A Simulation Study of Kanban Levels for Assembly Lines and Systems

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved November 2011 by the
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ARIZONA STATE UNIVERSITY

August 2012

ABSTRACT

In the entire supply chain, demand planning is one of the crucial aspects of the production planning process. If the demand is not estimated accurately, then it causes revenue loss. Past research has shown forecasting can be used to help the demand planning process for production. However, accurate forecasting from historical data is difficult in today's complex volatile market. Also it is not the only factor that influences the demand planning. Factors, namely, Consumer's shifting interest and buying power also influence the future demand. Hence, this research study focuses on Just-In-Time (JIT) philosophy using a pull control strategy implemented with a Kanban control system to control the inventory flow. Two different product structures, serial product structure and assembly product structure, are considered for this research. Three different methods: the Toyota Production System model, a histogram model and a cost minimization model, have been used to find the number of kanbans that was used in a computer simulated Just-In-Time Kanban System. The simulation model was built to execute the designed scenarios for both the serial and assembly product structure. A test was performed to check the significance effects of various factors on system performance. Results of all three methods were collected and compared to indicate which method provides the most effective way to determine number of kanbans at various conditions. It was inferred that histogram model and cost minimization models are more accurate in calculating the required kanbans for various manufacturing conditions. Method-1 fails to adjust the kanbans when the backordered cost increases or when product structure changes. Among the product structures, serial product structures proved to be effective when Method-2 or Method-3 is used to calculate the kanban numbers for the system. The experimental result data also indicated that the lower container capacity collects more backorders in the system, which increases the inventory cost, than the high container capacity for both serial and assembly product structures.

This research work is dedicated to my father Purna Chandra Sahu. His instructed virtues and values made me the person that I am today.

May his soul rest in peace.

ACKNOWLEDGMENTS

I owe a great deal of gratitude towards my thesis committee Co-Chairs Dr. Ronald Askin and Dr. Dan Shunk for their continuous guidance and support throughout this research study. Their regular supervision and intellectual support provided a significant platform to build this thesis. Without their timely comments and suggestions the quality of this work would not have been enhanced. I would like to convey my special thanks to Dr. John Fowler for serving in my committee.

It is a pleasure to thank Mr Brinton MacMillan for helping me to keep my laptop virus free and working during the research work. I am also thankful to my graduate advisor, Araxi Hovhannessian, for her support, inspiration and guidance throughout my graduate study. I would like to express thanks to Adrian Ramirez Nafarrate for providing a great deal of insight to the Arena Simulation Software. I am indebted to all my friends for their help, and encouragement directly or indirectly during this work.

Besides, I would also like to thank my husband Ashish Khandelwal, mother Parvati Devi Sahu, my siblings: Prasant Kumar Sahu, Pradeep Kumar Sahu, Prabhati Sahu, Pranab Kumar Sahu & my in-laws: Balabhadra Khandelwal and Krishna Khandelwal for their everlasting love, motivation and support throughout. Without their unconditional love and support, It would have not been possible for me to come this far.

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Chapter 1

INTRODUCTION

Background

Just-In-Time (JIT) Philosophy. JIT is an inventory strategy which aims to improve Return on Investment (ROI) by reducing the work-in-process inventories. JIT emphasizes achieving zero inventories, zero defects, and zero queues. As its name suggests, the items are being pulled/processed only when they are needed. Hence, it does not emphasize maintaining large inventories. It is an attempt to supply the right amount of the required item in the correct place at a precise time.

The Just-In-Time (JIT) manufacturing system was developed by Taiichi Ohno (Kumar & Panneerselvam, 2007). It is also known as Toyota Production System. JIT manufacturing systems are similar to lean manufacturing. Its primary goal is to continuously reduce and ultimately eliminate waste in the system (Kumar & Panneerselvam, 2007). The Just-In-Time manufacturing system is found to be effective due to the following reasons:

1. It increases the productivity of the chain by reducing lead time.
2. It increases the performance of the chain by reducing scrap and re-work.
3. It increases the product quality while saving cost. The reduced inventories lead to huge cost savings.

Since the 1980’s, the Just-In-Time approach has triggered various pull production systems which enable reacting to the actual demand instead of anticipated forecasted demand. However, JIT is suitable for repetitive manufacturing (Akturk & Erhun, 1999). If the demand cannot be predicted accurately and product variety cannot be constrained, it may not be possible to implement JIT effectively. This means, the final assembly schedule and capacity must be leveled and stable for a traditional JIT implementation to succeed (Akturk & Erhun, 1999).

Problem Statement

In the entire supply chain network, demand planning is one of the important aspects of the planning process. In case future demand is over estimated, the remaining products will be wasted, which eventually leads to revenue loss. On the other hand, if the future demand is under estimated, then the customers demand cannot be met, indicating loss of revenue. Hence, alignment of the supply with the future demand is very important. However, forecasting the future demand by analyzing the historical demand is not an easy task. Statistics reveal that most forecasting involves around 11% to 28% forecasting error and it is typically around 50% at the stock-keeping unit (SKU) and location level (Kinaxis, 2006). The above statistics hold well only when the market behaves in a similar fashion. It is very unlikely that the market stays predictable. Since an organization’s performance depends upon its demand planning, analyzing various methods to improve the inventory flow will significantly contribute in indentifying major loopholes in demand planning.

Research Scope

Among all the pull production systems, the Kanban system is the easiest Pull system to implement. It is also the most popular among all the pull systems for repetitive manufacturing environment (Kumar & Panneerselvam, 2007). This system contains one parameter per stage, i.e. number of kanbans, for each type of product. The number of kanbans helps to limit the maximum level of work-in-process (WIP) and the number of finished parts of a stage. Although most work in the literature has been done on Kanban systems, few simulation studies exist comparing various product structures for multi-line, multi-stage production lines. This thesis tries to analyze both serial and assembly structures for the multi-line, multi-stage production system by building a simulation model for a product type. Most research has been done on either multi line or on multi stage production systems. With growing globalization and a collaboration work environment, more complexities are being added to the system and multi-line multi-stage production environment needs further attention. There are many ways in which a system can be analyzed; however, system simulation provides a more accurate and dynamic way for analysis, which aids decision making.

Research Objectives

This section describes some of the questions this research is trying to address at various demand conditions:

1. What is the effective container size for a particular system?

2. What is the effective method to select the number of kanbans for the system?
3. What is the relationship between system utilization and customer order fulfillment time?
4. What is the effective system structure between serial and assembly product structure?

Research Methodology

In recent times, there has been extensive research on the demand planning aspect of supply chain management. Most of the research focuses on demand forecasting. Usage of historical sales data for forecasting is the most common phenomenon to plan the future demand. Most research states demand planning as forecasting, and it could possibly be misleading to the reader. Though better forecasting leads to better demand planning, it is not the only component which influences demand planning. Other variable factors like the consumer's buying capacity or their shifting interest also affect the planning phase.

Alignment of demand and supply by forecasting the historical data is difficult in today's complex, volatile market. However, focusing on strategic planning methods like inventory planning, lead-time reduction, consumer and retailer-centric demand planning would help to improve the demand planning processes. Hence, this research focuses on inventory planning by determining effective number of kanbans. The key to this approach is to minimize the order cycle time and the inventory cost. Three different methods have been used in this study to calculate the optimal number of kanbans in the system. They are: 1. Toyota Kanban Formula by Toyota Production Systems, 2. Histogram model proposed by Rees et al (1987), and 3. Cost minimization model proposed by Askin et al. (1993). The details on each method are available in Chapter-4, under the section: “Methods used to determine the number of kanbans”. The simulation model has been used as an instrument to analyze the JIT Kanban system for both serial and assembly product structure in order to achieve the research objectives.

Overview of the Document

This chapter provides an introduction to the topic of research and the concept of Just-In-Time philosophy. It defines the problem statement and the need for study. Finally, it discusses the scope and the objective of the current study.

Chapter-2 focuses on literature review. It introduces the various Pull systems that exists today, and focuses mainly on the literatures of Kanban systems. It also discusses the literatures on various modeling methodologies, such as Simulation, Deterministic, and Stochastic, to improve productivity of the kanban system. At the end, the benefits of kanban system have been discussed and a comparison study has been performed to provide a guideline on the methods that were used in the previous studies.

