes the total inventory, because of early or late completion of orders. Other than the main factors, any two character term on the Y-axis of Figure 7.1 represents the second-order interaction effect. It signifies the impact of the combination of multiple parameters on the performance (Refer Appendix D for normal plots).

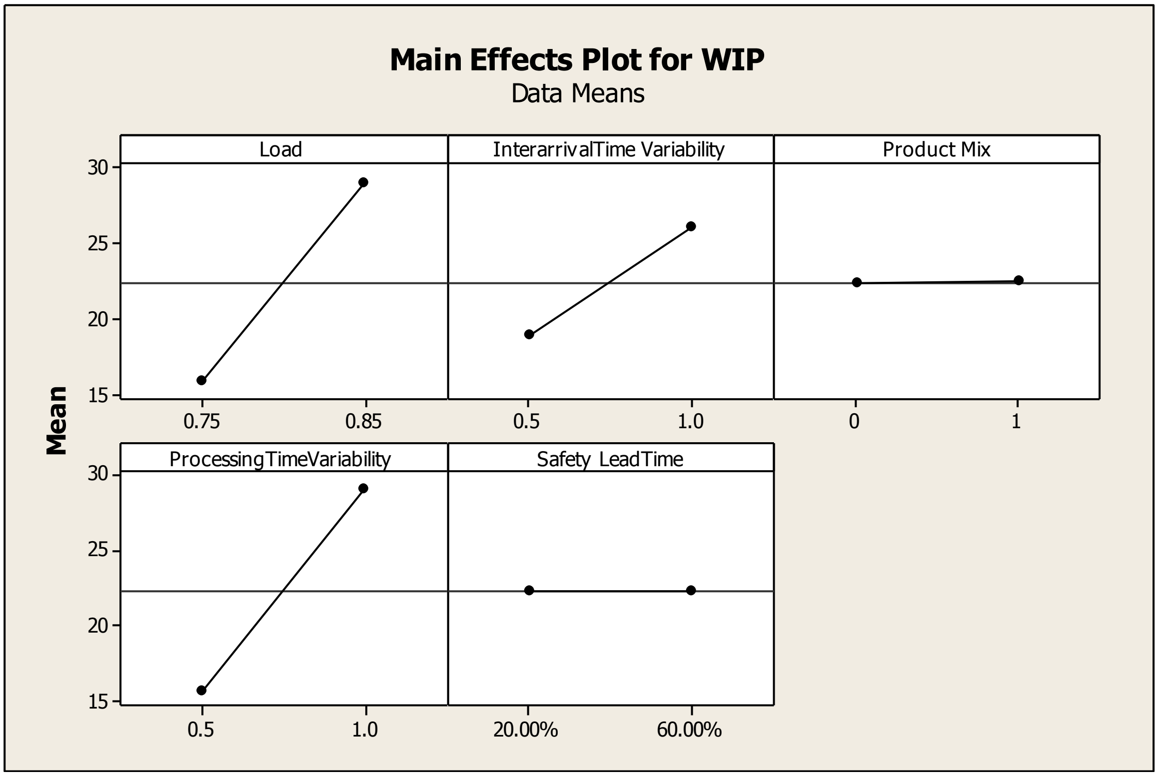

Figure 7.2: Effect of individual parameters on the WIP for POLCA strategy

From Figure 7.2 we observed the effect of every individual parameter on the WIP of POLCA system. Horizontal line indicates no change in output metric with changing input parameter.

7.2.2 Evaluation of the heuristic approach

As discussed in the previous chapter, we introduced a new heuristic approach for calculating the number of POLCA cards. The approach incorporates feedback from the shop floor to update the number of cards and release dates. Hence, the due date performance of the POLCA material control strategy should not vary based on the different input parameter settings.

To evaluate the heuristic approach, we performed the factorial analysis of the POLCA strategy and studied the due date performance for different input parameters for 20% safety lead time. Let us consider the plot in Figure 7.3 generated using Minitab's factorial analysis function.

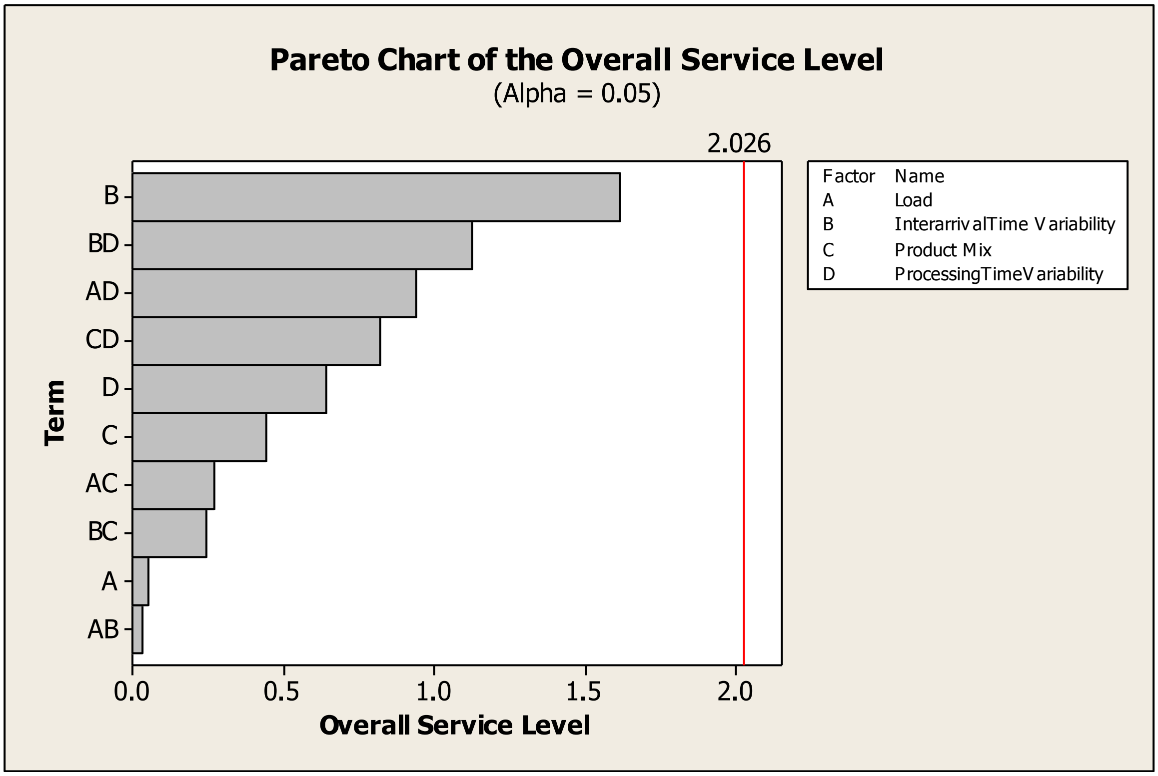

Figure 7.3: Effect of different input parameters on the service level of POLCA strategy

In Figure 7.3, the red line represents the level of significance. As we can see, not a single parameter crosses the red line, which indicates that none of the input parameter has a significant difference on the overall service level of the POLCA strategy. This confirms that the approach presented in the previous chapter to set the number of cards performs as expected and defines a POLCA system that produces the same due date performance for any manufacturing setting.

We have also analyzed the results for different safety lead time settings to further illustrate this point and created 3-D plots for various input parameters. (Please refer Appendix D for 3-D plots).

From Appendix D we can see that for different settings of input parameters we are getting the (statistically) same output at different levels of safety lead time. Hence, we can conclude that our heuristic approach keeps the same service level for different settings, which shows that it is a robust approach for defining the POLCA system.

7.3 Analyzing the GPOLCA Material Control Strategy

In this Section, we analyzed the behavior of the GPOLCA material control strategy for different manufacturing settings.

7.3.1 Effect of different parameters on the GPOLCA system

No research study that has been published so far which can provide an in-depth analysis of the GPOLCA system. In this research we have presented some of the important insights about the GPOLCA system. We have plotted the Pareto chart which can help us to analyze the effect of different parameters on the WIP of the GPOLCA strategy.

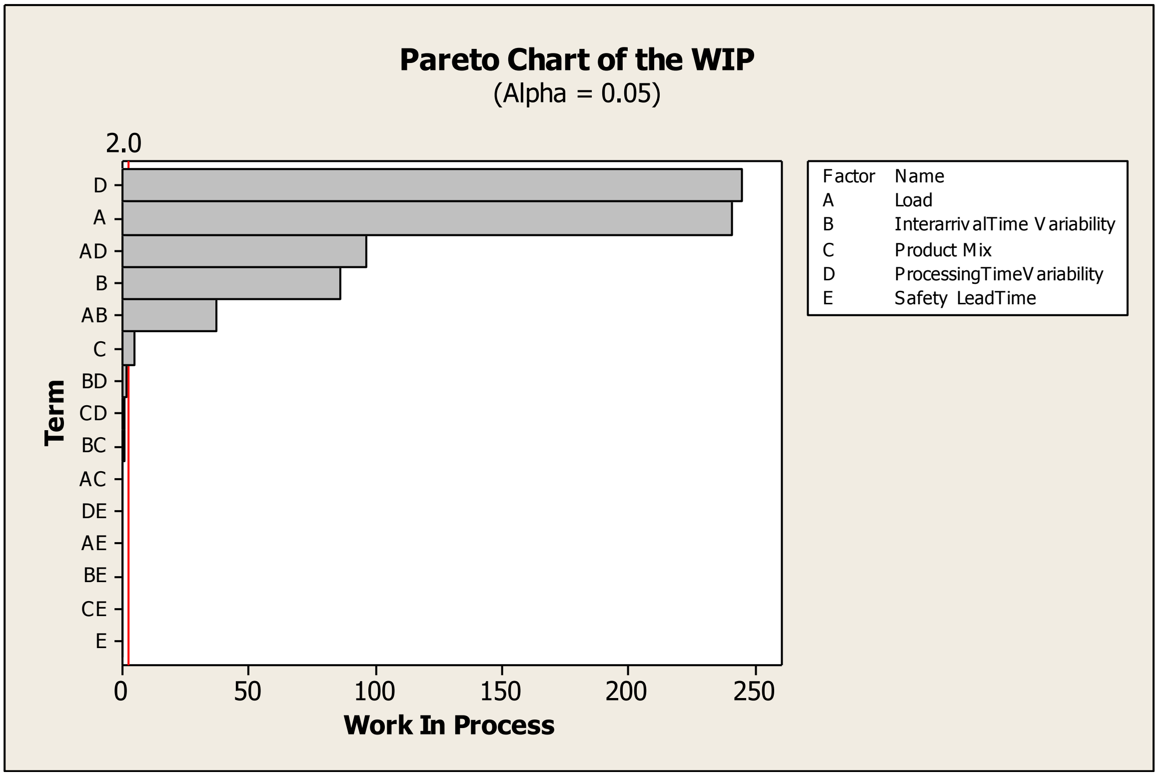

Figure 7.4: Effect of different input parameters on the WIP for the GPOLCA strategy

In Figure 7.4, the red line indicates the level of significance. We observed that variability in processing time has the maximum effect on the GPOLCA system's WIP. Then load, inter-arrival time variability and product mix significantly affect the performance based on WIP.

In Figure 7.5, we can see the effect of individual parameters on the WIP of GPOLCA system.

In this system, again we can see that product mix and safety lead time does not have any significant effect on the WIP of the GPOLCA system. Hence, we can see a near horizontal line in those graphs.

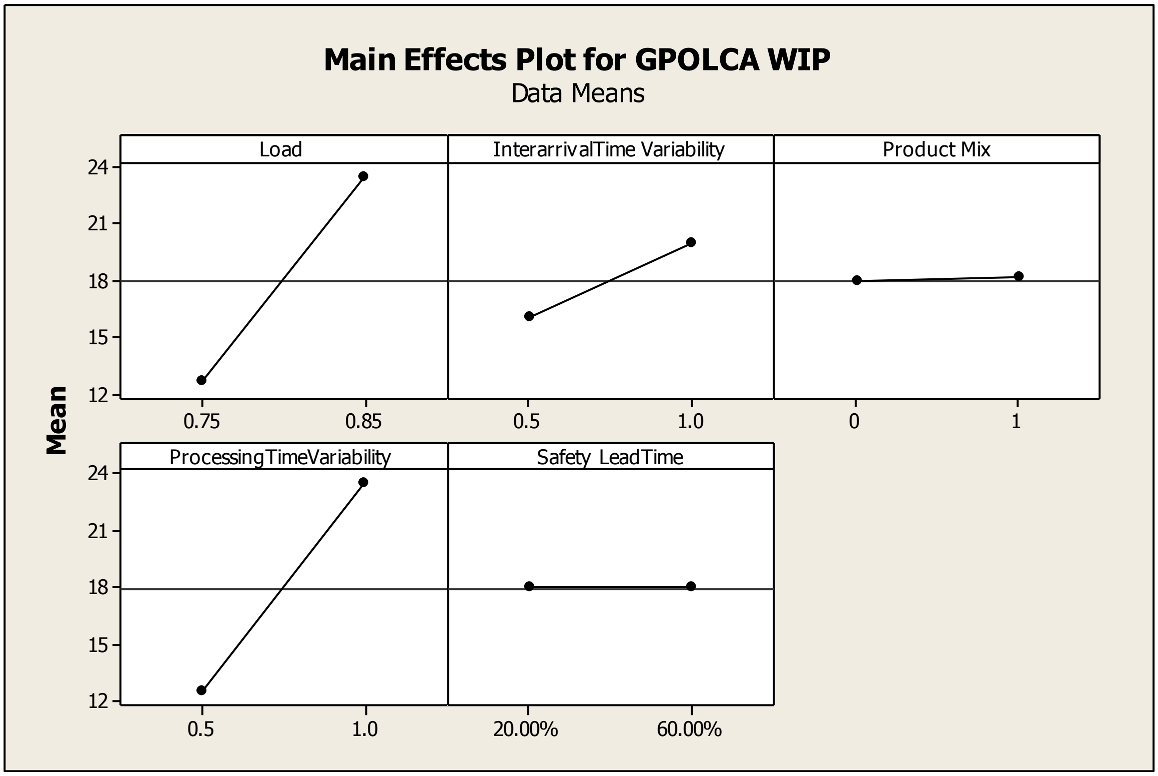

Figure 7.5: Effect of individual parameters on the WIP of GPOLCA strategy

7.3.2 Evaluation of the approach to define the GPOLCA system

In our research we developed an analytical approach for calculating the initial number of GPOLCA cards and it was based on Little's law as in the POLCA system. Also, while setting up the GPOLCA system, we used the same heuristic approach that we developed for POLCA. Similar to the validation that we did in the POLCA case, we first examined the due date performance of GPOLCA system.

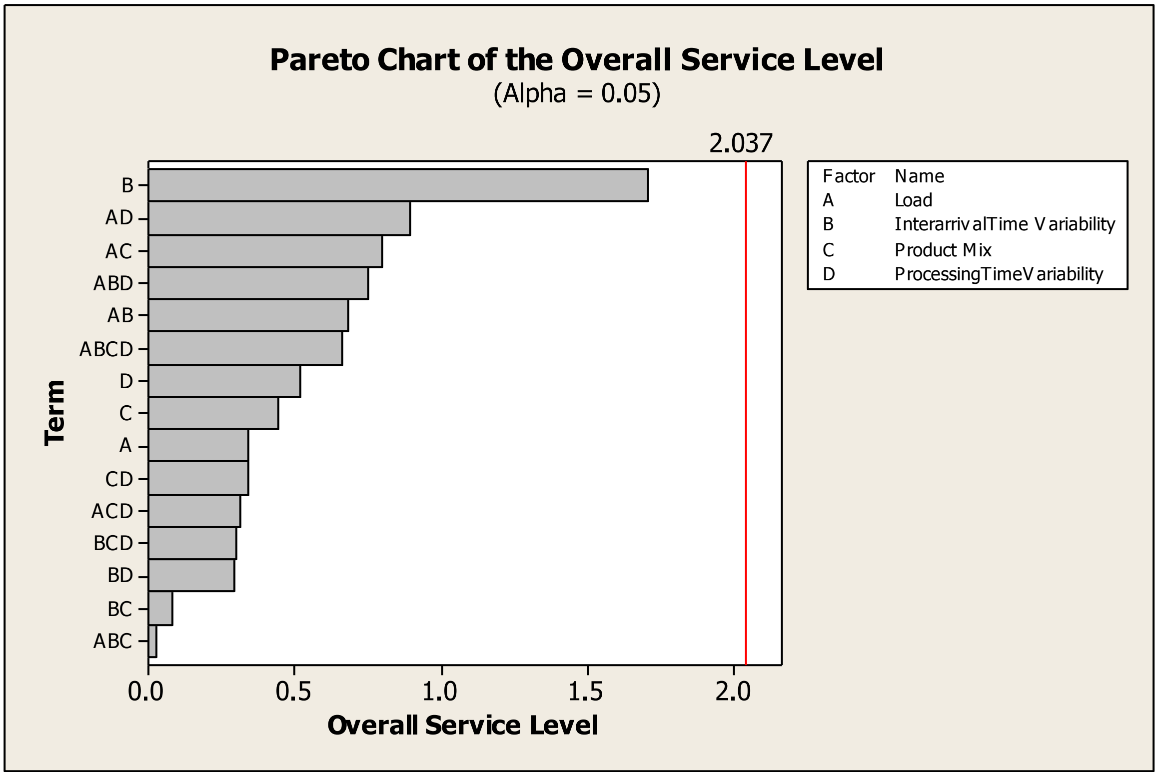

Figure 7.6: Effect of different input parameters on the service level for GPOLCA strategy

From Figure 7.6, we observe that none of the input parameter has a statistically significant effect on the due date performance of the GPOLCA system. Once again this confirms the validity of our heuristic approach in designing the GPOLCA system.