Chapter-3 describes the model used in the study. It introduces the assumptions that were made during the study of the system. Various variables, attributes that are used to build the system have been well defined. Finally, it focuses on verification and validation of the model.

Chapter-4 focuses on the research procedure, and details the research plan and methodology used in this research. It also explains the experiments that are designed for the study. It elaborates on the procedure that was used to conduct the research and finally discusses results of the study.

Chapter-5 is the final chapter of this thesis. This chapter outlines the conclusion of research and makes recommendations for future research based on the conclusion.

Chapter 2

LITERATURE REVIEW

Introduction

Japanese manufacturing techniques are popular across the world for their efficiency and effectiveness. There has been extensive literature written on the high productivity and efficiency of Japanese industry and the high quality of its products. Apart from their correct implementation, other factors such as social structure of Japanese society, their management style, and labor laws played an important role in making it possible (Cole, 1980; Hayes, 1981; Pascal, 1989). Their techniques have been in focus in the United States (Lee & Zipkin, 1992; Uzsoy & Martin-Vega, 1990). Japanese's Toyota Production System was a revolution and it introduced the Just-In-Time philosophy to the manufacturing world.

There is an enormous amount of literature already written on push and pull control systems. This chapter gives a brief overview of push system and its disadvantages, and provides the introduction to various pull system. However, the chapter mainly focuses on the systems that have used kanbans or authorizations cards in manufacturing systems. It will also review the methods that were used to analyze and improve the performance of the kanban systems.

Push Versus Pull systems

Push Systems. The Push Production System is a traditional manufacturing system. It schedules periodic release of raw material to the production line, attempting to match production to anticipated demand. Once a job is completed in a station, it is pushed to the succeeding station for further processing, and ultimately the job is pushed to the market. Demand forecasting plays an important role in this system. The actual demand often changes, and in order to meet it, the job deviates from its schedule and accumulates a lot of work-in-process inventory. Hence, the system encourages queues to cushion operations, and to increase work station utilization, but at a higher cost. If the forecasted demand matches the actual demand, which is highly unlikely, it would prove to be effective by reducing the throughput. In other words, the push production system maintains sufficient inventory in order to shorten the lead time. However, in most cases, the efficiency suffers due to the high probability of demand forecast errors. Since the system involves high inventory carrying cost, the Inventory cost goes up when the forecasted demand does not meet the actual demand. Spearman *et al.* (2000) have stated many advantages of pull systems over push systems (Hopp & Spearman, 2000; Spearman, Woodruff, & Hopp, 1990; Spearman & Zazanis, 1992). A schematic representation of the Push system is shown in Figure 1.

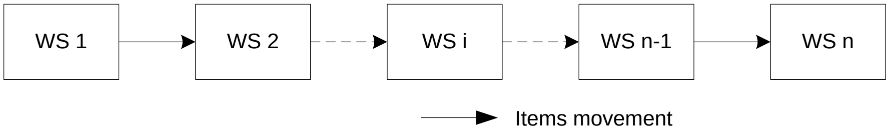


Figure 1. Push System

Pull Systems. In Pull production systems, a station starts processing only after it receives a request from a succeeding station. In other words, the job is pulled by the succeeding workstation instead of being pushed by its preceding work station. This system is totally demand driven and more robust in setting operating parameters. It can also adapt to demand changes if the basic rules are applied to adjust the production order and number of kanbans (Askin & Goldberg, 2002). A schematic view of the pull system is shown in Figure 2.

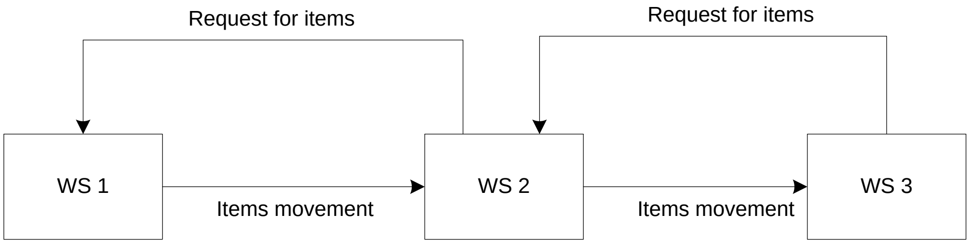


Figure 2. Pull System

Various Pull Systems:

A pull system can be implemented in several ways such as: Kanban Control System (KCS), Base Stock Control System (BSCS), and Constant Work-In-Process inventory system (CONWIP). The best known is Kanban Control System (Moden, 1983).

1. Kanban Control Systems (KCS). The most popular pull system is the Kanban System (KCS) (Monden 1983, Ohno 1988, Shingo 1989, Rees *et al.*

1987, Philipoom *et al*. 1987, and Berkley 1992). The Kanban control was originally used in Toyota production lines in the mid-seventies, and is often considered to be closely associated with the Just-In-Time philosophy (Zipkin 1991, Groenvelt 1993, Dallery et al 1997). In the Kanban control system, the production authorization cards, known as Kanban in Japanese, are used to control and to limit the release of parts into each stage of the production line. The advantage of this mechanism is that the number of parts in every stage is limited by the number of kanbans of that stage. If this philosophy is implemented, it’s controlled and reduced in-process inventory helps to achieve potential cost savings. A disadvantage of the system is that the system, especially in the upstream stages, may not respond quickly enough to the changes in the demand. The Kanban Control System (KCS) can be a ‘single-card system’ or a ‘two-card system’ (Kumar *et al*. 2005).

1.a) Single-Card Kanban System. This system operates by a card called Production Order Kanban (POK). If the distance between two workstations is small, a single buffer is used between the stations. This buffer works as an outbound buffer for the current station and an inbound buffer for the succeeding station (Kimura et al, 1981). When a station receives a demand, the Production Order Kanban is prepared, and sent to the Input buffer to pull the part. Once the POK is received by the Input Buffer, it is immediately sent to the previous work station. This station processes the POK and sends it back to the output buffer of the station. Finally, the part is sent to the succeeding station where the demand was originated. In a single card Kanban system, both output buffer of the current station and input buffer of the succeeding station are the same (Kumar *et al*. 2005). A schematic view of the single card kanban system is shown in figure below.

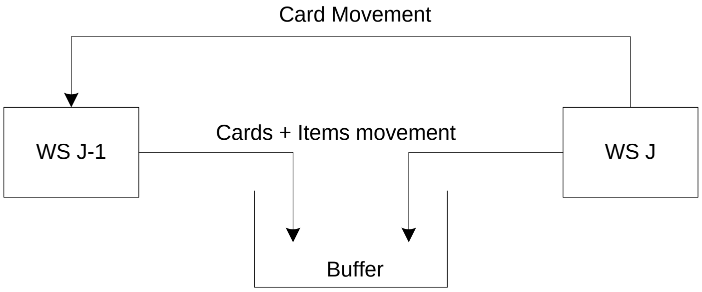


Figure 3. Single Card Kanban System

1.b) Two-Card Kanban System. This system operates by two different cards. One is them is the Production Order Kanban (POK) and the other is the Withdrawal Kanban (WK). The Production Order Kanban instructs the preceding station to send the required items. The Withdrawal Kanban sends a message to the succeeding station indicating the number of units to be withdrawn. A schematic view of the two-card kanban is shown in Figure 4.

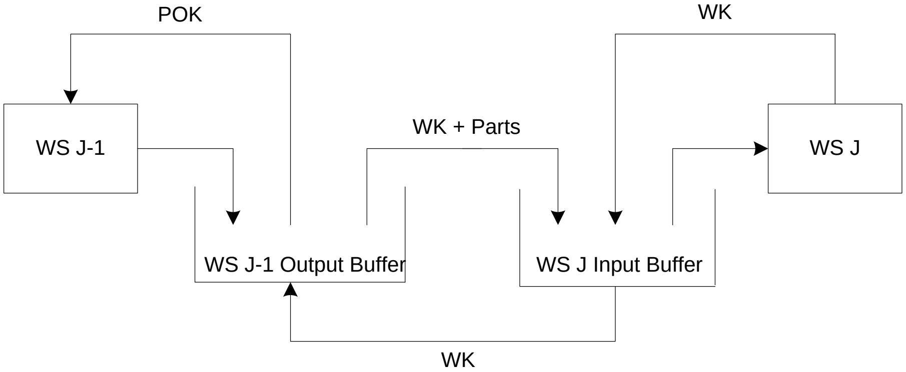


Figure 4. Two-Card Kanban System

The following steps illustrate how a two-card kanban system works:

1. When Station J extracts parts from its input buffer, it sends the empty containers with the withdrawal kanban (WK) to Station J-1 and the empty containers are placed in its outbound buffer.
2. If the containers are available,
    - POK is removed and placed on the POK post of Station J and the production starts as per the production order.
    - WK is added to the full container and it is moved to the input buffer of Station-J.
3. If the parts are not available, the station will wait for parts.
4. Station J-1 delivers the parts to inbound buffer of Station-J with WK attached. WK is finally placed in WK-post of the station- J.

2. Base Stock Control System (BSCS). Base Stock policy originated from inventory control techniques (Clark & Scarf, 1960; Geraghty & Heavey, 2004). This system is easy to implement like the Kanban systems (Duri, Frein, & Mascolo, 2000). This type of system is very reactive and efficiently driven by the parameter: number of finished parts in a stage. This system was initially proposed for production systems with infinite production capacity, and uses the idea of a safety stock for finished goods inventory as well as safety buffers between stages for coordination. This means, every stage has a target inventory of finished parts, known as the base stock. When a demand for an end item arrives, it is immediately transmitted to every stage to authorize the release of a new part. A queuing network of the Base Stock system, made up of three stages in series, is shown in Figure 5 (Duri, Frein, & Mascolo, 2000). In the figure, each process is represented by MP_i and the links between the stages are modeled by a station at the output of each stage. The station consists of two queues, one contains the finished parts of the stage (P_i), and the other contains the demand for products from the next stage (A_{i+1}). An advantage of this mechanism over kanban is that it avoids demand information blockage by transferring the demand information immediately to all production stages.

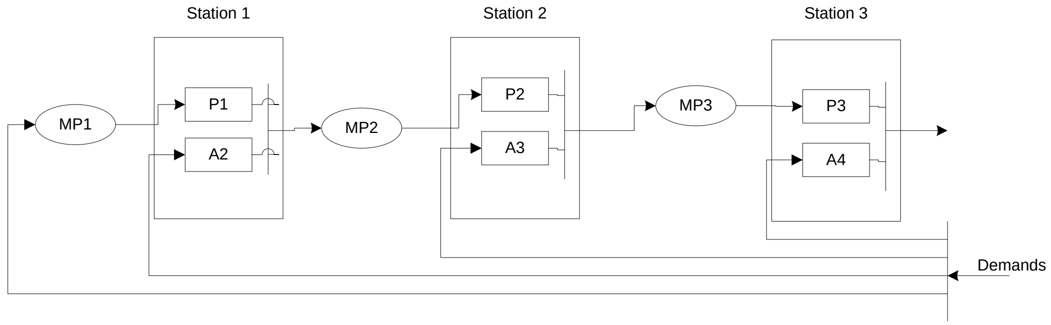


Figure 5. Base Stock Control System

3. Constant Work-In-Process Control System (CONWIP). The Constant Work-In-Process (CONWIP) control system was proposed by Spearman *et al.* (1990), and the system uses a single card type to control the total amount of WIP permitted in the entire line (Spearman et al., 1990). It can also be viewed as a single stage Kanban system. The CONWIP control system can be considered as a combination of pull and push system. It acts as a pull system at the end of the line, or a push system from the beginning of the line. Therefore, these systems can suffer from the problems that are associated with traditional push systems.

Hybrid Pull systems

Every pull system has its pros and cons. Hybrid systems are designed by combining the advantages of two or more pull systems. Following is a brief summary about hybrid pull systems: The hybrid systems are: 1. Generalized Kanban systems, 2. Extended Kanban Systems, 3. CONWIP Kanban systems and 4. Extended CONWIP Kanban systems.

1. Generalized Kanban Systems. These systems were proposed by Buzacott (Buzacott, 1989) and are basically designed for non-repetitive manufacturing systems (Junior & Filho, 2010). It includes the Kanban and Base Stock control system as special cases. Base stock systems react quickly to the demand and the Kanban system achieves better coordination in work-in-process inventories. Hence, a system combining respective merits of Base Stock and Kanban control systems leads to potential benefits. Unlike the Kanban and Base Stock systems, the Generalized Kanban control system depends on two parameters per stage, 1. Number of kanbans, 2. The amount of base stock of finished parts. These parameters help to limit the WIP and to avoid the demand information blockage. A generalized kanban system is more versatile than Base stock and Kanban systems. However, it is more complex than the other two. The complexity is due to the fact that demand information flow is communicated upstream rather than direct transfer of information upon demand arrival. The simulation study has shown that a generalized Kanban System is better than Kanban systems in dynamic environments (Junior & Filho, 2010). A queuing network of a generalized kanban system is shown in Figure 6 (Duri, Frein, & Mascolo, 2000).

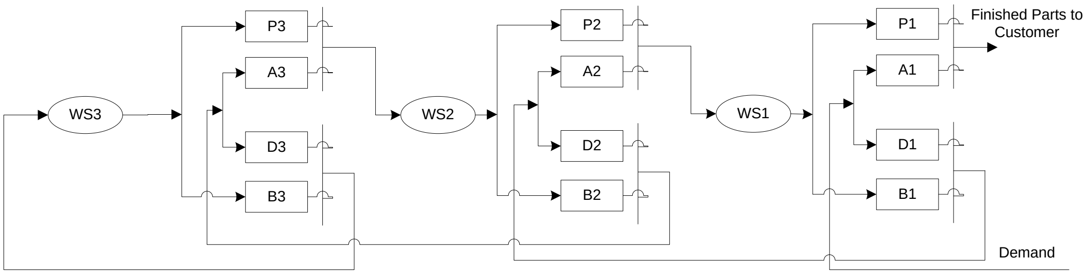


Figure 6. Generalized Kanban Systems

2. Extended Kanban Systems. The system is proposed by Dallery and Liberopoulos (Dallery & Liberopoulos, 2000), which is also a combination of base stock and kanban systems. The system is also controlled by two parameters, similar to base stock control system. However, there is a difference in the demand information sharing in both the systems. In the extended kanban control system, demand information is directly transferred to every stage using global demand flow, similar to the Base Stock system. Unlike the Generalized Kanban System, the roles of base stock and kanban are completely separated due to the global demand flow. Thus, an Extended Kanban Control System is conceptually less complicated than a Generalized Kanban control system, and also easier to implement. However, one drawback of Extended Kanban compared with Generalized Kanban is that it requires the amount of kanbans to be at least as large as the base stock level, which limits its configuration flexibility. A queuing network of an extended kanban system is shown in figure below.

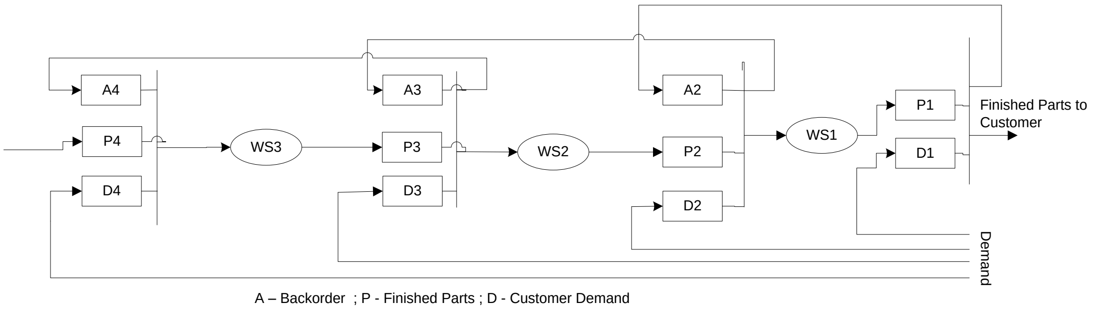


Figure 7. Extended Kanban System

3. CONWIP Kanban System. Bonvik *et al*. (1996) proposed another hybrid system, known as CONWIP Kanban control system (Bovnik, Couch, & Gershwin, 1996). This control system combines the local work-in-process control mechanism using kanbans and global inventory control using CONWIPs. Demand information is propagated directly using the CONWIP mechanism. Numerical experiments have shown that these systems are close to optimal for a two-stage production system.