To further illustrate this point, we have shown the due-date performance of the GPOLCA strategy for various input parameters in Appendix D. From Appendix D, we can see that none of the input parameters was significantly affecting the due date performance of GPOLCA system just like in case of the POLCA system. This provides enough statistical evidence to confirm that the POLCA and GPOLCA systems have been designed to yield the same service level. This allows us to compare the POLCA and GPOLCA strategies on equal footing. This part of the analysis is explained in the next Section.

7.4 Comparing the Performance of POLCA and GPOLCA Material Control Strategies

This section compares the two material control strategies on the basis of different performance measures.

7.4.1 Comparing the due date performance of POLCA and GPOLCA material control strategies

The heuristic approach for calculating the number of POLCA and GPOLCA cards is the same. It takes input from the system and based on that decides the number of cards. Also, the due dates are based on the output provided by the system. Hence, we should not get any statistically significant difference in due date performance of POLCA and GPOLCA strategies where percent on time delivery is the ratio of number of orders delivered on time to the total number of orders. We performed the statistical analysis for different levels of safety lead time to analyze the due date performance based on the type of material control strategy. The plots in Figures 7.7 to 7.12 were generated using Minitab's factorial analysis function.

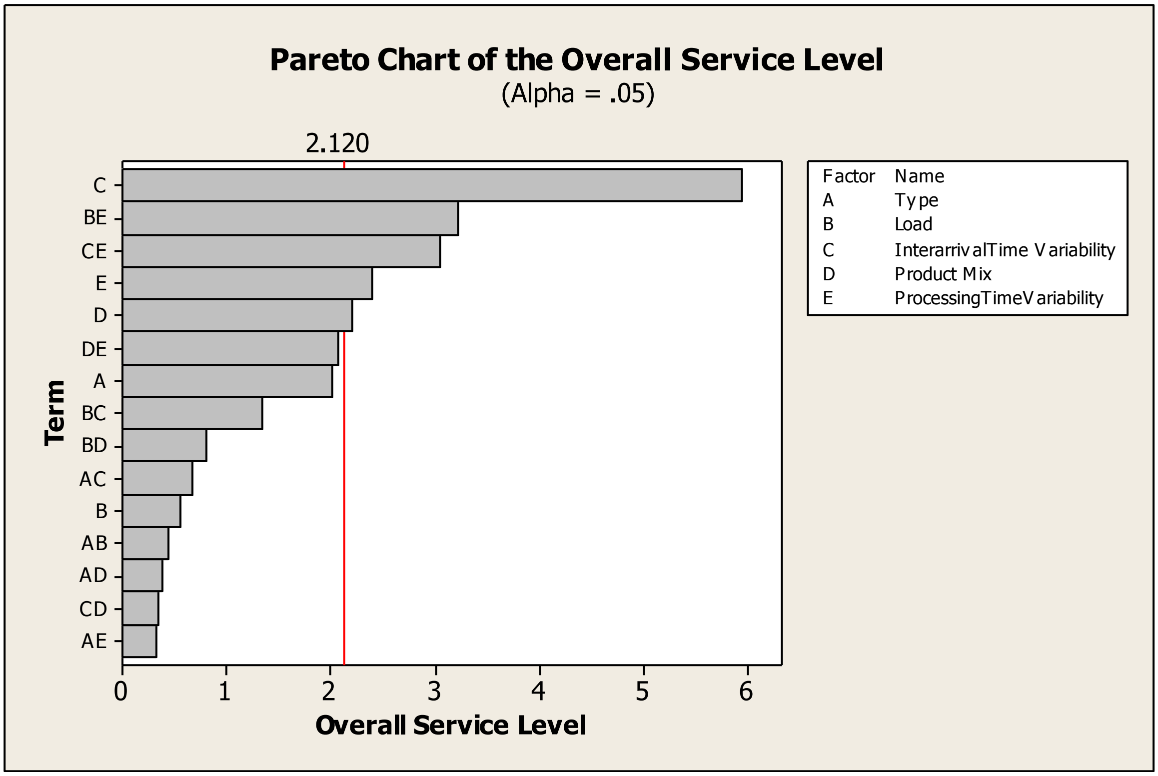

Figure 7.7: Effect of different input parameters on overall service level for 60% safety lead time

From Figure 7.7, we can observe that for 60% safety lead time there is no statistically significant effect on service level due to type of material control strategy (Factor A)

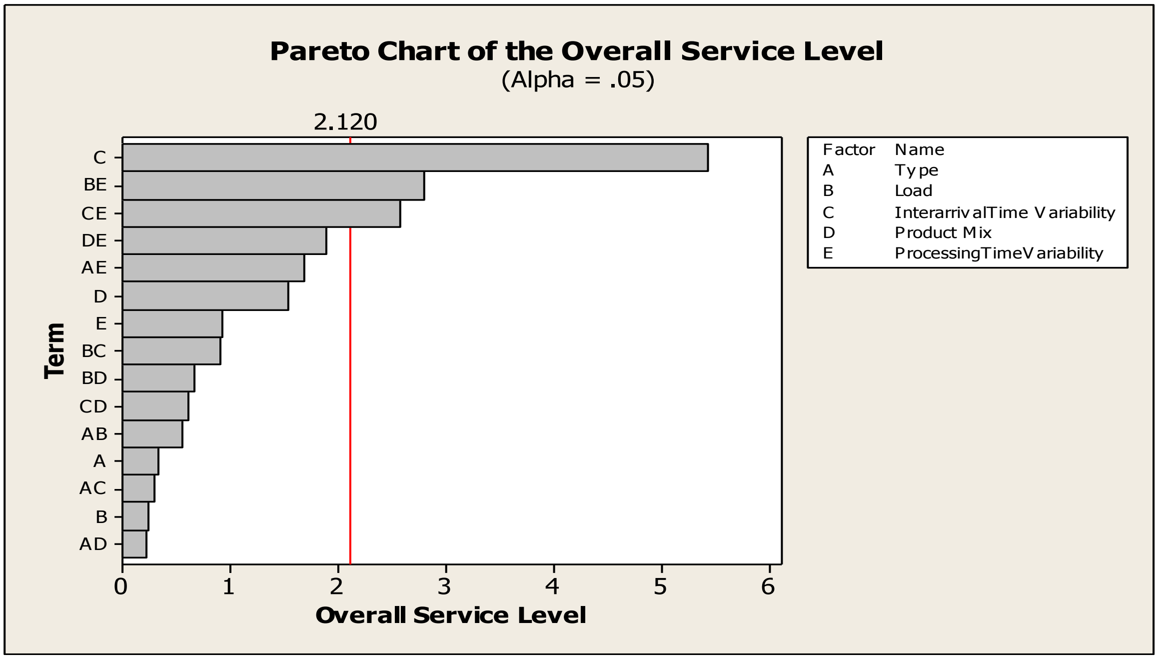

Figure 7.8: Effect of different input parameters on overall service level for 40% safety lead time

From Figure 7.8 we can also arrive at a similar conclusion for 40% safety lead time.

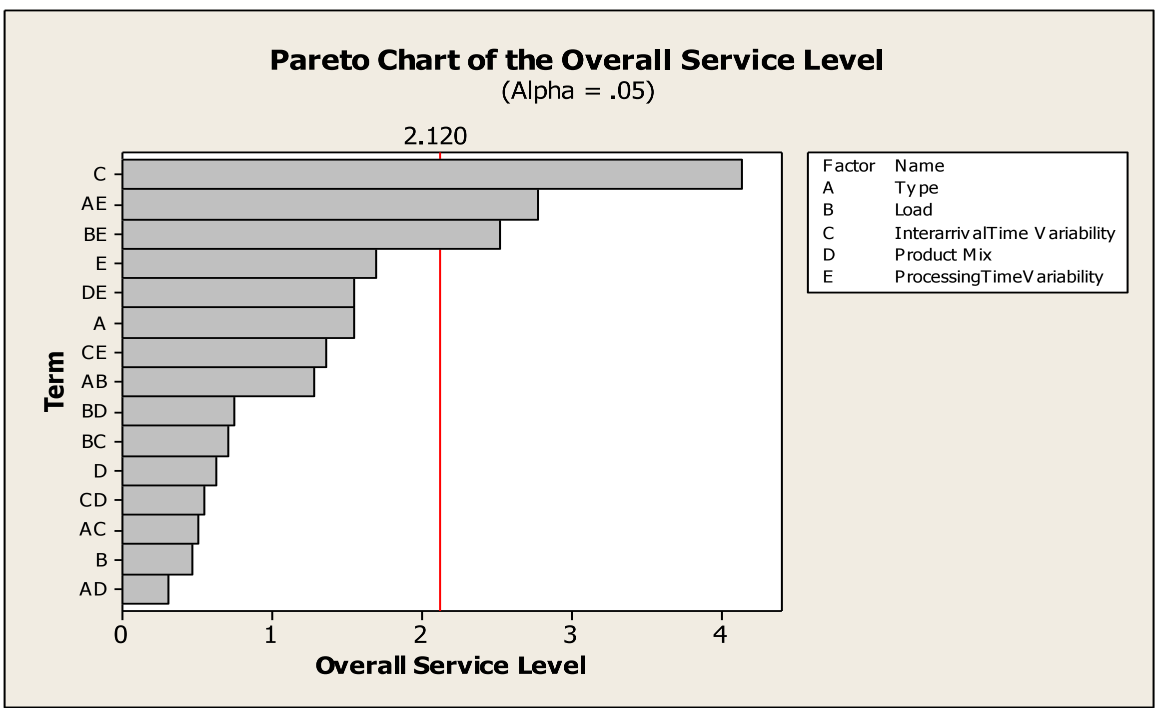

Figure 7.9: Effect of different input parameters on overall service level for 20% safety lead time

From Figure 7.9, we can see that the type of the material control strategy does not have statistically significant impact on the service level for 20% safety lead time. Though in this scenario, we can observe the interaction the effect of type on material control strategy and processing time variability on the due date performance. This indicates that there is still some room for fine tuning the heuristic approach. It is to be noted this interaction effect was statistically significant only for the smallest level of safety lead time. The graph of interaction effect is presented in Figure 7.10 to provide a better understanding.

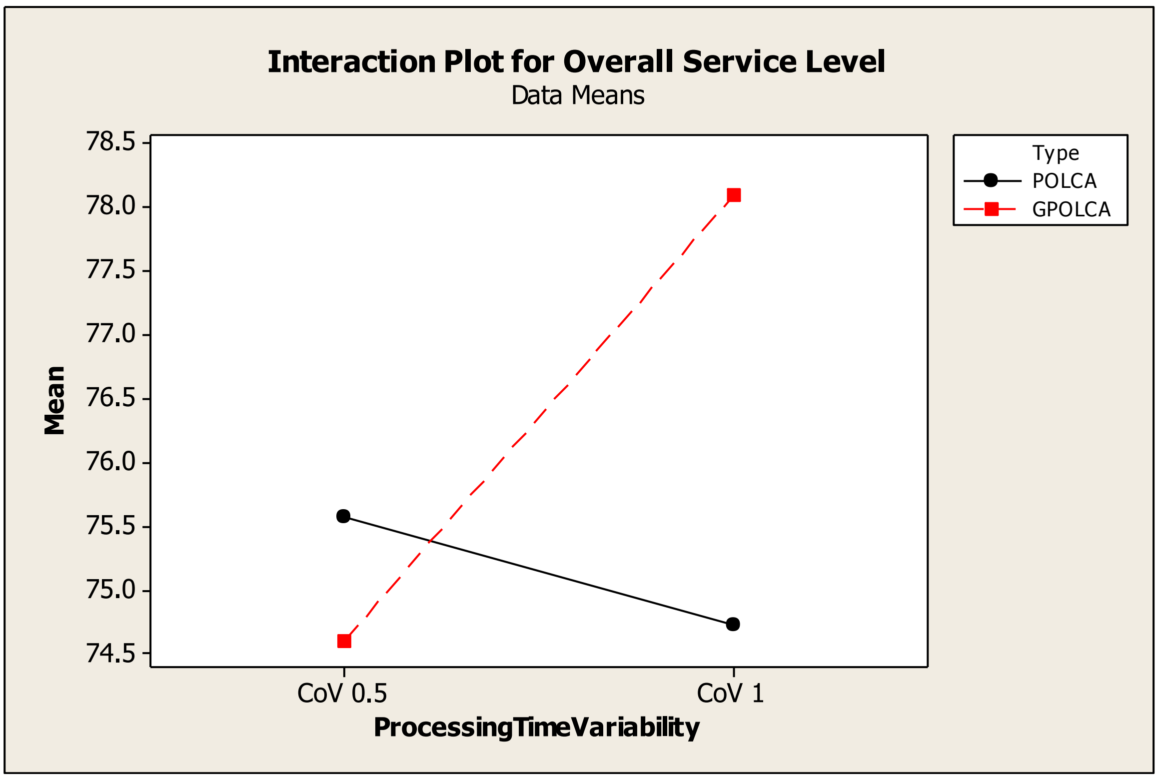

Figure 7.10: Interaction effect at 20% safety lead time

7.4.2 Comparing the POLCA and GPOLCA material control strategies

In this Section, we compare the behavior of the POLCA and GPOLCA material control strategies. The statistical analysis in the previous sub-section confirmed that we would get statistically the same service level for POLCA and GPOLCA strategies for the same manufacturing parameter settings. We now study the other output measures which are important in deciding which strategy is more effective on the shop floor.

7.4.2.1 Comparison based on WIP and Total Inventory

Factorial analysis was performed to study the effect of POLCA and GPOLCA material control strategies on work in process. The result of the analysis is presented in the Figure 7.11

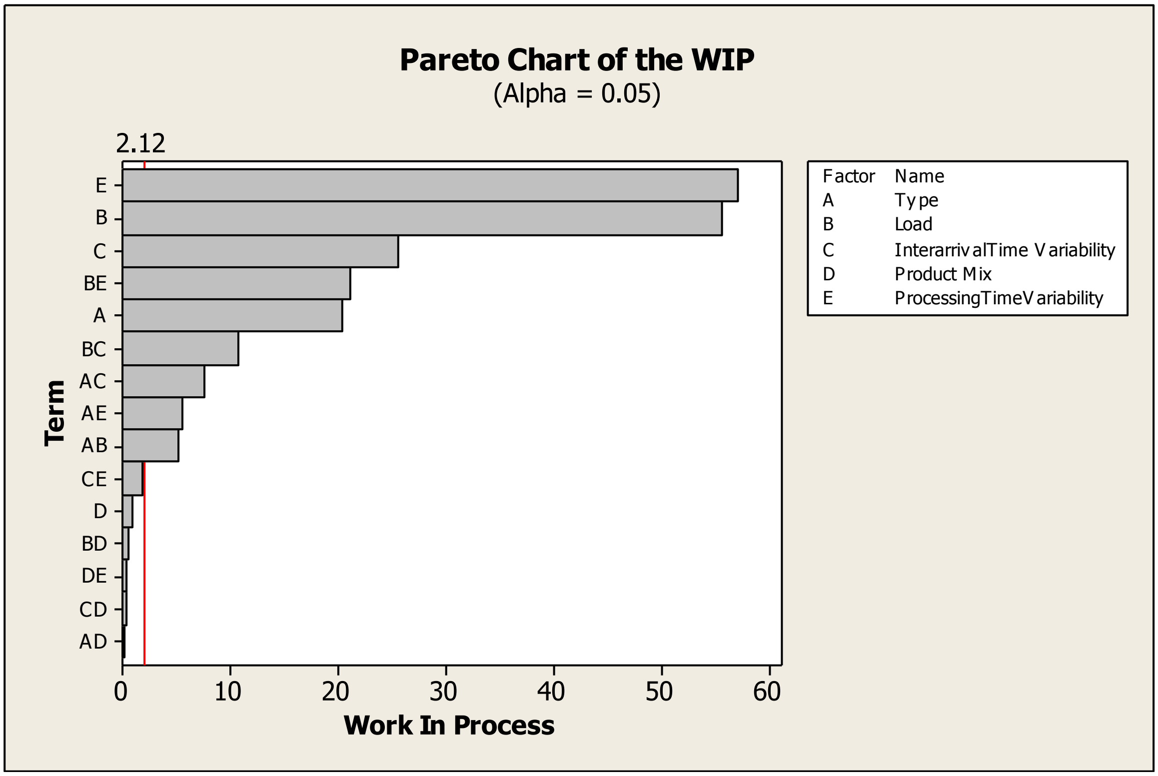

Figure 7.11: Effect of material control strategy on work in process

From above graph, we can see that the type of material control strategy (Factor A) itself is creating a statistically significant difference on the work in process. More than that, interaction effect of type of material control strategy was also observed. Let us consider graphs in Figure 7.12 to study the material control strategy's effect on the work-in-process.

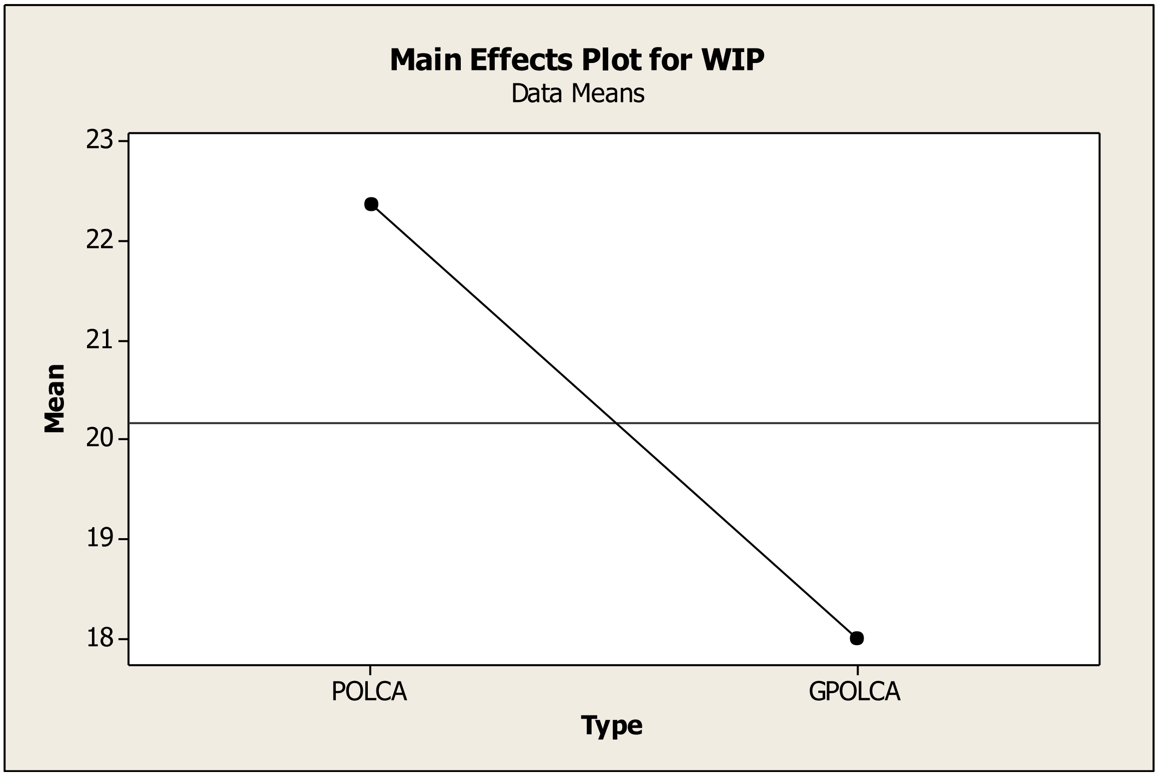

Figure 7.12: Effect of type of strategy on overall work in process

From Figure 7.12 and Table 7.1, we can conclude that GPOLCA can help us in achieve the same service level or due date performance with a smaller WIP compared to POLCA.

Type of material control strategy	Average work in process
POLCA	22.36
GPOLCA	17.98

Table 7.1: Average work in process of different systems

From Table 7.1, we can see that GPOLCA can achieve the same service level as that of POLCA material control strategy with nearly 20% less work in process. The main reason behind this is the difference between the order processing mechanisms of the two material control strategies. We highlight two major points of the POLCA mechanism. First one is that in the POLCA strategy we look for available capacity in the first loop and then release the authorized order to the shop floor. Then that released order waits into the output buffer for next POLCA card and increases the work in process. Secondly, we use the release dates for every individual cell in routing, hence orders waiting for authorization also increase the work in process. On the other hand, in the GPOLCA material control strategy, an order released on the shop floor does not wait for any other required card as the system seizes all the cards before releasing the order to the shop floor. Moreover, the concept of authorization at every single cell is not present in the GPOLCA strategy, hence no order waits for the card or for the authorization on the shop floor once it is released. It results into rapid moment of material on the shop floor, thus resulting into less work in process.

From above discussion, we can say that implementing GPOLCA can provide same service level as that of POLCA material control strategy with less work in process. But, in order to learn more about the effectiveness of the two strategies, we decided to look at other results as well. We have grouped and analyzed the total inventory of the system and number of orders waiting for cards to enter the first cell for different safety lead times and the findings are presented in the Table 7.2 and 7.3.

Safety Lead Time	POLCA Total Inventory	GPOLCA Total Inventory
20 % of flow time	31.76	35.22
40 % of flow time	36.29	41.69
60 % of flow time	41.25	48.72

Table 7.2: Average total inventory for different safety lead times

Type of Material Control Strategy	Average orders waiting for card to start first operation
POLCA	6.31
GPOLCA	26.49

Table 7.3: Average number of orders waiting for first operation

In Table 7.2, we can see that for 20% safety lead time we required 10.89% more total inventory in GPOLCA to achieve same service level as that of POLCA. Moreover, for 40% and 60% safety lead time, we required 14.88% and 18.10% more total inventory in the GPOLCA material control strategy. Hence, we can conclude that in GPOLCA we need more total inventory than POLCA material control strategy for achieving same service level.

In Table 7.3, we observed that as compared to POLCA material control strategy, on average 20 more authorized orders are waiting for cards in the GPOLCA strategy in order to start first operation. Hence, we can conclude that GPOLCA results in less work in process as compared to the POLCA material control strategy but at the cost of higher number of authorized orders waiting to enter the manufacturing system

7.4.2.2 Comparison based on the order flow time

In all simulation experiments we kept track of the actual flow time of every product type while setting up the due dates. Flow time is defined as the total time from authorization of an order till the completion of last operation. Hence, it includes the processing time of an order on different cells, waiting for cards and waiting time in queue. We have tabulated the average flow time of every type of product in two different systems in Table 7.4.

Product Type	**Average flow time in POLCA**	**Average Flow time in GPOLCA**
A	155.61	357.30
B	155.40	201.62
C	125.55	136.08
D	129.57	138.54

Table 7.4: Average flow time of different product types

Before considering the Table 7.4, let us consider the routing of the different product types,

1. Product A: Cell 1- Cell 2- Cell 3- Cell 4- Cell 5
2. Product B: Cell 1- Cell 2- Cell 3- Cell 4- Cell 6
3. Product C: Cell 1- Cell 2- Cell 4- Cell 5
4. Product D: Cell 1- Cell 2- Cell 4- Cell 6

Product A and Product B go through five different operations, and Product C and Product D require only four different operations. Hence, we can say that irrespective of the processing time parameter, Product A and Product B have to wait for one additional cell and card as compared to Product C and Product D to complete all the processing. From Table 7.4 we can observe that Product A and B are actually taking more time than Product C and D to complete all the processes.

Based on the results in Table7.4 we can say that average flow time in GPOLCA strategy as compared to POLCA strategy is more. For Products C and D, average increase in flow time in GPOLCA system is 8.38 % and 6.92% respectively, but for Products A and B it increased by 129.61% and 29.74% respectively. Hence, based on the order flow time, POLCA appears to be better than GPOLCA for the system considered. The point worth mentioning here is that average flow time of Product A and Product B went up drastically as compared to Product C and D. The graphical representation of the flow time of every order type for different settings is shown in the Appendix D. Again, from Appendix D we can confirm that the flow time of Product A and B is much greater in GPOLCA strategy. The main reason behind the difference in flow time in GPOLCA system is 'wrong prioritization of the orders while sequencing them for processing'. To explain this point in more detail, let us assume the following scenario.

Consider that we have implemented the GPOLCA strategy on the shop floor and according to HL/MRP, Product A and Product C are authorized to start processing on Cell 1 in a sequence.

Product A needs Card C1/C2, Card C2/C3, Card C3/C4, and Card C4/C5 to start the process on the first Cell. Similarly, Product C needs Card C1/C2, Card C2/C4 and Card C4/C5 to start the process on the first cell. The chance of getting a smaller number of cards at one time is greater than the chance of getting a larger number of cards together and it causes the Product C to start early just because we need fewer cards. To understand it better, let us consider that Cell 3 is currently running behind the schedule and every other operation is on time. Just because of the longer processing time on Cell C, we do not have Card C2/C3 or Card C3/C4 available for processing an order for Product A on Cell 1, which ends up selecting less important order which is of Product C for processing on Cell 1. Now, any delay on the processing of Order C will also create an additional delay on Order A, because Order A will be the next job to be processed on Cell 1 and Cell 2 after the processing of Order C. This type of wrong prioritization delays orders which requires a larger number of operations and disturbs the planning, and orders requiring fewer operations complete before their scheduled time and increase the total inventory. Hence, selection of the wrong order based on the cell capacity is called as 'wrong prioritization of the order while sequencing them for processing' and it is the major reason behind very high flow time of an order which requires more operations.

In the POLCA system, we cannot observe the wrong prioritization of orders because of the following reason,

Which authorized job to process on a cell is decided only by using the available cards between two cells. The capacity of a third downstream cell does not create a significant effect on the sequencing of the order.

When we implement any material control strategy, it becomes our top most priority that it should support and enhance the production plan. This is happens with POLCA material control strategy, but in GPOLCA, we went against our planned schedule. We can back up our conclusion by studying the average tardiness of every order. It is desirable to achieve good service level and low tardiness. Better service level is always a priority but in case of late orders, delay in completing the order should stay small in order to avoid the high penalties. The plot of average tardiness of different product types in different scenarios in POLCA and GPOLCA material control strategies (Refer to Appendix E for plotted graphs) shows that average tardiness is very high in the GPOLCA strategy compared to the POLCA strategy. We have tabulated the average tardiness of different product types in the following Table.

Product Type	Tardiness with POLCA strategy	Tardiness with GPOLCA strategy
A	55.36	176.39
B	54.67	99.51
C	60.64	76.77
D	59.14	74.14

Table 7.5: Average tardiness of different product types

In Table 7.5, we can observe that the tardiness in the POLCA strategy stays almost same for all order types, but in case of GPOLCA strategy, it goes up drastically for an order with more operations. As concluded earlier, wrong prioritization discourages the orders with more number of operations from entering into the system because of wrong allocation of the cards. Hence, it not only increases the flow time but also increases the tardiness of those orders.

CHAPTER VIII

SUMMARY AND FUTURE WORK

8.1 Summary of the Results

Previous research based on the POLCA and GPOLCA material control strategies was more focused on the development and modification of the material control strategies. Their performances were evaluated and compared by using a simple three-stage manufacturing system. In this thesis research we conducted a more detailed study which captures certain characteristics of the real system such as overlapping of product routings, product based processing times etc. A simulation based research study was carried out for analyzing the performance of POLCA and GPOLCA material control strategies for different shop floor conditions.

The summary of the research work is presented as follows.

1. A new equation based on Little's law was derived for the calculation of GPOLCA cards. This equation can be used as a substitute for the previous random iterative method of calculating the number of GPOLCA cards and hence we could use this method as part of implementation of a GPOLCA material control strategy in the real world.
2. A new heuristic approach was developed for the design and implementation of POLCA and GPOLCA material control strategies for different manufacturing conditions. This new approach allows us to achieve a desired service level at different manufacturing conditions. Hence, we can not only implement the material control strategy but also modify it based on the manufacturing settings.

This new approach also makes the system more predictable in terms of on time delivery which is very important for implementing any material control strategy on the shop floor.

3. While comparing the two different strategies, we concluded that GPOLCA requires less work-in-process as compared to the POLCA strategy to achieve the same service level.
4. On other hand, in the GPOLCA system, we reserve the capacity at all the required cells together and because of that an order which requires a fewer operations usually gets the priority over the order which needs a larger number of operations. This results in wrong sequencing of the orders on different cells.
5. Wrong sequencing leads to more average total inventory, higher flow time and higher tardiness in the GPOLCA system as compared to the POLCA system, which contradicts the findings of the previous study which showed that the GPOLCA system performs better as compared to POLCA system (Fernandes et al., 2006).
6. In the GPOLCA system, average tardiness and total inventory of any particular product changes based on the number of operations which is not a case with the POLCA system. This indicates that implementation of GPOLCA system violates the basic objective of a material control strategy because a material control strategy should help in better planning on the shop floor in order to achieve stable production and a low level of tardiness. Hence, this research has provided a deeper insight into the working of POLCA and GPOLCA strategy compared to existing literature.

8.2 Future Work

The heuristic approaches developed for determining the cards in the POLCA and GPOCLA systems can certainly be improved as indicated by the experimental results.

More research on the two material control strategies should be done by considering other practical consideration, which could lead to firm guidelines for recommending a specific strategy for a particular manufacturing environment. After GPOLCA, there was one more modification that done to the POLCA system known as Load Based POLCA (LB-POLCA). A detailed study of these three different material control strategies could be the next step in future research. Just like the GPOLCA strategy, previous literature concluded that LB-POLCA strategy is better than POLCA strategy based on a very limited study. Hence, an indepth study of these modifications of the POLCA strategy is needed.

One more very important area for future research was also identified during this thesis work. Research is needed to determine optimal settings for the different material control strategies. There is no existing equation or algorithm available in literature which can be used to find out the optimum number of cards in every loop of POLCA and GPOLCA material control strategies to achieve a desired objective.

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APPENDICES

Appendix A. Calculating Number of POLCA Cards

Suri (1998) has presented a formula for calculating the number of POLCA cards in a loop, on the basis of possible lead times and projected load in the loop. Further research has been done on calculating the number of POLCA cards by considering wait and queue time between two cells (Riezebos, 2010).

For this research we use the formula from Suri (1998). The number of POLCA cards can be calculated by following equation:

$$N_{A/B} = [LT_A + LT_B] \times [NUM_{A,B}/P]$$

Where,

$N_{A/B}$ = Number of POLCA cards in loop A − B

LT_A , LT_B = Estimated average lead time across cell A and B

$NUM_{A,B}$ = Possible total number of jobs travelling from Cell A to Cell B

P = Planning Period

Appendix B. Determination of Warm-Up Period, Number of Replications and Run Length

Initial simulation runs were conducted on the system without any card control to determine the warm up period, number of replications and run length. First part of this process was deciding the number of replications. After that, warm period was calculated for different settings. Run length was decided based on the tightness of the confidence interval.

B.1. Determination of warm up period

In this study, the flow time is taken as the base measure to calculate the truncation point (T_o) of warm up period. For very high product variability and high system load we calculated the flow time for Product A. The simulation was run for 10 independent replications and truncation point was found from Welch's graphical method (Law et al., 2000) which consists of following four steps.

Step 1: Ten independent replications of the system were conducted. Each simulation experiment is aborted after 22,000 of order Product A were processed in the system. The flow time of all the orders of Product A are recorded separately in $Y_{ij,}$ where 'i' indicates the flow time of order i of Product A (1,2,…,22000) and 'j' indicates the replication number (1,2,…,10).

Step 2: The average of all the i^{th} order's flow time is calculated to represent the mean flow time of i^{th} order. The following formula is used to calculate the mean value of order flow time.

$$Y_i = \sum_{j=1}^{10} Y_{ij}/10 \qquad \text{For i=1, 2, …, 22,000}$$

Step 3: Different window sizes were selected for calculating moving average. These help to smoothen out the high frequency oscillations. The moving average is calculated as follows,

$$Y_i(w) = \frac{\sum_{s=-(i-1)}^{(i-1)} Y_{i+s}}{2i+1} \qquad \text{For i = 1, …, w}$$

$$Y_i(w) = \frac{\sum_{s=-w}^{w} Y_{i+s}}{2w+1} \qquad \text{For i = w+1,…, 22000-w}$$

For our experiments, we tried different window sizes such as 500, 1000, 2000 and 5000.