4. Extended CONWIP Kanban Systems. This system is proposed by Boonlertvanich (Boonlertvanich, 2005), and is a superposition of Kanban, Base Stock and CONWIP control systems. Demand information is transferred by both the CONWIP mechanism and the global demand flow mechanism. However, the system is complex and not as easy to implement as other pull systems.

Paired Cell Overlapping Loop of Cards with authorization (POLCA)

In late 1990's, Suri came up with a new concept of POLCA which is neither Push nor Pull. He challenged to think beyond the Toyota production system and researched on the new emerging market strategy called POLCA. It maintains a constant WIP level between two stations similar to CONWIP systems. Whenever a part is released from a station, it requires an appropriate kanban card as well as an authorization card. The system assumes that the factory has been partitioned into non-overlapping manufacturing cells. POLCA achieves a better trade-off between WIP and throughput time, as compared to other pull systems (Suri, 1998).

Literature on Kanban Systems

As discussed, extensive research has been done on various pull systems and their frameworks. Their studies have shown that a particular type of pull system is suitable only for a particular production environment. Kanban Systems have proven to be very stable and effective for a single product type manufacturing environment. Thus, the kanban system is suitable for repetitive manufacturing systems.

Majority of the published research is focused on finding the number of kanbans to optimize performance, comparison of various kanban systems, and modeling of Kanban systems in environments that are heavily repetitive in nature. There have been many attempts to make the kanban system more effective and efficient. Moden (1983) had stated that number of kanbans should be minimized, under the assumption that the number between two adjacent stations represents the maximum inventory level and, therefore, should be kept to a minimum (Moden, 1983). Later, Rees et al. specifically addressed the problem of determination of number of kanbans for a variety of production configurations.

Philipoom et al. (1987) developed a simulation analysis to show how major factors, such as machine utilization rate, variation in processing time etc., affects the number of kanbans. They assumed the demand rate to be relatively constant (Philipoom, Rees, Taylor III, & Huang, 1987).

Rees et al. (1987) considered the problem under a dynamically varying production environment and proposed a heuristic for adjusting the number of kanbans periodically using estimated values of lead time (Rees, Philipoom, Taylor III, & Huang, 1987). Gupta et al. (1989) built a two-line, three-stage dual kanban system and investigated using system-dynamic concepts. The behavior of the system was analyzed by the following levels: 1.decreasing the number of kanbans in the system, 2. decreasing the size of the containers, and 3. increasing the size of the containers and decreasing the number of kanbans. A tradeoff between increased inventory carrying costs and overtime cost was determined, but no specific information was proposed (Gupta & Gupta, 1989).

Bitran and Chang (1987) proposed a mathematical programming approach to a deterministic kanban system using a discrete period collection assumption. The cost function used as a basis of the optimization procedure represents the sum of material and labor. Other manufacturing costs, such as shortage and setup costs, have been neither specified nor ignored. The authors have, however, questioned large-sized and partially filled containers at various stages of production (Bitran & Chang, 1987). A critical and comprehensive survey of models related to kanban-based demand pull systems has been provided by Uzsoy and Martin-Vega (Uzsoy & Martin-Vega, 1990). They observed that the three main approaches to modeling, i.e., simulation, deterministic and stochastic methods, gave broadly similar results for the simple systems modeled to date.

Benefits of Kanban Systems:

The benefits of kanban systems have been described by many authors (Buzacott, 1989; Chan, 2001; Duri et al., 2000; Huang, Rees, & Taylor III, 1983; Kumar & Panneerselvam, 2007; Sohal, 1989). Following are some of the benefits:

1. Inventory is controlled by the number of kanbans. Hence, there is no scope of over production or increase in WIP.
2. Low WIP leads to reduction of lead time as a function of Little’s law i.e. Lead time = WIP / Throughput.
3. Low inventory level frees up a lot of space in the inventory for other purposes, and also reduces the inventory carrying cost.
4. Transfer of defective parts to the next stage is prevented, resulting in better quality production in lesser time.
5. Production problems are prominent due to kanbans in the system.
6. Communication between stages is improved, which helps sending feedback faster. The quicker feedback system aids quality production.
7. Repetitive production makes it easier to identify opportunities for improvement.

Modeling of Kanban Systems:

The modeling of kanban systems has been divided into three different categories, namely, 1. Simulation Models, 2. Deterministic Models, and 3. Stochastic Models.

Simulation models. The simulation models have been used to explore the relationship between different system parameters on the performance of Kanban systems as well as optimization of performance measures. The factors that are usually examined include: line imbalances, variability in process time and demand, station utilization, number & size of kanban. Some of the performance measures studied includes WIP levels, backorder levels, utilization, and throughput (Kumar & Panneerselvam, 2007; Uzsoy & Martin-Vega, 1990). There are many simulation softwares available to carry out the research, such as: SLAM-II, SIMAN, ARENA, SIMULINK, Q-GERT, GPSS etc.

Huang *et al.* (1983) developed a simulation of a kanban system that was based on a Q-GERT model (Huang et al., 1983). They concluded that environmental changes are necessary for implementation of kanban systems to US manufacturing. Rudi De Smet et al. (1998) developed a simulation model to study feasibility of plans to produce some subparts of the product in a kanban-controlled manner to determine parameters such as number of kanban and kanban size. This feasibility study was carried out in two simulations: 1. All subparts were produced in a kanban controlled manner, 2. Only the productions of fast moving parts on two of the machines were kanban controlled. Results showed that kanban control is the best method for fast moving parts (De Smet & Gelders, 1998). Fallon et al.

(1987) made a comparison study of performances of the simulation models based on the JIT philosophy and Material Requirement Planning (MRP) schedules. They used SLAM (Simulation Language for Alternate Modeling) to build the model. Their study shows that the JIT model performs better than the MRP model. They built an EOQ (Economic Order Quantity) Model to show how reduction of set up time reduces the inventory cost (Fallon & Browne, 1987). Philipoom *et al* (1987) developed an optimization model which solved the problem of number of kanbans, container size, and product sequence in a JIT environment with kanbans (Philipoom et al., 1987).

Deterministic models. Bitran *et al.* (1987) designed an optimization model for the kanban system by using nonlinear integer formula to set the number of kanbans in an assembly product structure environment. Their objective function was set to minimize the total number of kanbans in the system, and used number of kanbans per stage per period as decision variables. In order to control the level of inventory by determining the number of kanbans used at each stage, they converted the nonlinear model to a linear model with deterministic demand (Bitran & Chang, 1987).

Philipoom et al. (1990) used a mathematical programming approach to determine the optimal lot sizes while using a single kanban. They used special a type of single kanban at the work stations which had relatively high set up time as an alternative to JIT Technique. However, this approach was unable to reduce set-up times at all workstations (Philipoom, Rees, Taylor III, & Huang, 1990). Extensive research has been done in the past to show how variability in demand can affect the upstream stages. It has been noted that a small fluctuation in demand at the final stage can be amplified into a much larger fluctuation at earlier stages.

Stochastic models. Deleersnyder et al. (1989) used a discrete time Markovian chain to study the effect of number of kanbans, machine reliability, processing time and demand variability (Deleersnyder, Hodgson, Muller, & O'Grady, 1989). Askin et al. (1993) developed a continuous time, steady state Markov model to determine the optimal number of kanbans for each stage, for each part type. The model dynamically calculates and adjusts the safety factor to cope with the foreseen shift of the demand, thus reducing the time required by the JIT system to adapt to the demand change (Askin, Mitwasi, & Goldberg, 1993).

Hurrion (1997) developed a simulation meta model of a Kanban System to find the optimum number of kanbans needed to control the manufacturing system. He first built a simulation model. Using the simulation model results, he then built the neural network meta model to optimize the discrete event stochastic system. The use of a meta model helped in getting a trade-off between the time to find the optimum solution and the accuracy of the result (Hurrion, 1997).

The table created below categorizes the reviewed papers into various modeling methods that were discussed in this chapter.