Step 4: In the last step, we plotted order number verses observation value Y_i. The resulting graphs are shown in Figure B.1 through Figure B.4.

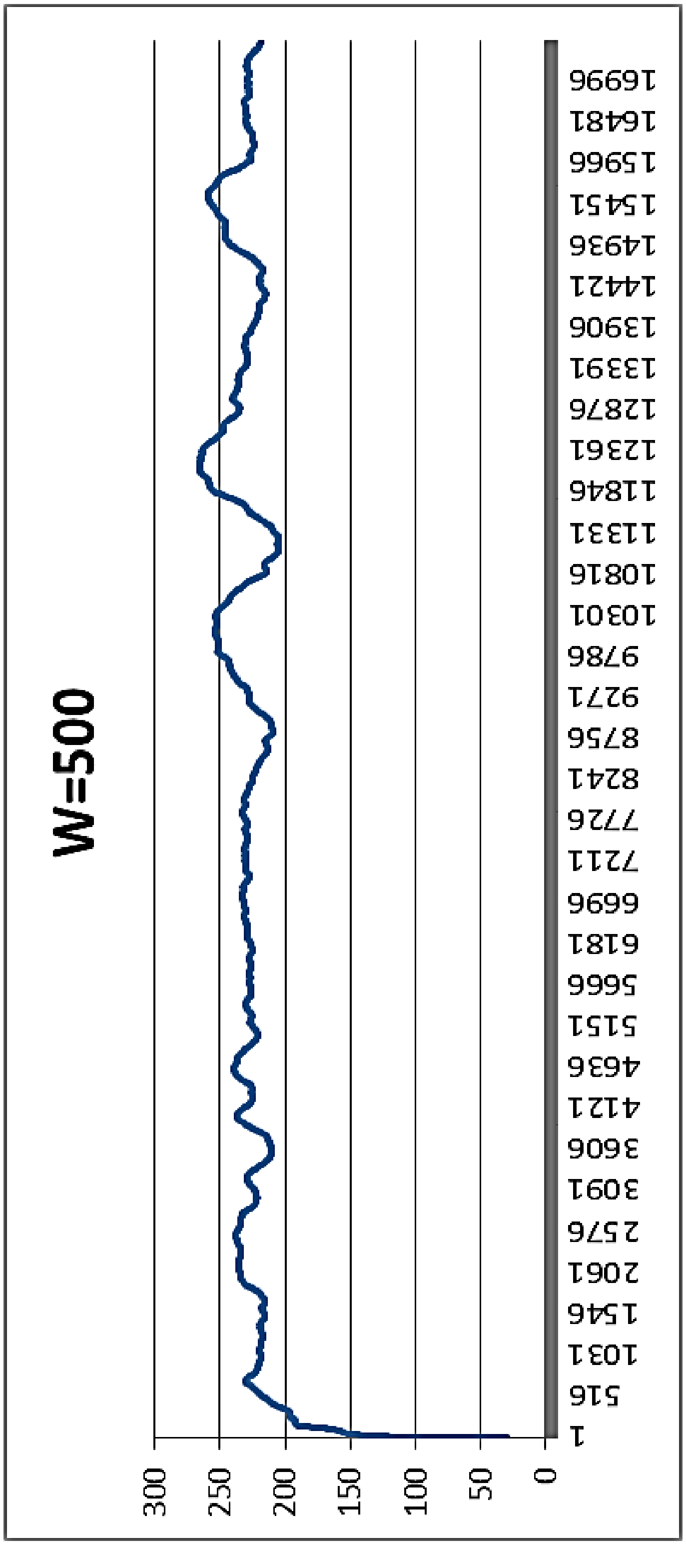

Figure B.1: Moving average plot for flow time with window size of 500

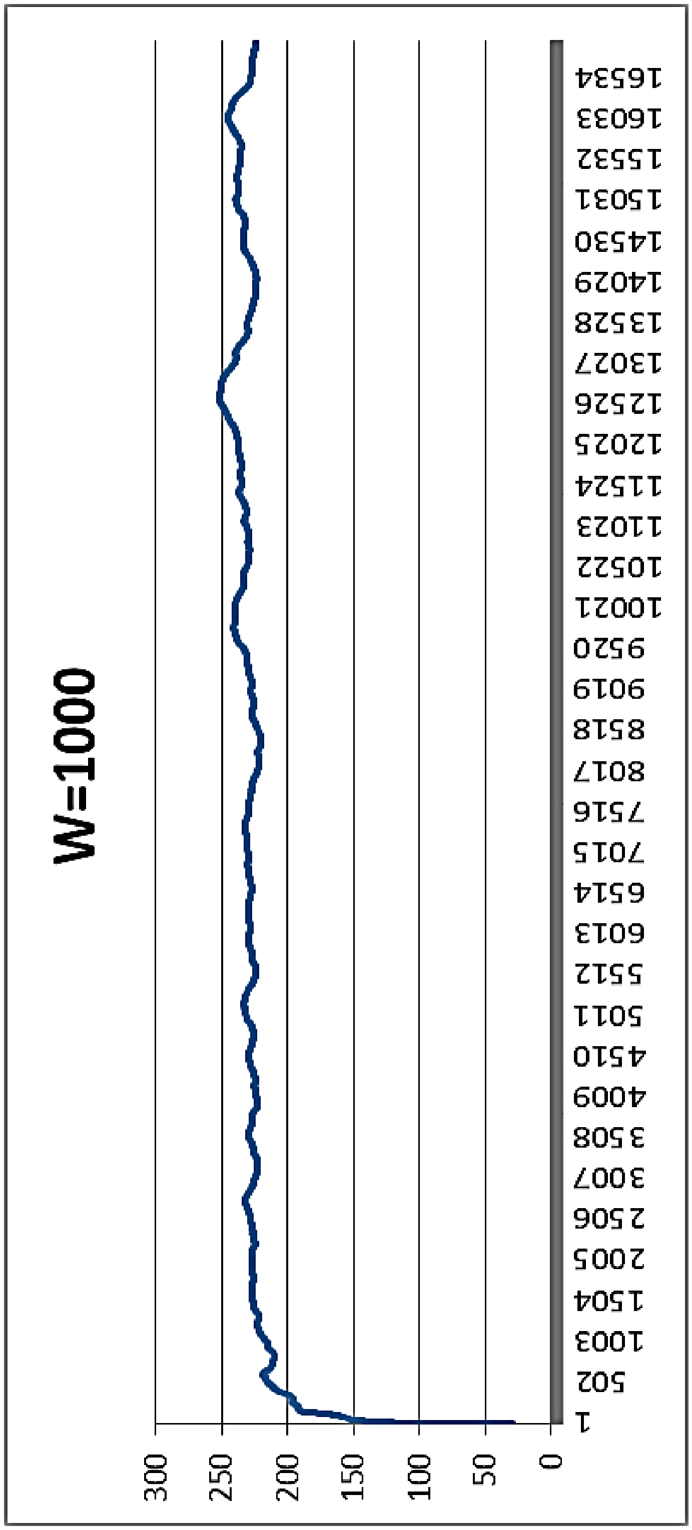

Figure B.2: Moving average plot for flow time with window size of 1000

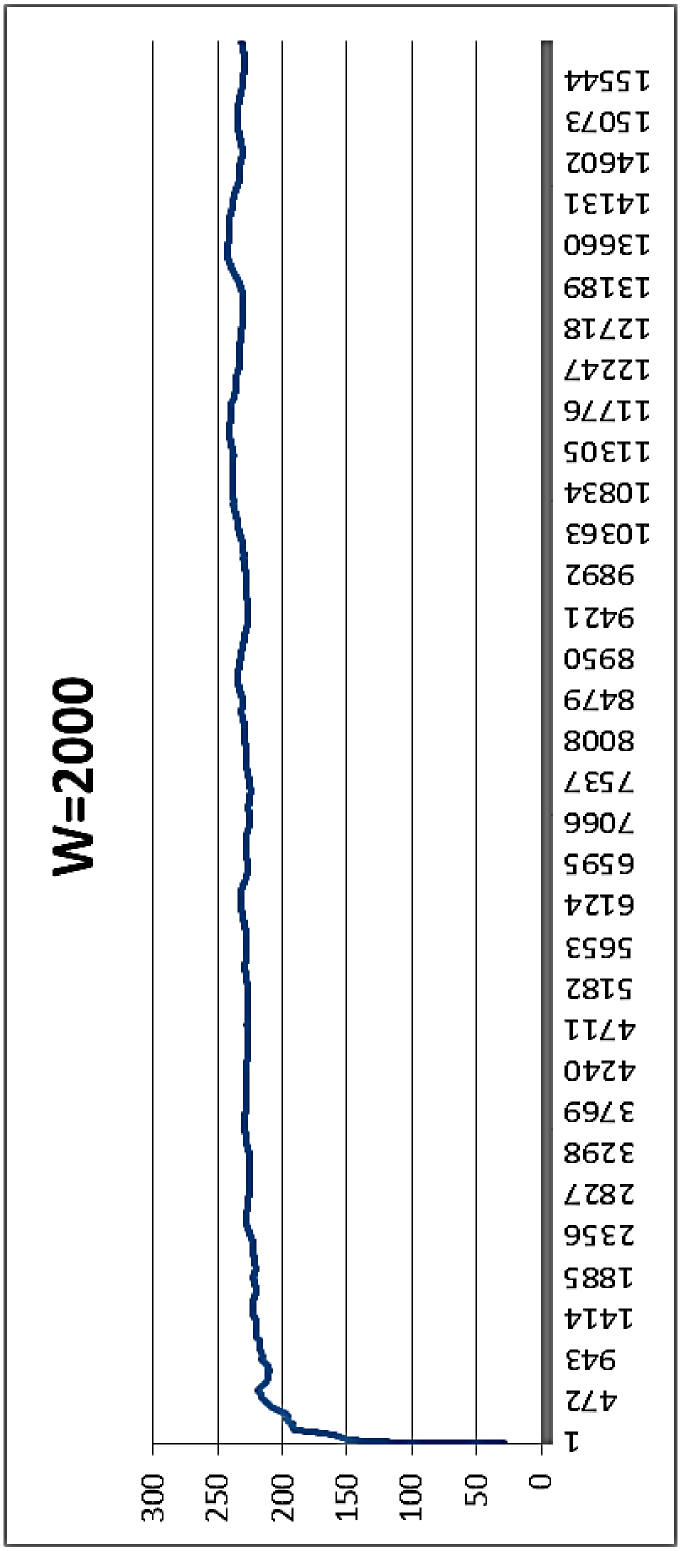

Figure B.3: Moving average plot for flow time with window size of 2000

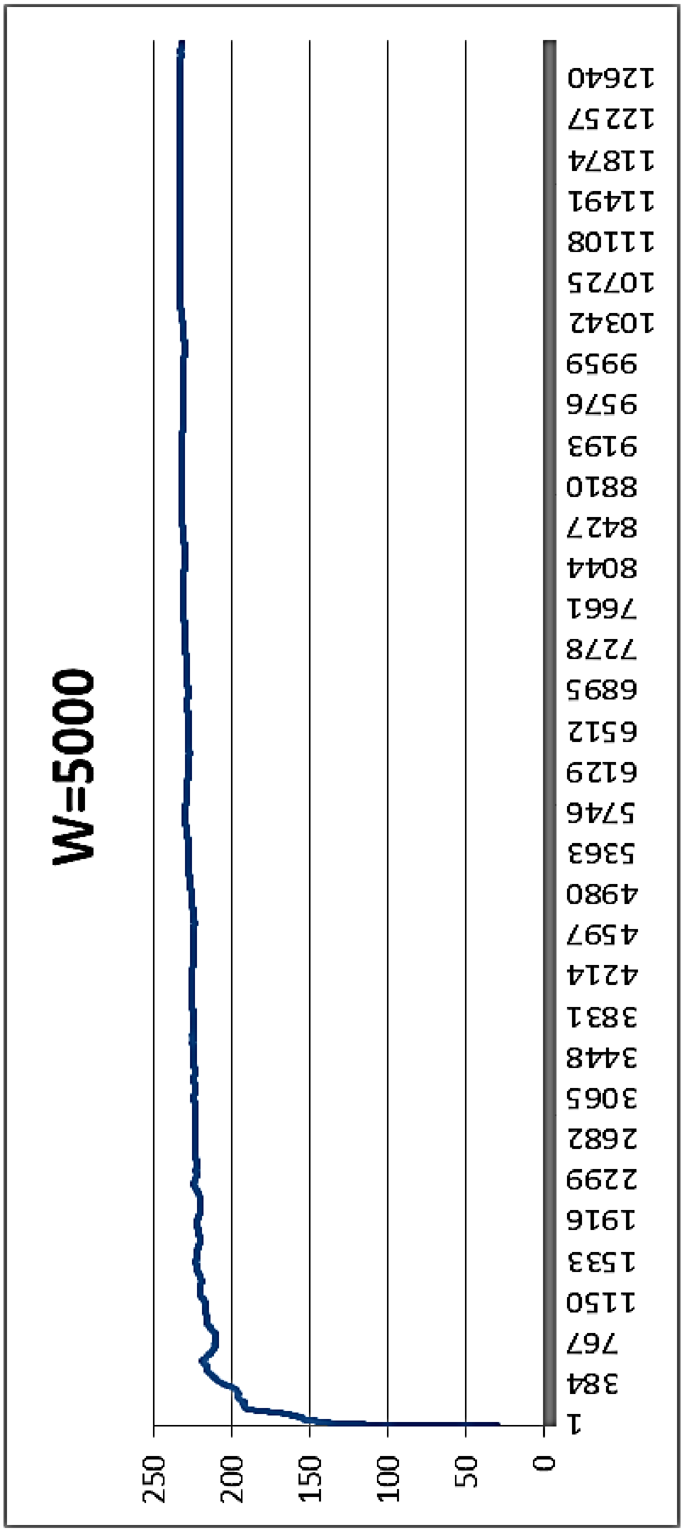

Figure B.4: Moving average plot for flow time with window size of 5000

Truncation point (T_o) is found from the state change of the graph. It is the point from which the graph is flattens out or reaches the steady state. The longest truncation point in the above Figures is in Figure B.4, it is approximately at 1500th order. It represents 19,000 time units. Hence, for all experiments we set the warm-up period to 19,000 time units.

B.2. Determination of run length and number of replications

For our experiments we set the number of replications to 10. For this study it was decided that the half-width of the confidence interval should be less than 5% of the mean.

In order to decide run length, we used the trial and error method of estimation. Simio can generate the value of half width for every scenario. Hence, we used this function and calculated the mean and half width for different scenarios. The results are summarized in Table B.1.

No.	T_0	Run Length	No. of Replications	Mean Flow Time	1/2 L	(1/2L)/Mean
1	19000	114000	10	227.39	6.64	2.92%
2	19000	150000	10	228.78	9.88	4.31%
3	20000	120000	10	227.31	7.23	3.18%
4	20000	150000	10	228.81	9.81	4.29%

Table B.1: Effect of different warm up periods and run lengths on accuracy

From Table B.1, we can observe that accuracy of statistical experiments is within desirable range for all combinations. Hence, the warm-up period was set to 19,000 time units and run length to 114,000 time units.

Appendix C. Results and Observations

This appendix presents the detailed results which were obtained by running the simulation.

In some of the next tables, we have used the experiment numbers instead of repeating all the input settings. Hence, in the results table we have shown experiment numbers associated with the input settings.

Experiment Number	**Cell Load**	**Inter-arrival Time Variability**	**Product Mix**	**Processing Time Variability**	**Safety Lead Time**
1	0.75	Erlang Distribution	Uniform	Erlang Distribution	20%
2	0.75	Erlang Distribution	Uniform	Erlang Distribution	40%
3	0.75	Erlang Distribution	Uniform	Erlang Distribution	60%
4	0.75	Erlang Distribution	Uniform	Exponential Distribution	20%
5	0.75	Erlang Distribution	Uniform	Exponential Distribution	40%
6	0.75	Erlang Distribution	Uniform	Exponential Distribution	60%
7	0.75	Erlang Distribution	Uneven	Erlang Distribution	20%
8	0.75	Erlang Distribution	Uneven	Erlang Distribution	40%
9	0.75	Erlang Distribution	Uneven	Erlang Distribution	60%
10	0.75	Erlang Distribution	Uneven	Exponential Distribution	20%
11	0.75	Erlang Distribution	Uneven	Exponential Distribution	40%
12	0.75	Erlang Distribution	Uneven	Exponential Distribution	60%
13	0.75	Exponential Distribution	Uniform	Erlang Distribution	20%
14	0.75	Exponential Distribution	Uniform	Erlang Distribution	40%
15	0.75	Exponential Distribution	Uniform	Erlang Distribution	60%
16	0.75	Exponential Distribution	Uniform	Exponential Distribution	20%
17	0.75	Exponential Distribution	Uniform	Exponential Distribution	40%
18	0.75	Exponential Distribution	Uniform	Exponential Distribution	60%

19	0.75	Exponential Distribution	Uneven	Erlang Distribution	20%
20	0.75	Exponential Distribution	Uneven	Erlang Distribution	40%
21	0.75	Exponential Distribution	Uneven	Erlang Distribution	60%
22	0.75	Exponential Distribution	Uneven	Exponential Distribution	20%
23	0.75	Exponential Distribution	Uneven	Exponential Distribution	40%
24	0.75	Exponential Distribution	Uneven	Exponential Distribution	60%
25	0.85	Erlang Distribution	Uniform	Erlang Distribution	20%
26	0.85	Erlang Distribution	Uniform	Erlang Distribution	40%
27	0.85	Erlang Distribution	Uniform	Erlang Distribution	60%
28	0.85	Erlang Distribution	Uniform	Exponential Distribution	20%
29	0.85	Erlang Distribution	Uniform	Exponential Distribution	40%
30	0.85	Erlang Distribution	Uniform	Exponential Distribution	60%
31	0.85	Erlang Distribution	Uneven	Erlang Distribution	20%
32	0.85	Erlang Distribution	Uneven	Erlang Distribution	40%
33	0.85	Erlang Distribution	Uneven	Erlang Distribution	60%
34	0.85	Erlang Distribution	Uneven	Exponential Distribution	20%
35	0.85	Erlang Distribution	Uneven	Exponential Distribution	40%
36	0.85	Erlang Distribution	Uneven	Exponential Distribution	60%
37	0.85	Exponential Distribution	Uniform	Erlang Distribution	20%
38	0.85	Exponential Distribution	Uniform	Erlang Distribution	40%
39	0.85	Exponential Distribution	Uniform	Erlang Distribution	60%
40	0.85	Exponential Distribution	Uniform	Exponential Distribution	20%
41	0.85	Exponential Distribution	Uniform	Exponential Distribution	40%
42	0.85	Exponential Distribution	Uniform	Exponential Distribution	60%
43	0.85	Exponential Distribution	Uneven	Erlang Distribution	20%

44	0.85	Exponential Distribution	Uneven	Erlang Distribution	40%
45	0.85	Exponential Distribution	Uneven	Erlang Distribution	60%
46	0.85	Exponential Distribution	Uneven	Exponential Distribution	20%
47	0.85	Exponential Distribution	Uneven	Exponential Distribution	40%
48	0.85	Exponential Distribution	Uneven	Exponential Distribution	60%

Table C.1: Input settings for the experiments

Table C.2 includes the results obtained from the POLCA material control strategy.

Experiment Number	Overall Service Level	Average Tardiness	WIP	Total Inventory
1	76.2092	22.3745	9.43007	12.8506
2	85.6621	21.8399	9.43007	14.7433
3	91.3041	21.0386	9.43007	16.8138
4	74.6347	67.1999	17.8827	26.6947
5	82.7023	65.8559	17.8827	30.5628
6	88.1646	63.7061	17.8827	34.7572
7	82.2128	11.47	9.90853	12.6559
8	92.4819	10.8928	9.90853	14.4631
9	96.9442	10.5993	9.90853	16.4127
10	75.4048	51.9379	17.8929	25.2373
11	84.0495	51.5362	17.8929	28.8321
12	89.1961	50.4001	17.8929	32.7387
13	74.3336	42.2475	13.2104	18.877
14	82.615	41.4767	13.2104	21.5595
15	88.1097	40.4498	13.2104	24.4805

16	74.7306	80.8718	22.1485	32.917
17	82.9415	78.3738	22.1485	37.6554
18	88.4686	75.4525	22.1485	42.8348
19	74.3114	33.7251	13.4971	18.4699
20	83.8892	32.8138	13.4971	21.0194
21	90.0507	32.1191	13.4971	23.8187
22	71.8598	62.1148	22.8226	31.9469
23	80.4613	57.9194	22.8226	36.3018
24	86.5433	53.4109	22.8226	41.0967
25	77.379	29.3023	15.3026	20.0786
26	87.2984	28.1962	15.3026	22.8627
27	92.88	26.6169	15.3026	25.9064
28	76.0347	102.183	32.0004	49.3713
29	85.1729	88.8224	32.0004	57.2485
30	91.9956	77.2176	32.0004	65.9713
31	76.7616	25.2476	15.2294	19.68
32	87.3145	24.3073	15.2294	22.4328
33	93.1913	23.2466	15.2294	25.4408
34	73.9089	73.2134	32.884	45.7565
35	84.0938	63.2956	32.884	52.2807
36	90.808	55.6854	32.884	59.5675
37	70.236	78.3707	24.6049	35.3983
38	79.0269	74.2346	24.6049	40.3005
39	85.2519	69.5104	24.6049	45.6441
40	76.6036	143.003	43.7418	65.1626

41	84.04	128.284	43.7418	74.5034
42	89.3369	113.768	43.7418	84.8062
43	73.0876	56.1949	24.0201	32.602
44	82.4927	52.789	24.0201	37.0205
45	88.7343	48.7414	24.0201	41.8688
46	74.5973	109.63	43.1986	60.5004
47	83.7768	97.0426	43.1986	68.7802
48	90.7245	86.4418	43.1986	77.865

Table C.2: Results of POLCA material control strategy

Table C.3 includes the results obtained for the GPOLCA material control strategy

Experiment Number	Overall Service Level	Average Tardiness	WIP	Total Inventory
1	76.7977	19.334	8.23464	11.213
2	86.576	19.7763	8.23464	12.8702
3	92.0617	20.2116	8.23464	14.6847
4	77.4824	147.336	14.5127	30.4201
5	83.5943	151.987	14.5127	36.2195
6	87.928	154.893	14.5127	42.4093
7	76.6227	20.3193	8.24641	11.3719
8	86.5464	20.4244	8.24641	13.1014
9	92.2618	20.704	8.24641	14.996
10	75.931	136.462	14.9369	31.6686
11	82.5956	136.46	14.9369	37.4751
12	87.1453	134.649	14.9369	43.6751

13	72.8876	35.1664	10.1403	14.7967
14	81.5627	35.2858	10.1403	16.9619
15	87.5188	35.4897	10.1403	19.3279
16	77.8019	105.282	17.0265	28.6167
17	84.6189	108.501	17.0265	33.1989
18	89.0879	111.376	17.0265	38.1337
19	73.7323	34.1711	10.3722	14.9608
20	82.8443	35.0463	10.3722	17.1566
21	88.8542	36.6124	10.3722	19.5583
22	74.0843	88.3467	17.1774	27.984
23	81.9239	90.5246	17.1774	32.4596
24	87.4118	94.298	17.1774	37.329
25	73.6156	35.0847	12.7371	17.782
26	82.8675	35.643	12.7371	20.4158
27	88.7883	36.803	12.7371	23.2963
28	83.1415	434.5	28.3762	88.4528
29	87.7352	422.644	28.3762	108.737
30	90.5939	402.002	28.3762	130.389
31	78.2983	34.2835	13.1382	18.1024
32	87.5183	35.5453	13.1382	20.7849
33	92.7374	36.71	13.1382	23.7084
34	83.4844	456.232	28.2377	99.1692
35	88.1417	407.683	28.2377	122.523
36	91.9032	375.082	28.2377	148.613
37	72.3791	63.139	18.4637	26.9153

38	81.0979	62.0284	18.4637	30.6991
39	86.92	60.7562	18.4637	34.8341
40	73.7653	186.565	33.4857	55.2442
41	80.8122	187.765	33.4857	63.9412
42	85.8881	187.523	33.4857	73.303
43	72.4745	56.261	18.4942	26.4425
44	81.3491	54.3148	18.4942	30.1752
45	87.6459	53.3757	18.4942	34.2724
46	79.1407	225.713	34.1428	60.3415
47	84.8278	230.245	34.1428	70.3134
48	88.3114	229.039	34.1428	81.0055

Table C.3: Results of the GPOLCA material control strategy

POLCA iteration number	WIP	Flow Time
1	66.02	330.17
2	55.92	297.28
3	49.07	250.73
4	45.12	232.67
5	44.99	225.19
6	46.68	241.58
7	44.91	226.09
8	44.56	222.48
9	43.71	220.41
10	43.15	215.86

Table C.4: Result of the POLCA iterative run

Appendix D. Graphs and Plots

1. Normal Plot for POLCA system

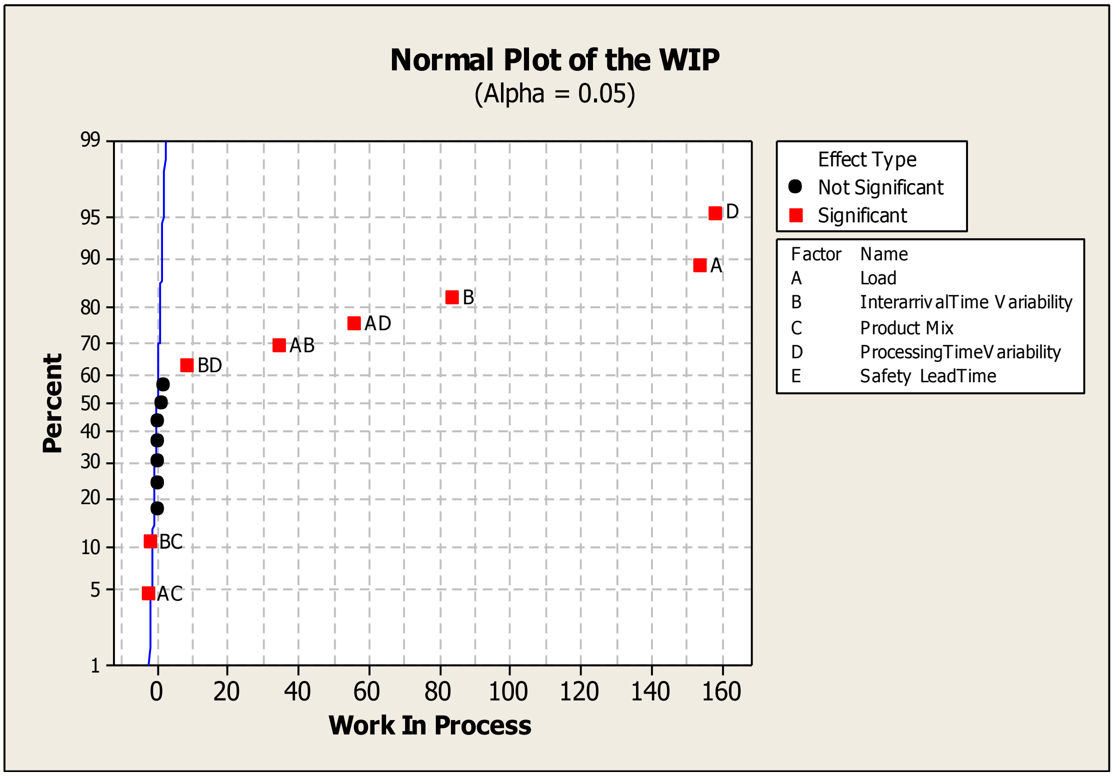

Figure D.1: Factors affecting the WIP in the POLCA system

2. 3-D plots for service level in POLCA strategy

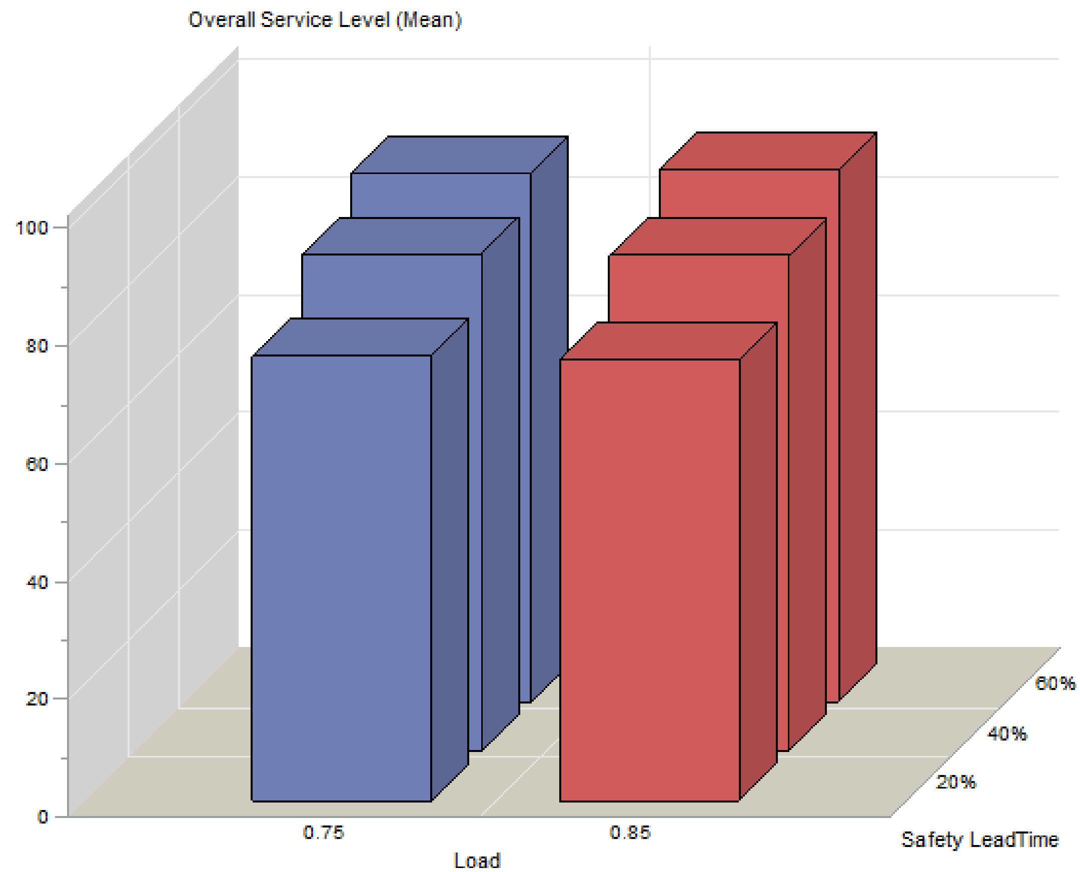

Figure D.2: Load vs. Overall service level of POLCA strategy

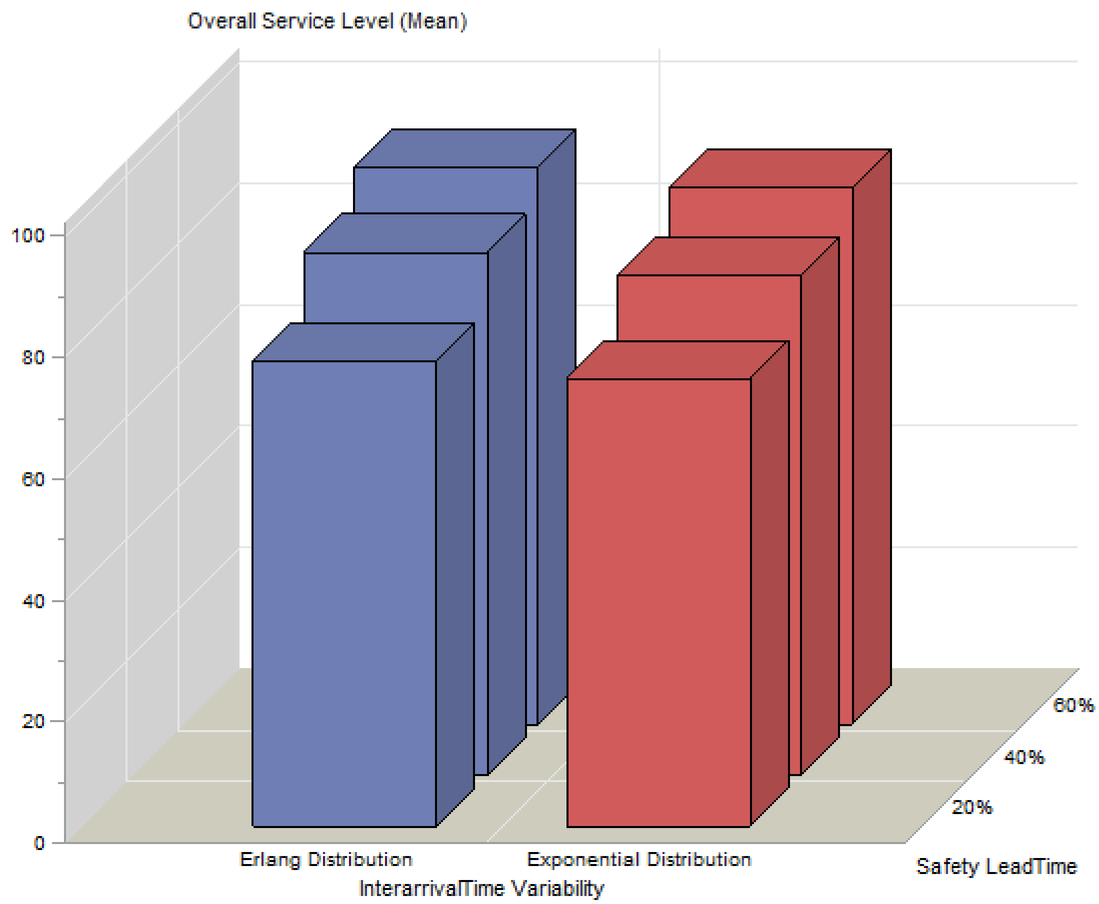

Figure D.3: Inter-arrival time variability vs. Overall service level of POLCA strategy