Table 1

*Classification of *reviewed articles*

Area of Research	Citation of the papers related to the Area of research
Simulation Model Method	(Chu & Shih, 1992; De Smet & Gelders, 1998; Fallon & Browne, 1987; Huang et al., 1983; Singh & Brar, 1992; Starr, 1991; Uzsoy & Martin-Vega, 1990)
Deterministic Model Method	(Bitran & Chang, 1987; Philipoom et al., 1990)
Stochastic Model Method	(Askin et al., 1993; Buzacott, 1989; Hurrion, 1997; Liberopoulos & Dallery, ; Markham, Mathieu, & Wray, 1998; Seki & Hoshino, 1999)

*This is a brief summary of the research in this area. The bibliography contains a more extensive listing.

Conclusion

As it was shown in this brief literature review, Kanban pull systems have been extensively studied. Efforts to develop models of kanban-based pull systems have resulted in considerable insights into their performance in various scenarios. However, extensive research attempts have not been made to expand the above mentioned area of research to include multi-line, multi-stage, and more flexible systems in an environment. In particular, the container capacity, and its relationship to the number of kanbans, needs much attention in pull manufacturing environments. With an increase in the inherent complexity of JIT Kanban systems, previous studies provide evidence that the simulation model approach would offer the most promising approach for system analysis.

Chapter 3

SIMULATION MODEL DESIGN

Purpose of Simulation

Computer simulation is used to study the behavior of real world complex systems by applying computer programs that replicate the system. The simulation model acts as a central element in a manufacturing decision support system which could address a wide range of decisions in planning, operations, and control (Starr, 1991). Computer simulation aids management decision making by allowing one to visualize how a system works, and analyze various configurations and its possible effects before they are implemented. Simulation softwares are becoming very popular over recent decades for their affordability, versatility and ability to deal with complex models of complicated systems. This is one of the primary reasons why simulation was chosen to perform analysis of this research.

Simulation Language

There are many simulation languages used across academia and industry. However, the simulation language ARENA by Rockwell Automation was chosen to accomplish the task for this research.

Simulation Model Logic

Two multi stage production lines were modeled from the instance a customer demand was received to the instance the demand was finally met. The models differed in their product structures. The first model was a serial structure, and the second model was an assembly structure.

Serial Product Structure. Serial Product Structure is the simplest type of product structure. In this structure, material gets transferred from the first stage to the last stage sequentially (Askin & Goldberg, 2002). The model was simulated using five stages, namely, Finished Goods, Assembly unit, Manufacturing, Raw Material, and Supplier. A serial structure of the simulation model is shown in Figure 8.

Model Logic. The customer demand (order) is received by the finished goods unit and it is dispatched immediately if the inventory is available at the finished goods station. If the inventory is not sufficient to fulfill the demand, the demand gets partially fulfilled and waits until the finished goods inventory gets replenished from assembly unit. If the inventory is empty, then the order remains on hold and waits in the queue indefinitely until the inventory gets replenished. Once the inventory is replenished by the previous station, the hold orders are fulfilled by First-In First-Out (FIFO) policy. The replenishment request is sent whenever there are empty containers present in the system. All other stations, such as: Assembly, Manufacturing, Raw Material & Suppliers Unit, react and process the orders from their respective previous stations. The hold queue has infinite capacity and orders sit there indefinitely to get fulfilled. Assembly unit reacts to finished goods station request and sends the empty containers to manufacturing unit for replenishment. Similarly, the raw material unit reacts to manufacturing unit orders and sends the replenishment request to suppliers. The final stage of the system is Suppliers Unit. The whole chain works in the similar fashion. The information is transferred upstream and the materials/parts are transferred downstream. In other words, whenever there is an empty container in the system, it is immediately sent to the previous station for replenishment. Similarly, whenever a container is processed and ready, it is sent to the succeeding station.

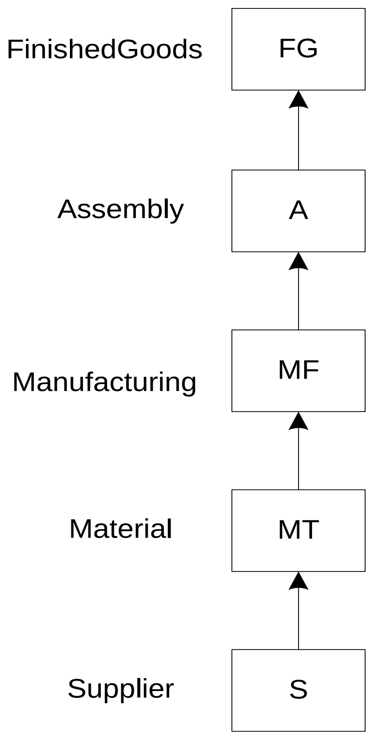


Figure 8. Serial Structure of the Simulated Model

Assembly Product Structure. The second simulation model of the study was an assembly product structure model. The final product was the assembly of more than one part types. The structure of the supply chain is shown in Figure 9.

In this model, each production stage has at most one successor but may have several predecessor stages (Askin & Goldberg, 2002). In the simulation model, the supply chain was comprised of two assembly lines and three stages. The stages were: 1. Finished Goods, 2. Manufacturing & Assembly, and 3. Raw Material. The model is similar to three stage multi-line production system for a product type.

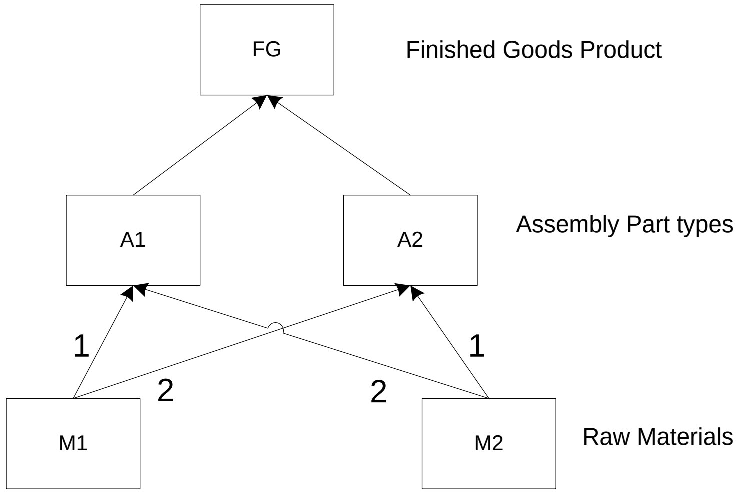


Figure 9. Assembly Structure Model

Model Logic. The finished goods product (FG) is made out of final assembly of two different parts A1 and A2. Assembly part types A1 and A2 are made up of raw materials M1 and M2. A1 comprises of one part of M1 and two parts of M2, while A2 comprises of two part of M1 and one part of M2.

Every workstation of this model has a separate input buffer and output buffer. The finished goods output buffer stores ready-to-go final products, while the assembly output buffer stores the assembled items made up of part type A1 and A2. Similarly, material output buffer stores the ready-to-go material MA1 and

MA2 made up of raw materials M1 and M2 to send to assembly input buffer as raw material to A1 and A2 respectively. The material unit input buffer gets the raw material from the supplier and processes it further to transfer raw materials for its output buffer. This model follows the same logic as the serial structure model logic. Whenever an empty container is found in the system, it is immediately transferred to its previous work station. Once a container is processed and is ready-to-go, it is sent to the succeeding buffer/station immediately for further processing. If the inventory is insufficient to fulfill the order, the order is partially fulfilled and is held in the queue until the inventory is replenished. If the inventory is empty, order is directly routed to the hold queue and waits indefinitely until there is inventory to process the order.

Simulation Model

Both of the Just-In-Time Kanban systems described above, were modeled in ARENA simulation software by using various modules from basic process, advanced transfer, and advanced process. After the model was made error-free and ready to compile, validation was performed in order to use the model as an instrument for experiments. For verification and validation, a hypothetical model was built, the details of which are described at the end of this chapter.

The simulation model works similar to Just-In-Time Kanban system. Figure 10 shows the ARENA simulation flowchart illustrating process logic.