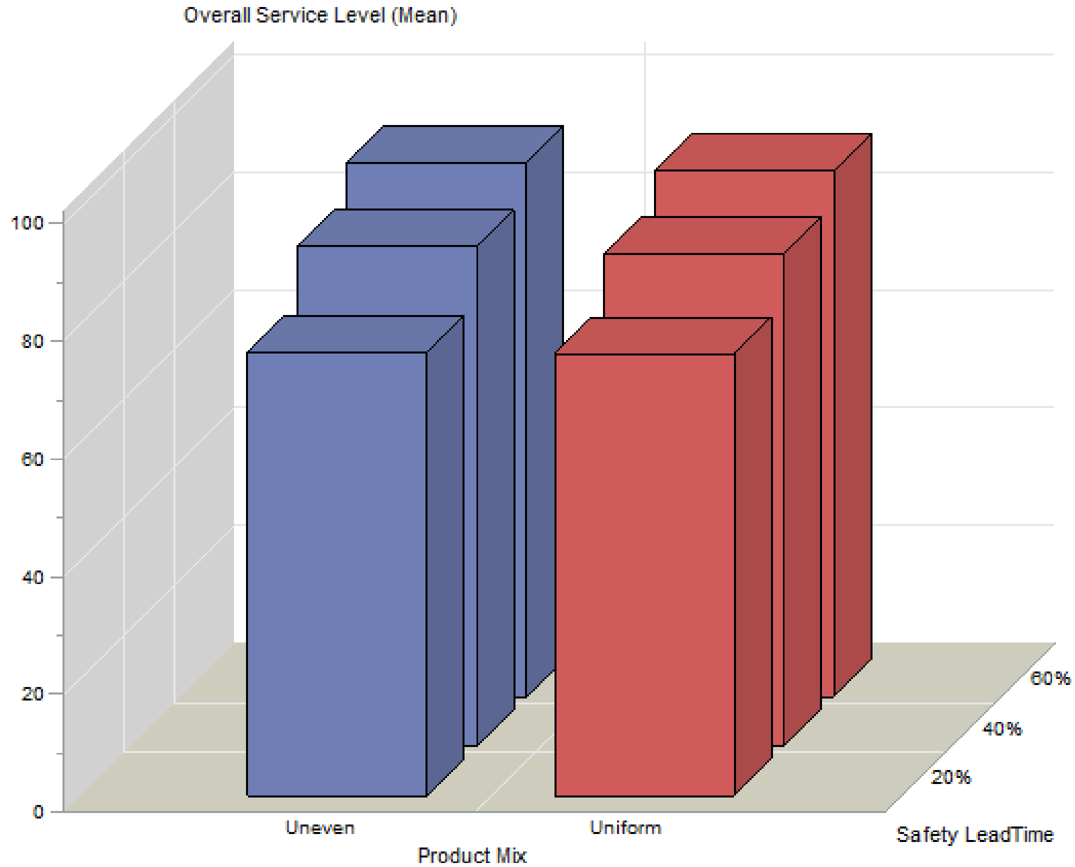

Figure D.4: Product mix vs. Overall service level of POLCA strategy

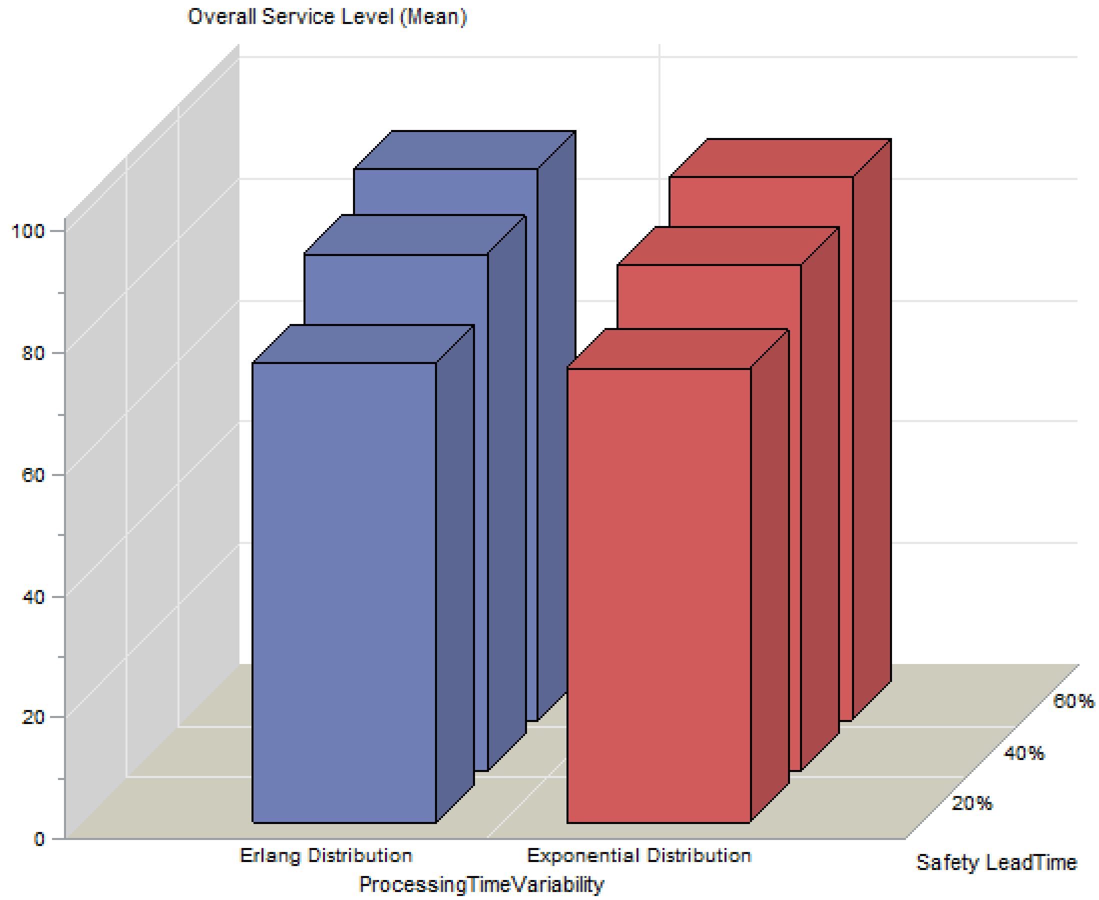

Figure D.5: Processing time variability vs. Overall service level of POLCA strategy

3. Normal Plots for GPOLCA

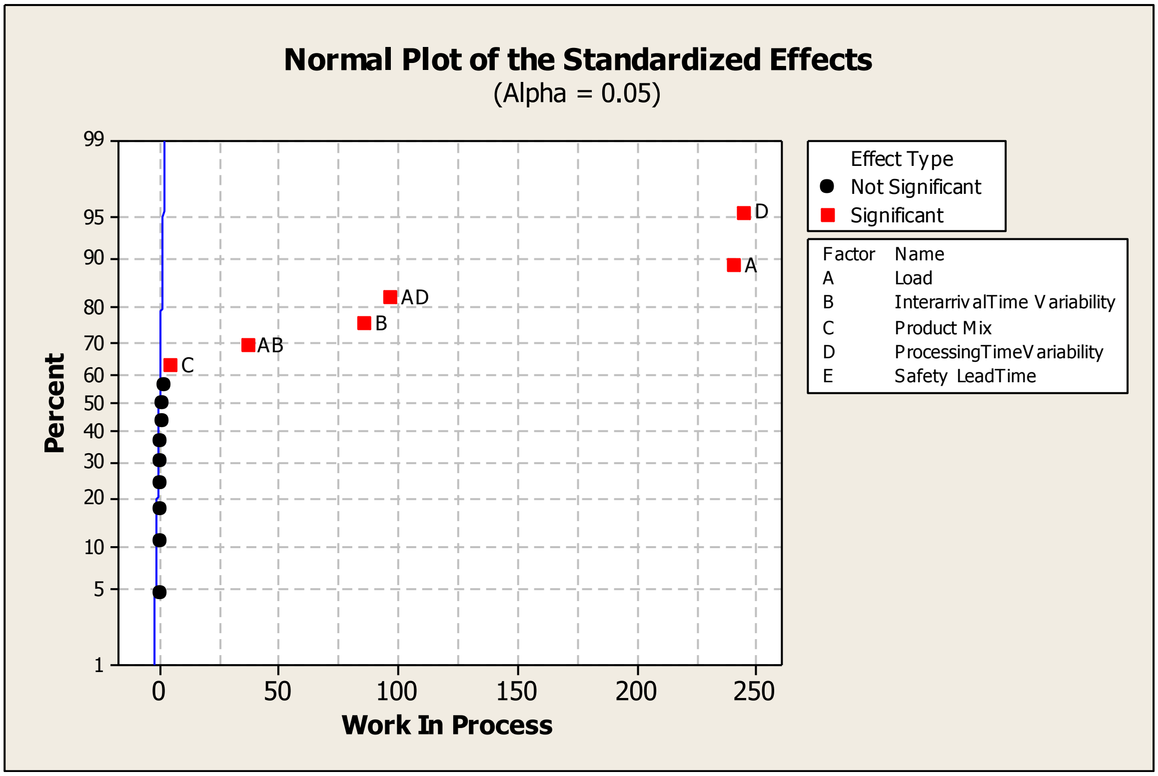

Figure D.6: Factors affecting the WIP in the GPOLCA system

4. 3-D plots for service level in the GPOLCA strategy

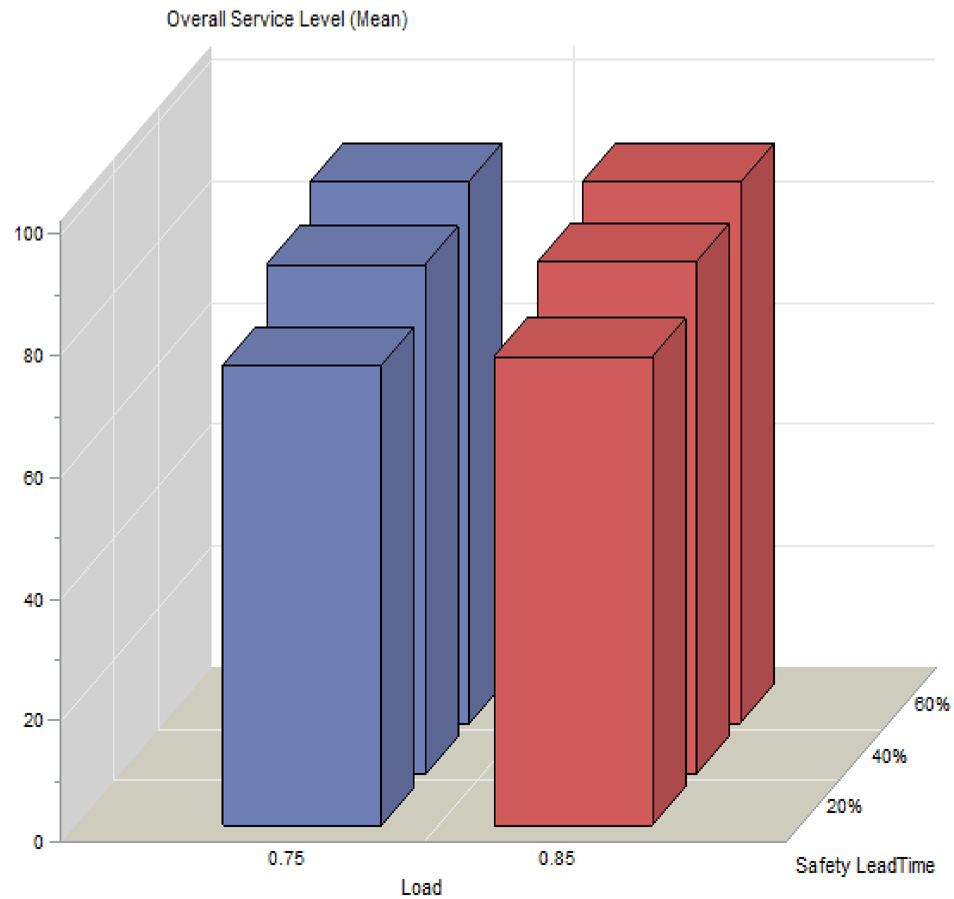

Figure D.7: Load Vs. Overall service level of GPOLCA strategy

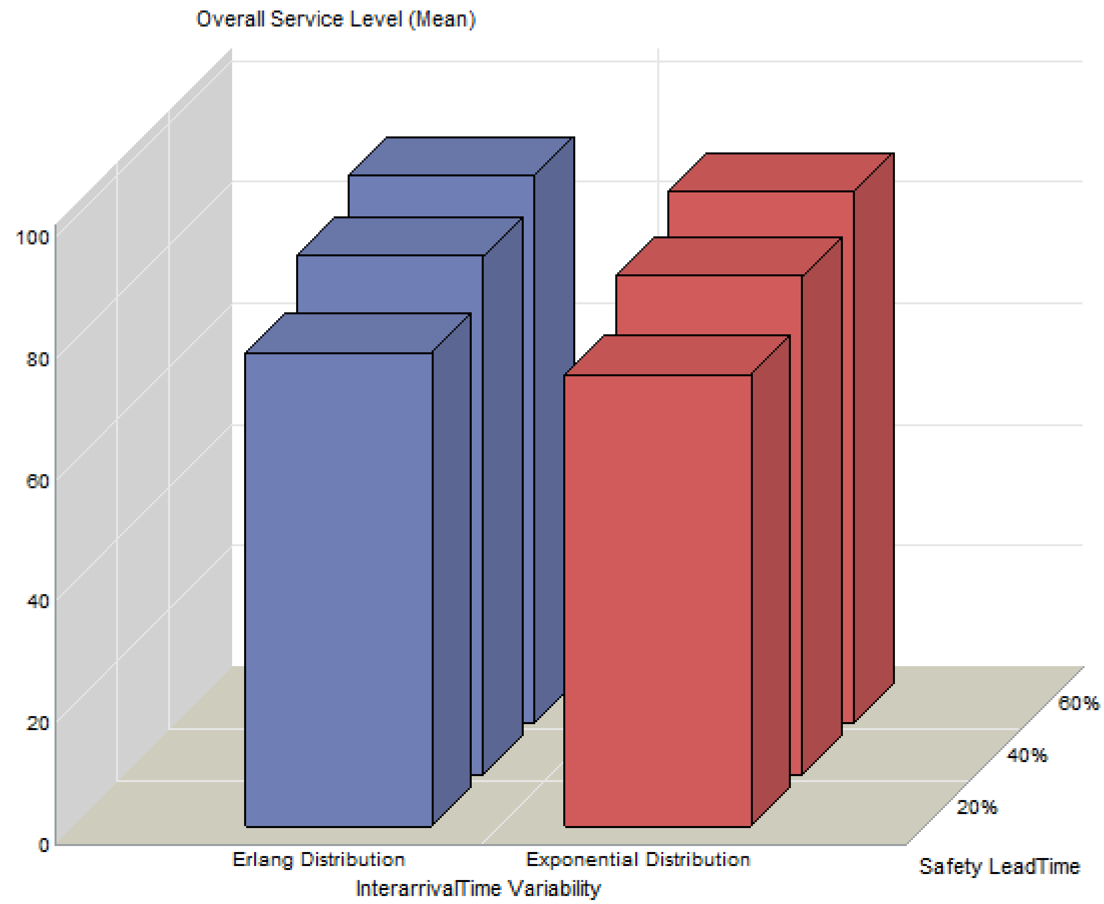

Figure D.8: Inter-arrival time variability vs. Overall service level of GPOLCA strategy

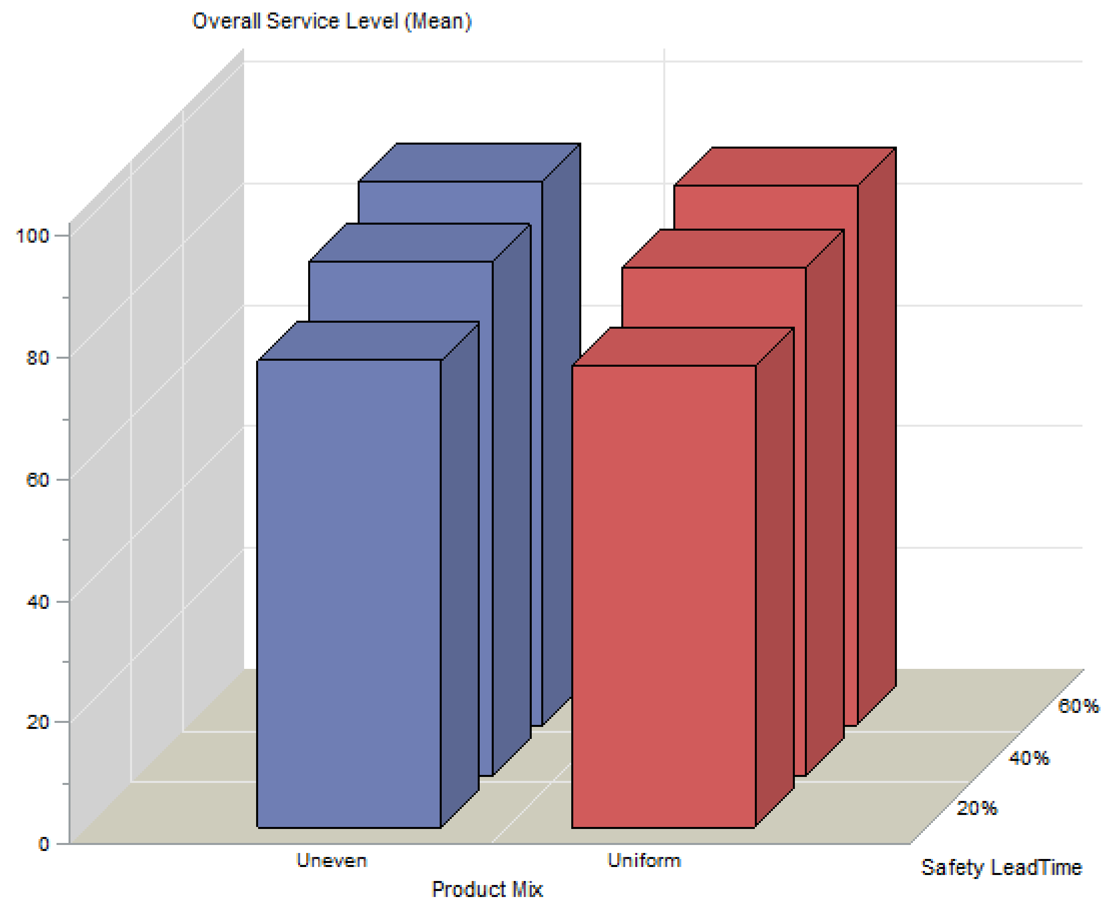

Figure D.9: Product mix vs. Overall service level of GPOLCA strategy

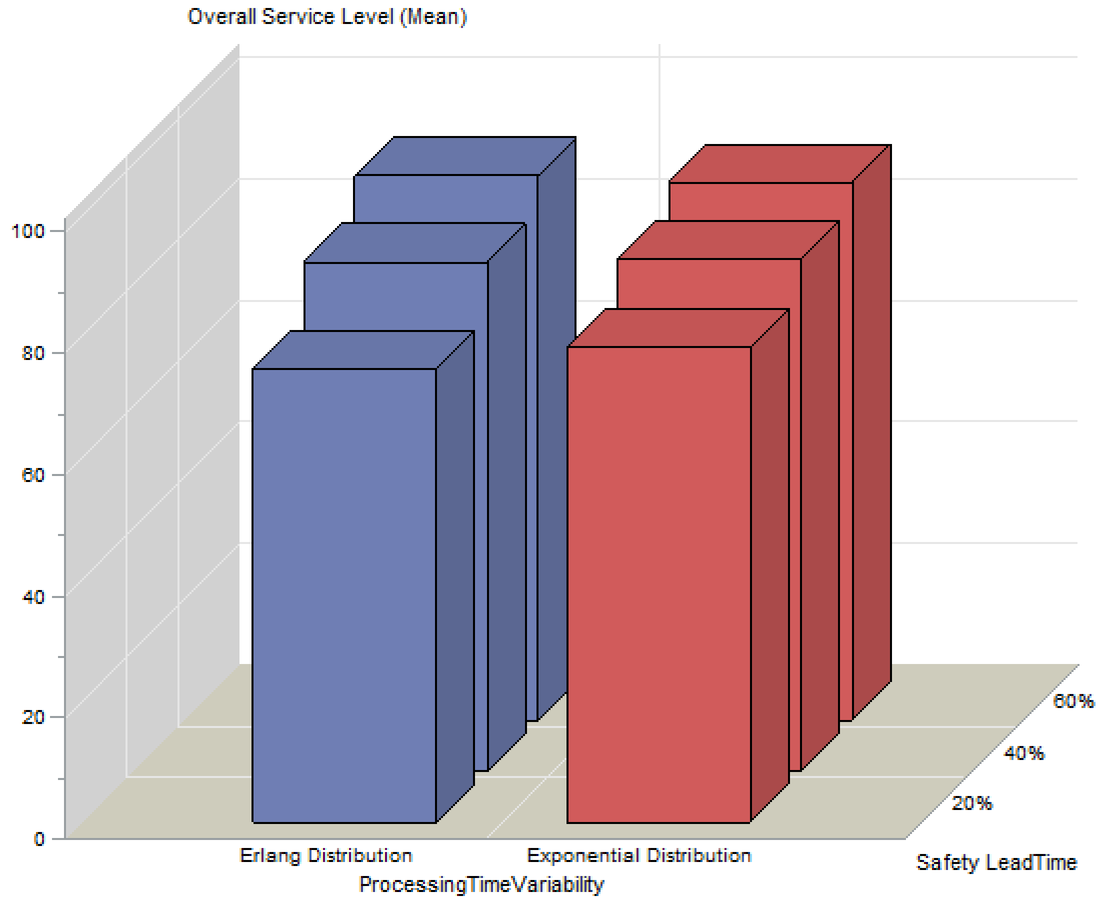

Figure D.10: Processing time variability vs. Overall service level of POLCA strategy

Appendix E: Flow Time of Different Order Types

In this appendix we have presented the flow time of different order types for the POLCA and GPOLCA material control strategies. The average value has been used for the comparison of two different systems in the results section.

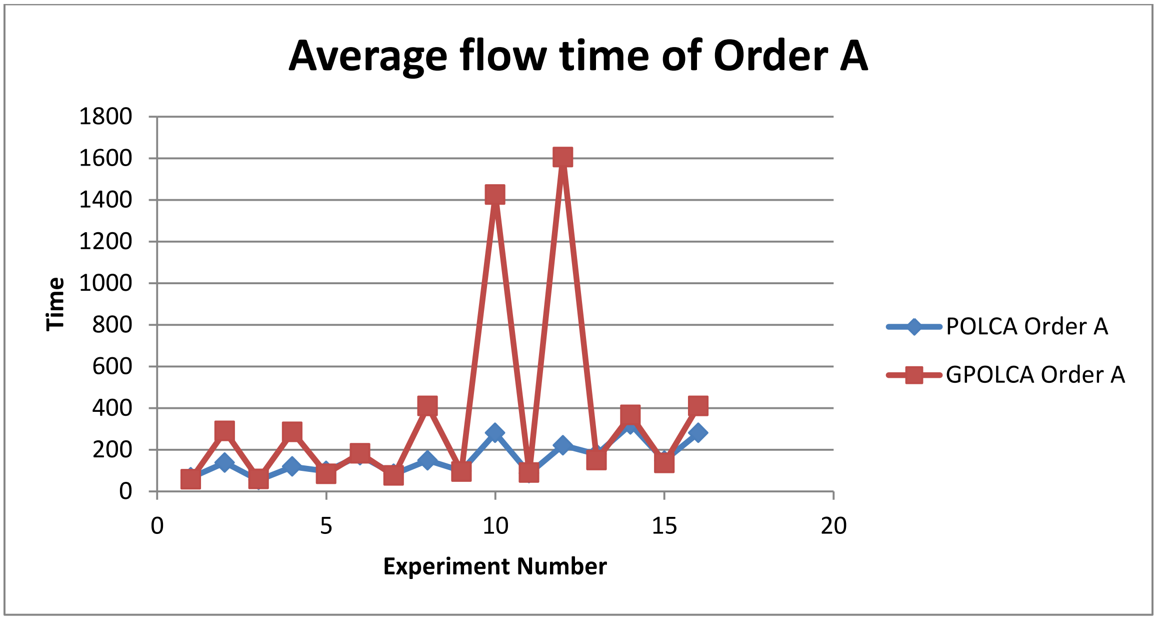

Figure E.1: Flow time of Product A in POLCA and GPOLCA material control strategies

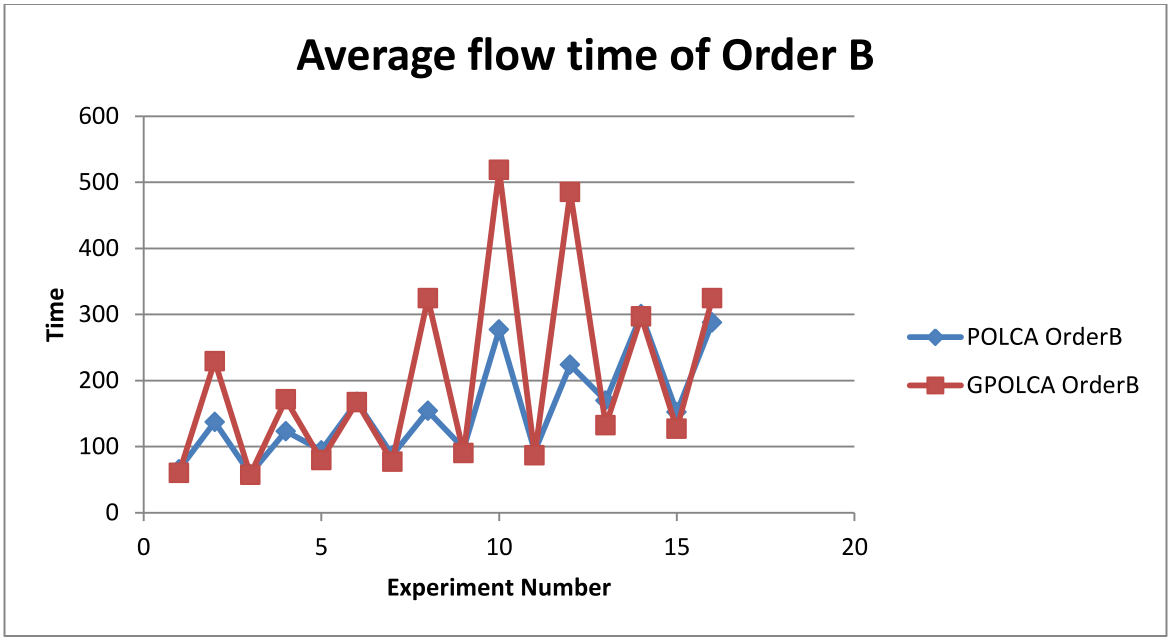

Figure E.2: Flow time of Product B in POLCA and GPOLCA material control strategies

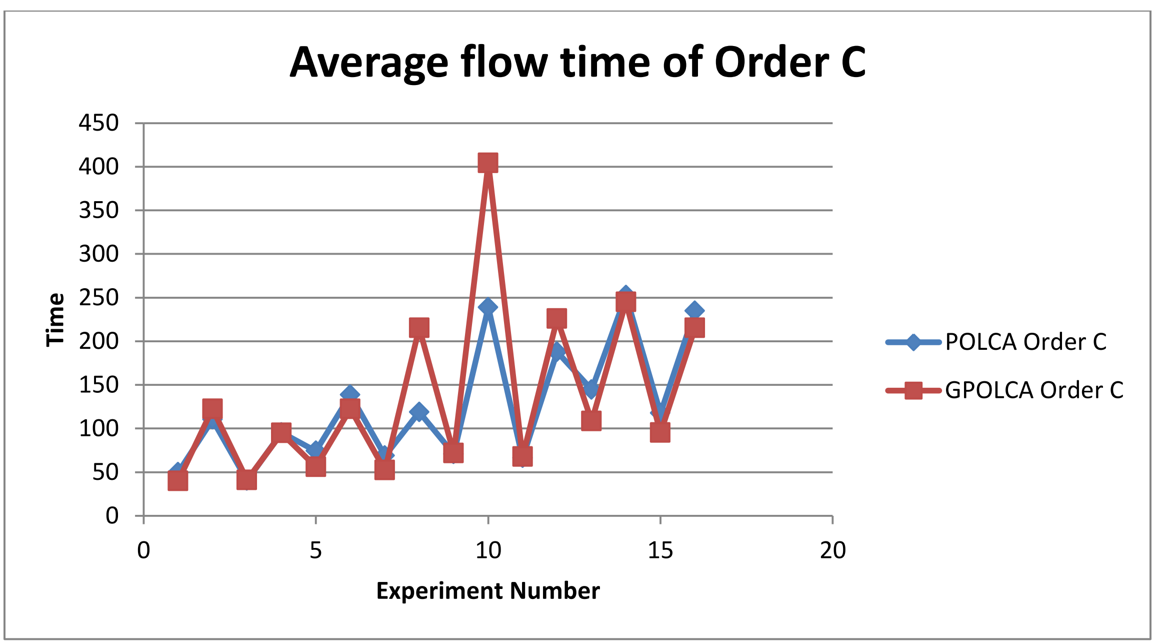

Figure E.3: Flow time of Product C in POLCA and GPOLCA material control strategies

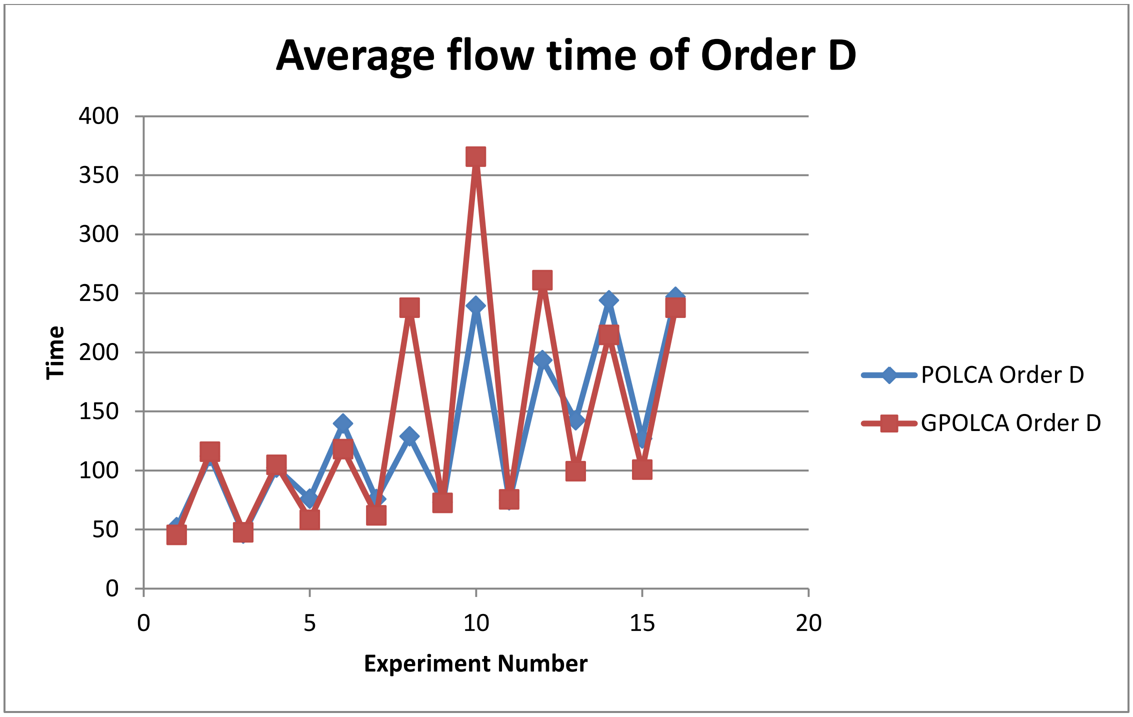

Figure E.4: Flow time of Product D in POLCA and GPOLCA material control strategies

Appendix F: Tardiness Plots

In this appendix, we have graphically presented the tardiness of different order types in the POLCA and GPOLCA material control strategies. We can visually verify our conclusion about the tardiness of the different strategies from the following plots. These plots are also helpful to understand the difference in the order handling mechanism of POLCA and GPOLCA material control strategies. As concluded earlier, the average tardiness of different orders in the POLCA strategy remains almost same, but in case of GPOLCA material control strategy, it varies drastically based on the number of operations required to complete that order.