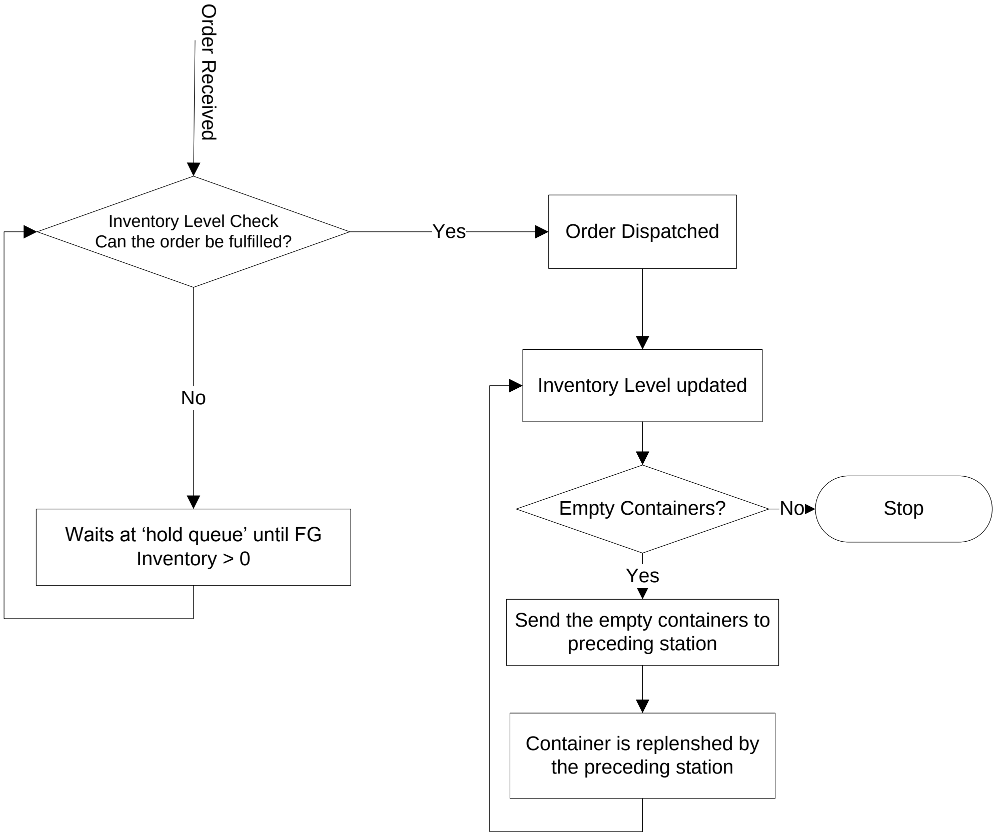


Figure 10. Model Logic Snapshot

The initial inventory capacity is set for every stage. The inventory capacity is the product the number of containers and the container capacity. Whenever there is an empty container in the system, it is sent to previous station for replenishment. When the demand is received by the finished goods, the inventory level is checked immediately to make sure that there is sufficient inventory to fulfill the demand before the order is processed. Once the order is processed, the inventory level is updated. In case the inventory is not sufficient, finished goods partially fulfill the demand by emptying the inventory and direct the updated demand to the hold queue. Once the inventory is replenished by the preceding station, the previously held demands are processed and dispatched.

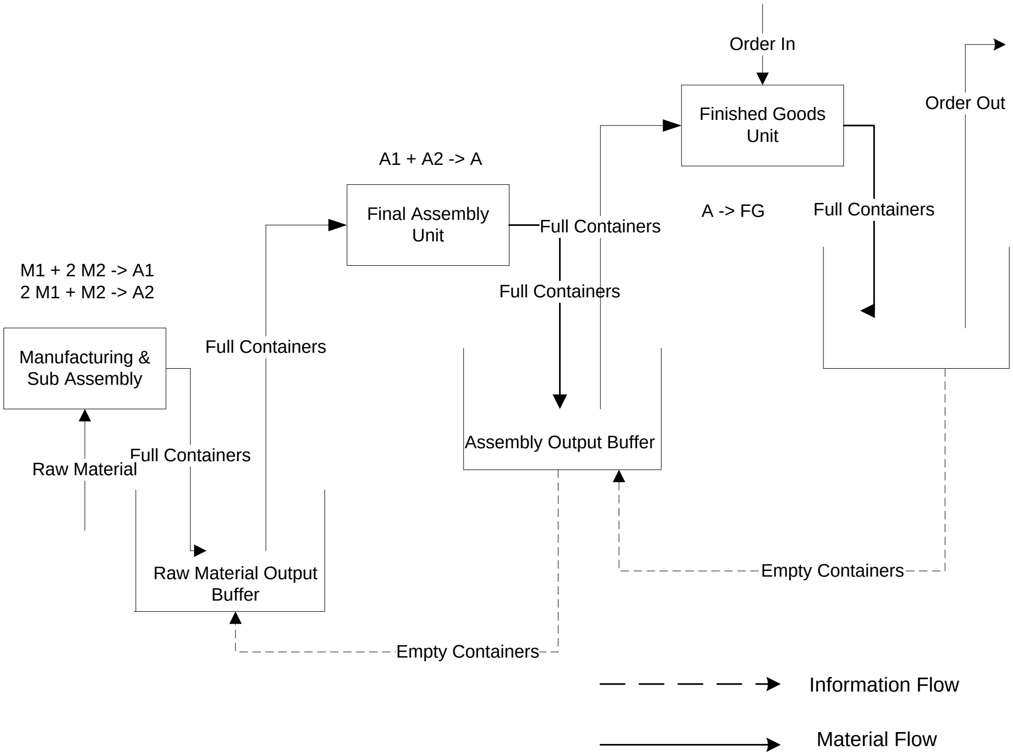


Figure 11. Assembly & manufacturing input buffer logic snapshot

The assembly & manufacturing unit has a fixed capacity for items stored initially in the output buffer. As soon as a container gets emptied in the output buffer, it is sent to the input buffer for replenishment. The input buffer sends the manufactured parts to the output buffer for assembly. If the input buffer does not have enough items to manufacture, it waits until it receives the materials from materials unit. The input buffer manufactures A1 and A2 out of raw material M1 and M2. This process is simulated by using match, hold, and batch module together in a series. If the materials unit container is empty, then material M1 and M2 is processed in the input buffer. In the model, the two subassembly lines run parallel to each other and use the same logic, with the only difference being the variables, entities, and resources specific to each line.

Model Assumptions

The following assumptions were made during construction of the Arena model to simplify its study by reducing the number of variables in the system.

1. Each container has a fixed number of parts.
2. Number of kanbans used is fixed for each stage. All the stages have same number of kanbans when the simulation starts.
3. Information, such as Kanban, is transferred between the stages instantly.
4. Time between demand arrivals (TBA) is exponentially distributed.
5. Demand per time period is constant i.e. one per every time period.
6. Processing of the demands follows first come first serve policy.
7. Service times are deterministic and computed from system utilization and mean arrival rate.
8. The container is sent for replenishment only when it is empty.
9. There is a possibility of starving of raw material in material stations.

Verification & Validation of the model

Verification refers to the process of confirming if the conceptual model was accurately translated into an operational program (Fallon & Browne, 1987). Various animation modules were used while running the simulation step by step to note down each event happening at each unit of time. Simultaneously, the variables were recorded for each stage. After comparing the results from animation with the expected variable values, it was confirmed that the simulation was performing per expectation.

Validation refers to the process of confirming if the conceptual model was applicable or useful by demonstrating an acceptable correspondence between the computational results of the model and the actual data (Fallon & Browne, 1987). To further validate the built models, two hypothetical examples were constructed that transformed the model into a deterministic model. Following is a description of the deterministic model. The expected results for both series and assembly product structures have been summarized in Table 2.

Serial structure validation model. A hypothetical deterministic model was designed for the validation of this model. The model assumed 100% system utilization and the demand rate was 1 per every 10 minutes. The processing time at each stage was 1.5 minutes. The number of kanbans used in the system was 2 per stage. The container size was 5 for finished goods and 10, 15, 20, 25 in the downstream respectively. This means the container size of assembly unit was 10; manufacturing unit was 15, and so on.

The expected results are shown in Table 2, followed by the validation results. At t=0, the inventory of each units were full. After every 10minutes demand for one unit arrives. The first demand of 1 unit arrived at t=10. The demand was fulfilled immediately and balance of FG Inventory went down to 9 units. Gradually at t=50, the FG Inventory went down to 5units leaving behind one empty container. This empty container was sent to Assembly unit as a demand immediately. The assembly unit inventory was unused until this point.