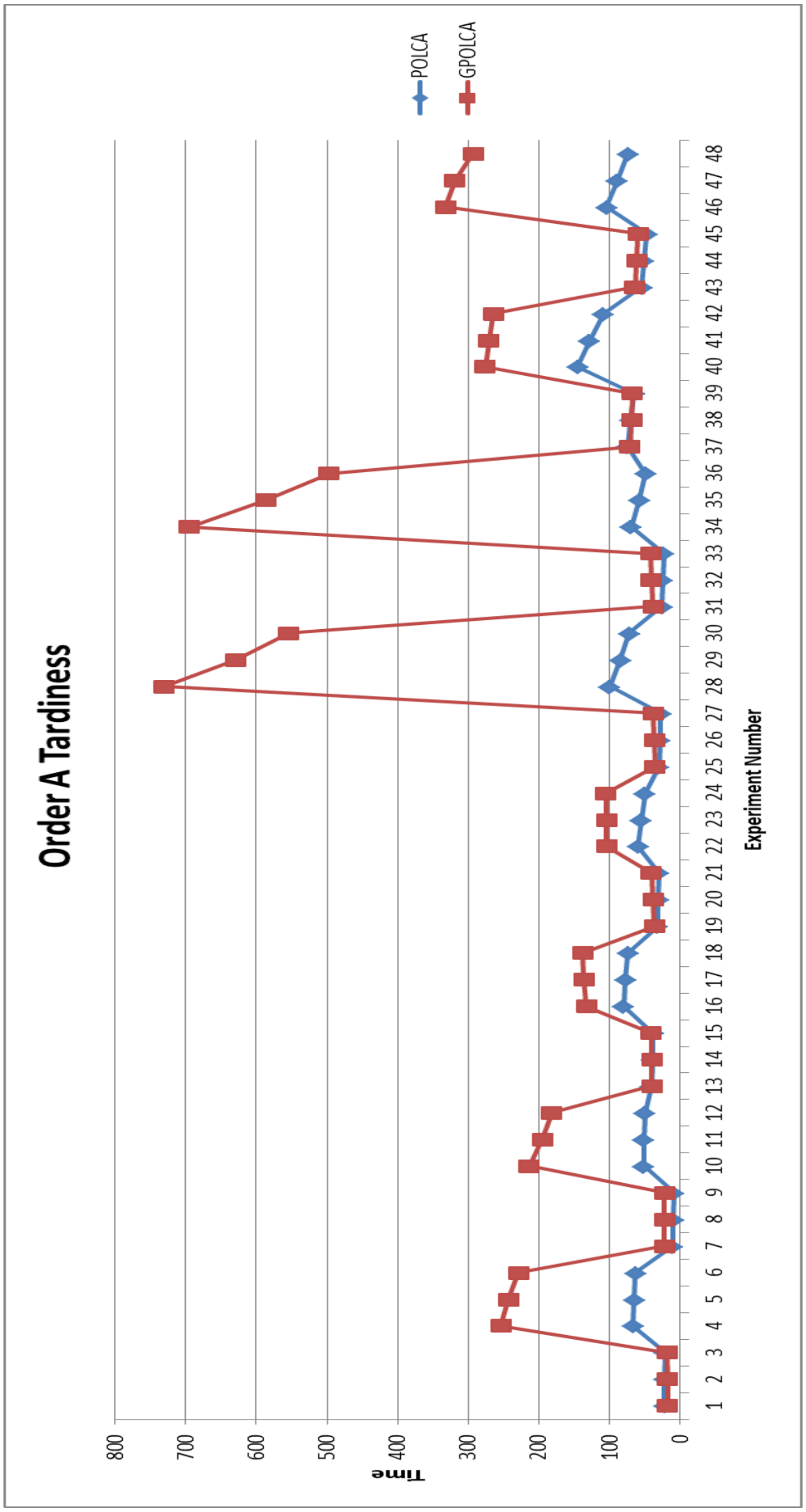

Figure F.1: Average Tardiness of Product A in POLCA and GPOLCA material control strategies

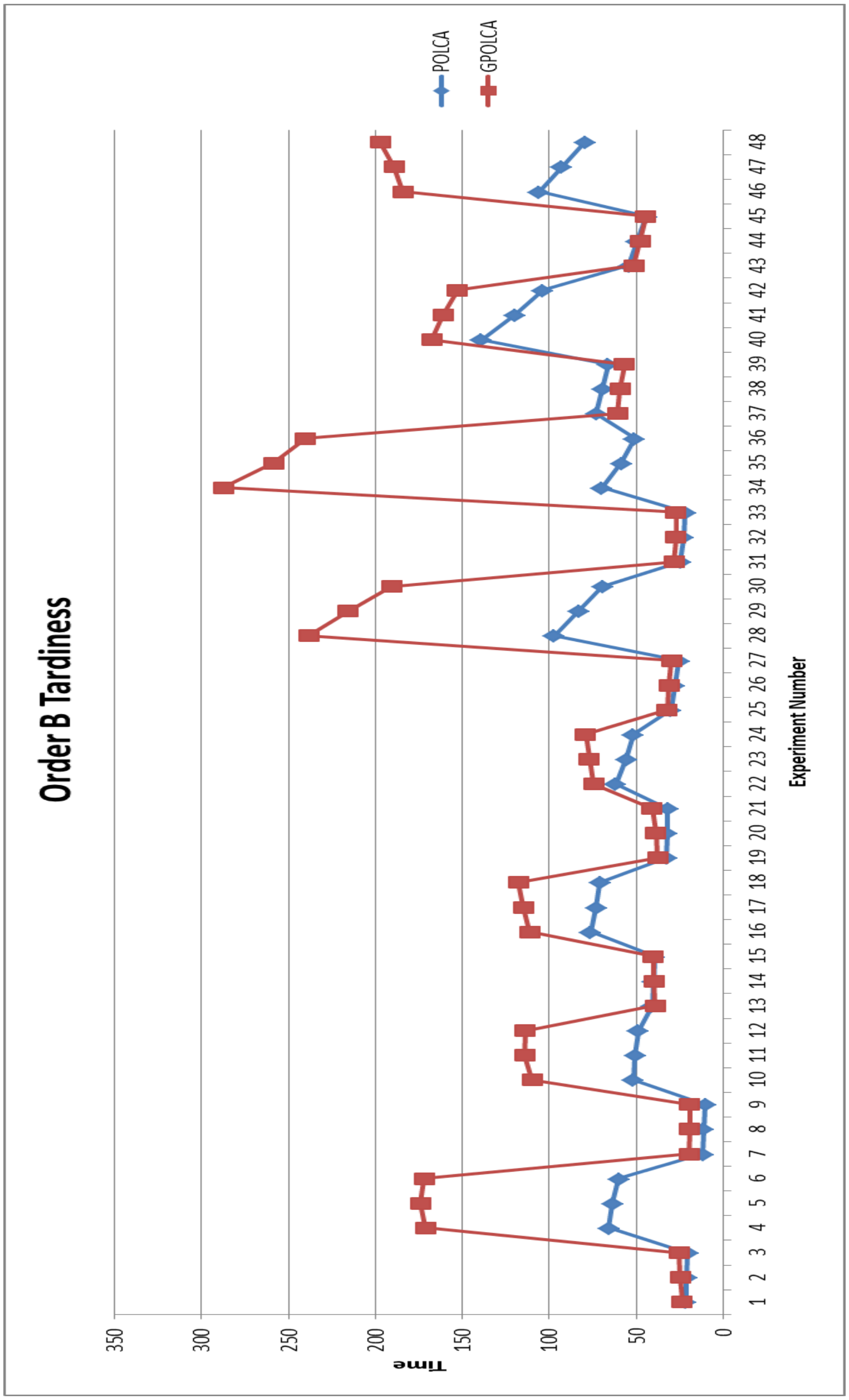

Figure F.2: Average Tardiness of Product B in POLCA and GPOLCA material control strategies

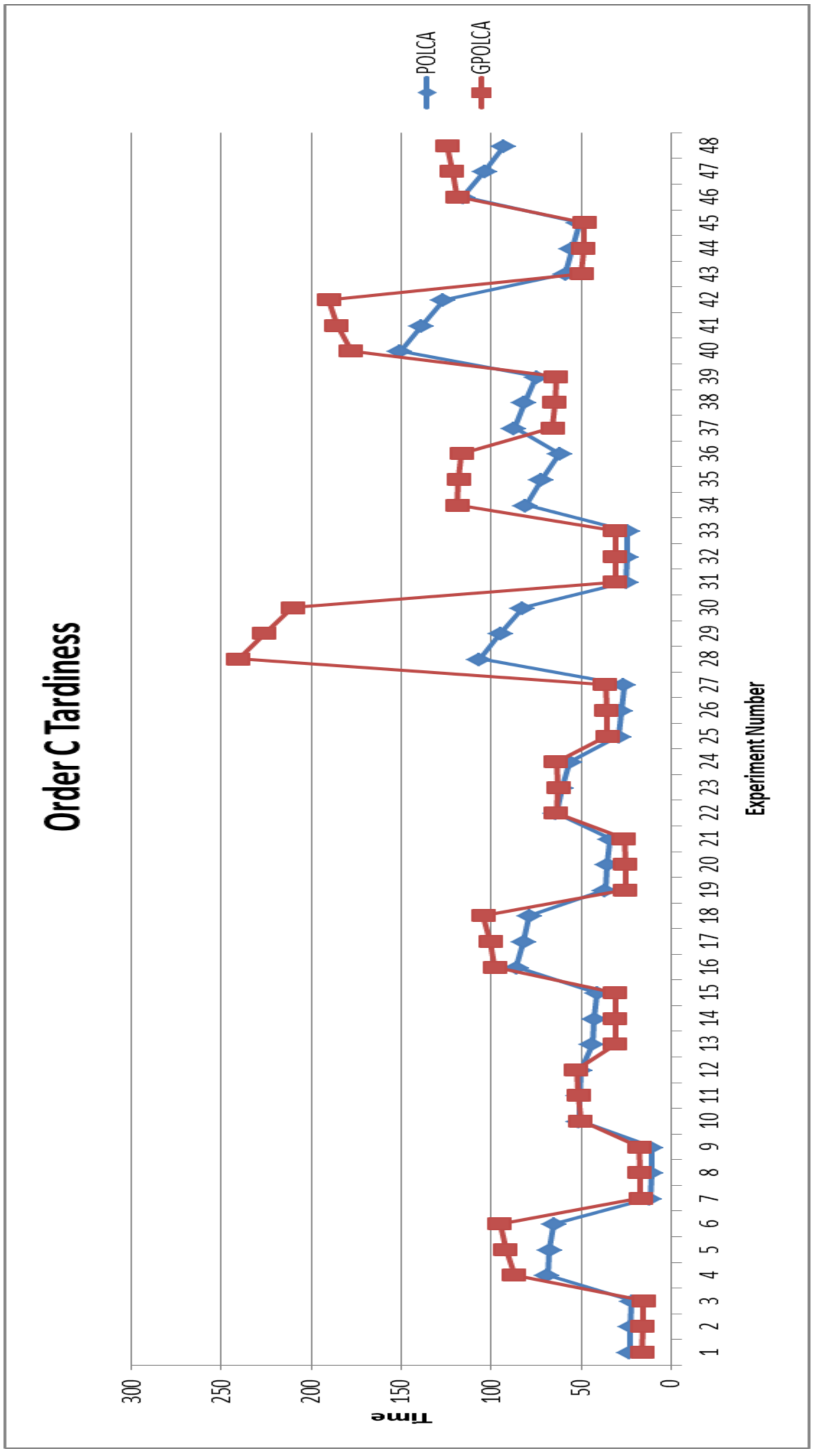

Figure F.3: Average Tardiness of Product C in POLCA and GPOLCA material control strategies

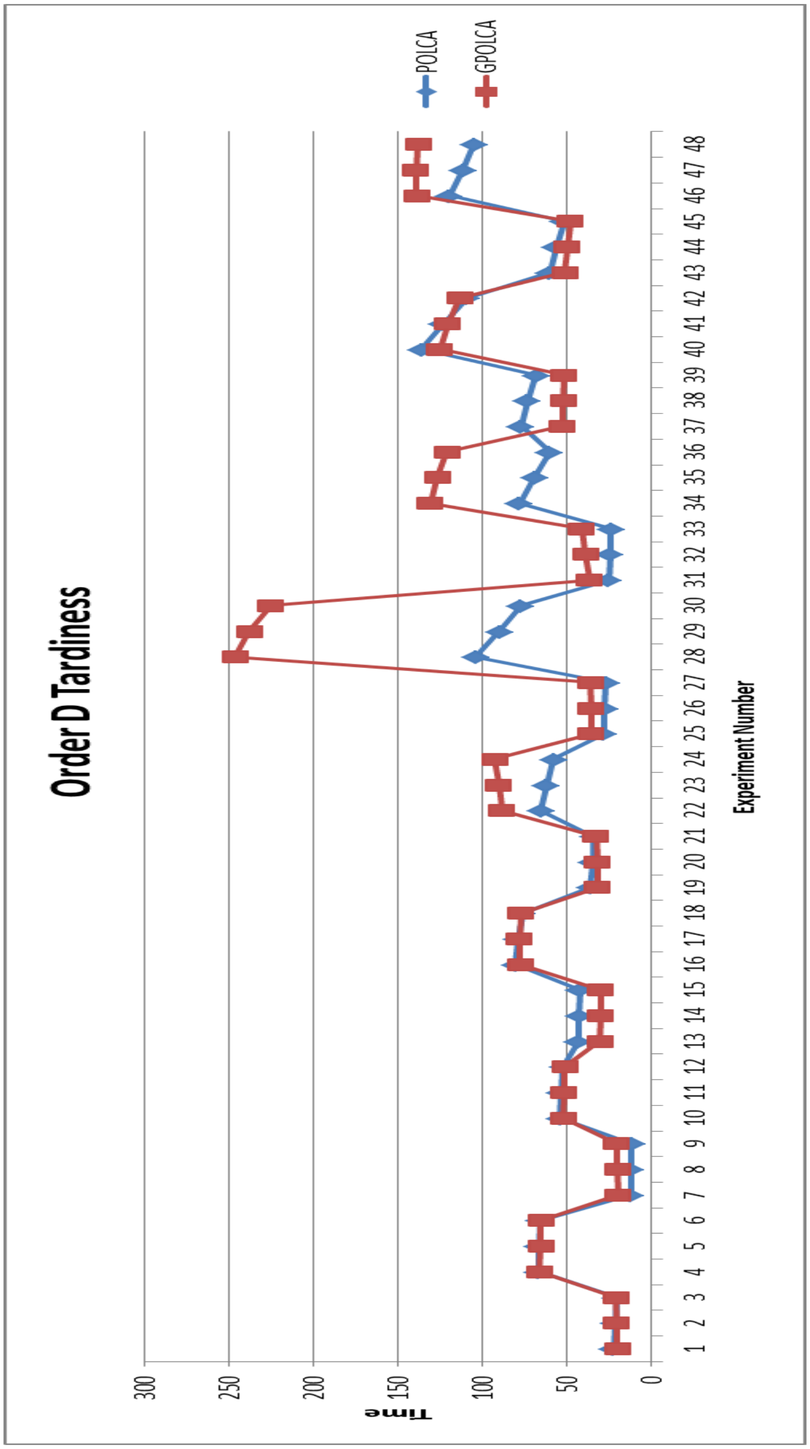

Figure F.4: Average Tardiness of Product D in POLCA and GPOLCA material control strategies

VITA

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