The material was shipped immediately and assembly unit inventory went down to 15 units. This replenishment turnaround time was 10 minutes and at *t*=60, the FG inventory replenished one full containers (5 units) to its inventory. Similarly, all the simulation events were estimated for this model and checked against the expected values. The results are shown in Figure 12. The scenarios were considered to be ‘pass’ when the simulation results matched with the expected results at each stage.

Table 2

Deterministic model for serial structure simulation model

Time	Demand	FG Inventory	Demand A	A Inventory	Demand M	M Inventory	Demand MT	MT Inventory	Demand S	S Inventory	Simulation Result
0	0	10		20		30		40		50	pass
10	1	9									pass
20	1	8									pass
30	1	7									pass
40	1	6									pass
50	1	5	5	15							pass
60	1	10									pass
70	1	9									pass
80	1	8									pass
90	1	7									pass
100	1	6									pass
110	1	5	5	10	10	20					pass
120	1	10		20							pass
170	1	5	5	15							pass
230	1	5	5	10	10	10	15	25			pass
240	1	10		20		25					pass
290	1	5	5	15							pass
350	1	5	5	10	10	15	15	10	20	30	pass

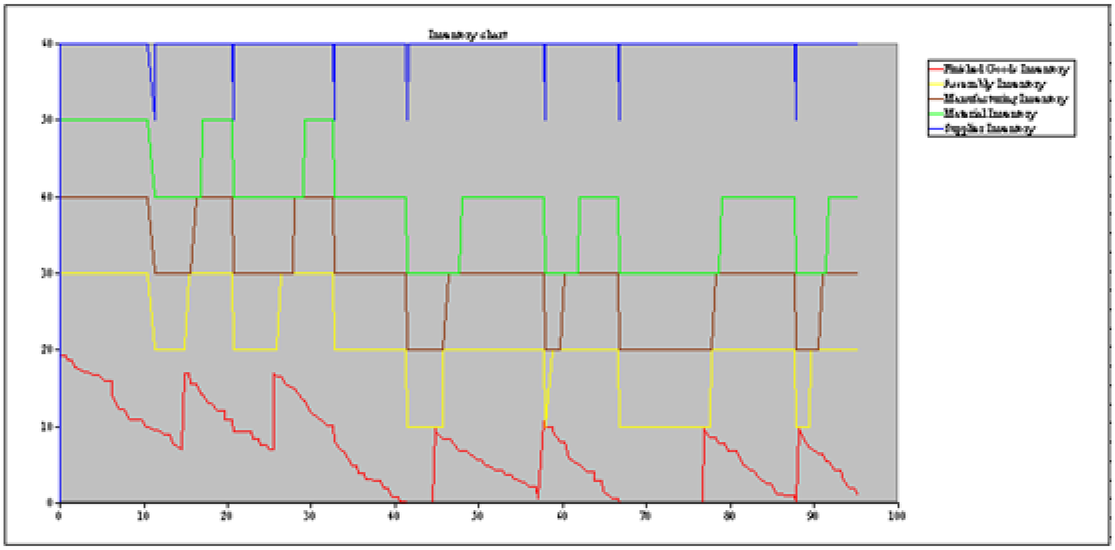


Figure 12. Gantt Chart for serial structure

Assembly structure validation model. Another hypothetical deterministic model was designed to validate this model. It was considered that at 100% system utilization, the demand rate of 1 per every 1.5 minute was received. The processing time of finished goods was 1.5 minutes, processing of assembly and manufacturing input buffer process and output buffer processes were 2.5 minutes and 2 minutes each respectively. Material unit's input and output buffer process had the processing times of 2 minutes and 1.2 minutes each. The time to route the information, or sending the signal between the stages, was negligible. The initial inventories (container capacity x number of kanbans) were 30 for finished goods, 40 and 80 for assembly & manufacturing output buffer, 120 and 200 for material output and input buffer respectively. The numbers of containers used for finished goods and assembly & manufacturing input were three and two respectively. However, four containers were used for other stages of the model.

Table 3

Deterministic model for assembly structure simulation model

Time	Demand	FG Inventory	Demand A	A Inventory	Demand A1	A1 Inventory	Demand A2	A2 Inventory	Demand MA1	MA1 Inventory	Demand M A2	M A2 Inventory	Demand M1	M1 Inventory	Demand M2	M2 Inventory	Simulation Result
0	0	30		40		80		80		90		90		200		200	Pass
1	1	29															Pass
2.5	1	28															Pass
14.5	1	20	10	30													Pass
17		19+10															Pass
17.5	1	28															Pass
29.5	1	20	10	20	20	60	20	60	20	70	20	70					Pass
31.5				20+ 20		60+ 20		60+ 20									Pass
32		19+ 10		40		80		80									Pass
32.5	1	28															Pass
44.5	1	20	10														Pass
46	1	19		30													Pass
47		19+ 10															Pass

Time	Demand	FG Inventory	Demand A	A Inventory	Demand A1	A1 Inventory	Demand A2	A2 Inventory	Demand MA1	MA1 Inventory	Demand M A2	M A2 Inventory	Demand M1	M1 Inventory	Demand M2	M2 Inventory	Simulation Result
47.5	1	28															Pass
62.5	1	20	10	20	20	60	20	60	20	50	20	50	30	170	30	170	Pass
63.5										50 + 30		50 + 30					Pass
64	1	19								80		80					Pass
64.5				20 + 20		60 + 20		60 + 20									Pass
65		19 + 10		40		80		80									Pass
77.5	1	20	10														Pass
79	1	19		30													Pass
80		19 + 10															Pass
95.5	1	20	10	20	20	60	20	60	20	60	20	60	30	140	30	140	Pass
96.5										50 + 30		50 + 30					Pass
97	1	19								90		90					Pass
97.5				20 + 20		60 + 20		60 + 20									Pass
98		19 + 10		40		80		80									Pass
100	1	27															Pass

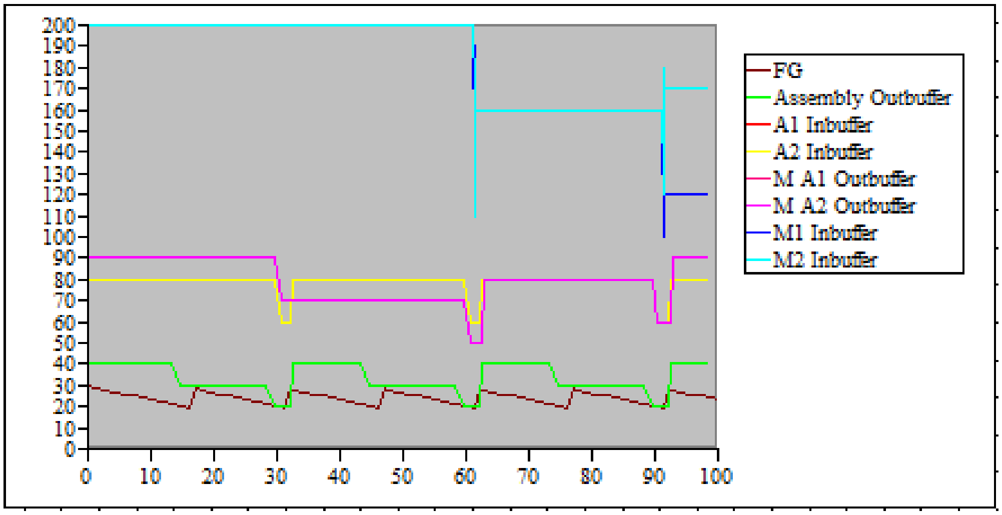


Figure 13. Gantt chart for assembly structure

At *t*=0, the inventories were full. Simulation started at *t*=1. In every 1.5 minutes, 1 unit demand was received. Hence, at *t*=14.5, an empty container was sent to Assembly Unit for replenishment. The replenishment lead time was 2.5 minutes. At *t*=17, the FG Inventory was replenished with 10 units and making the inventory balance to 19 units. Similarly, the simulation events were determined and represented in Table 3.

The model was run for 100 minutes. Computational results were recorded while running the model. Gantt chart (shown in Figure 13) was plotted to compare the simulation results with the expected results (shown in Table 3). Other individual Gantt charts are given in Appendix A. Finally, Table 3 results were compared with the actual simulation results (shown in Figure 13) and the scenarios were considered to be 'pass' when the simulation results matched with the expected results at each stage.

Summary of the chapter

The chapter detailed the serial and assembly product structures and their simulation model logics. Serial product structure had one part type whereas, assembly product structure had more than one part types in the production line. A justification was given for using computer simulation to carry out this research and detailed the procedure how the simulation model was built. The model assumptions were defined and stated clearly. Two hypothetical models were built to verify and validate the serial and assembly product structure models. The model was run for a week’s time to compare the simulated results with expected results. From the verification and validation process, it was confirmed that the simulated models can be used for this research. The variables were then modified as per the experimental design to collect the results. Chapter-4 details out the design of experiment process and finally list the results.

Chapter 4

RESEARCH PROCEDURE, EXPERIMENTS & RESULTS

Design of Experiments

The activities included in the design of experiment stages are: selecting experimental factors and measure of performances, determining the steady state condition, determining the length of the simulation run, and the number of replications. After designing the experiment, a significance study is done to understand the significance of factors affecting the system performance.

Simulation Model Parameters

In order to assess the effects of various parameters on the system performances, three factors were selected at two different levels and Kanban numbers were calculated by using three different methods. Table 4 summarizes the various levels for each factor that were considered for the study.

The responses (measure of performance) selected for this study are: Total average inventory, Rate of backorder fulfillment, Customer order fulfillment time and Total Inventory cost.

Measure of Performance

1. Total average inventory: The total average inventory of the system at any point during the day.
2. Rate of backorder fulfillment: The percentage of fulfilled order that was backordered

3. Customer Order fulfillment time: Time taken to fulfill a customer order.
4. Total Inventory Cost: The total cost incurred by the system due to backorders and holding inventory.

Table 4

Experimental factors used in simulation

Parameters	Levels
No. of Kanbans	1. Method-1: Toyota Formula (Moden et al., 1983) 2. Method-2: Histogram Model (Rees et al., 1987) 3. Method-3: Cost minimization Model (Askin et al., 1993)
Kanban (container) Size	1. Container Capacity = 10; 2. Container Capacity = 1
Inter-arrival time distribution (TBA)	1. Exp(1); 2. Exp(4)
Utilization Levels	1. Utilization = 90%; 2. Utilization = 65%

Methods used to determine the number of kanbans

For this study, three different methods were considered to determine the number of kanbans.

1. Toyota Formula implemented by Toyota production system (1981).
2. Histogram Model proposed by Rees et al (1987).

3. Cost-minimization model proposed by Askin et al (1993).

Method-1: Toyota Formula. The formula used by Toyota Motor Company to determine the number of kanbans is called Toyota kanban formula. The formula has been modified to fit the assumption i.e. a container is sent for replenishment only when it is empty. It is presented as below:

$$K = \left\lceil \frac{LD(1+\alpha)}{C} + 1 \right\rceil \qquad (1)$$

Where, *K* is the number of kanbans

L is the lead time

D is the mean demand rate, total arrivals per minute.

α is the safety factor

C is the container capacity

$\lceil x \rceil$ is the smallest integer greater than or equal to x.

Past researches' had shown that the most used value of safety factor (α) is 0.1 (Monden 1983, Ohno 1988). Hence, this study also uses a safety factor of 0.1. To implement this model the lead time was estimated. Processing time (m_s) is determined at various utilization factors by using GI/G/1 Queuing model as shown below. The calculated values of processing time for various levels of utilization factor are given in APPENDIX B.

$$m_s = \frac{1}{\mu} = \frac{\rho}{C\lambda} \qquad (2)$$

Where,

m_s is the processing time per container μ is the service rate per container

λ is the arrival rate per unit

ρ is the utilization factor, the ratio between arrival rate (λ) and service rate (μ).

The waiting time in the queue (W_q) is calculated using GI/G/1 queuing model. It is calculated as shown in the equation:

$$W_q = \left(\frac{C_a^2 + C_s^2}{2}\right)\left(\frac{m_s * \rho}{1-\rho}\right) \tag{3}$$

Where, C_a is the coefficient of variation for inter-arrival time distribution

C_s is the coefficient of variation for service time distribution

The coefficient of variation is defined as the ratio of the standard deviation of the distribution and mean rate of distribution. The service time is assumed to be deterministic. Hence, C_s = 0 for all cases. The square of the coefficient of variation for arrival distribution(C_a^2) is given in Table 5.

Table 5

Square of Coefficient of variation for inter-arrival time distribution

Container Size (C)	Inter-arrival distribution	Mean inter-arrival rate (units per minute)	Variance	C_a^2 for unit	C_a^2 for container
10	Exp(1)	1	1	1	0.1
10	Exp(4)	0.25	0.0625	1	0.1
1	Exp(1)	1	1	1	1
1	Exp(4)	0.25	0.0625	1	1

The lead time (L) is defined as the total time taken by a container to get replenished. Collection is assumed to be instantaneous. Hence, it is the sum of waiting time (W_q) and processing time (m_s) and indicated as follows:

$$L = m_s + W_q \tag{4}$$

The optimal number of kanbans are calculated and summarized in Table 6 at different utilization levels for two possible container sizes (1 and 10).

Table 6

Optimal number of kanbans using Toyota formula (Method-1)

Results at Safety Factor (α) = 0.1 ; Container Size (C) = 10

No	ρ	D	m_s	W_q	L	K
1	0.9	1	9	4.05	13.05	3
2	0.9	4	2.25	1.01	3.26	3
3	0.65	1	6.5	0.60	7.10	2
4	0.65	4	1.62	0.15	1.77	2

Results at Safety Factor (α) = 0.1 ; Container Size (C) = 1

No	ρ	D	m_s	W_q	L	K
1	0.9	1	0.9	4.05	4.95	7
2	0.9	4	0.225	1.01	1.24	7
3	0.65	1	0.65	0.60	1.25	3
4	0.65	4	0.162	0.15	0.31	3

Method-2: Histogram model method. This method was proposed by Rees at el (1987) to dynamically adjust the number of kanbans in a Just-In-Time

Production system by estimating the lead time from the histogram. Periodically, the number of kanbans at the work center is adjusted based on forecasted demand for the next month and collected observations of lead time during the past month. Below is the formula for determining the number of kanbans (n).

$$n = [\,\widehat{D}\ \times\ L_{Max}] \qquad (5)$$

Where,

$\widehat{D}$ is the mean forecasted demand over a time period

L_{max} is the maximum lead time over the measurement time period

The detailed steps of methodology are:

1. 100 observations of lead times are collected from the previous simulation runs and the estimated autocorrelations r_k [at lag k] calculated for k = 0, 1, 2… 24. Collected observations of lead time are listed in APPENDIX C. Those observations were utilized to generate the correlograms.
2. The autocorrelation function indicates the autocorrelation behavior of the data. APPENDIX D lists all of the autocorrelation functions for various conditions. From the data shown in Figure 14, it is observed that autocorrelation is less than 0.05 at lag 9. Thus, lag 9 was used for the scenario(C=10, ρ=1, D=1) to create least autocorrelation. This means, independent observations spaced every 9 lead times were collected for the above scenario.

3. 100 independent observations were collected for each case. A histogram was developed from these observations to estimate the density function of the lead time.
4. Demand for final product replenishment request was analyzed in two levels i.e. *D*=1 and *D*=4. *D*=1 when the inter-arrival time distribution is exp (1) same as Method-1.
5. The density function of lead time was estimated and combined with forecasted demand value to produce the probability mass function for number of kanbans (*n*). This is accomplished by determining the density of n', where $n' = DL$, and then the pmf of *n* (where *n* = [DL]) can be found. $f_{n'}(n')$ is defined as the probability density function of the random variable n' and $f_L(L)$ as the density of the random variable L. Since *D* is considered a deterministic constant over the forecasted time period, the $f_{n'}(n')$ can be shown as (Rees, Philipoom, Taylor III, & Huang, 1987),

$$f_{n'}(n') = \frac{1}{|\widehat{D}|} f_L\left(\frac{n}{|\widehat{D}|}\right), \widehat{D} \neq 0$$

$$\text{Or, } f_{n'}(n') = \frac{1}{\widehat{D}} f_L\left(\frac{n}{\widehat{D}}\right), \widehat{D} > 0 \qquad (6)$$

where $\widehat{D}$ = the observed sample value of *D*.

As equation indicates that n' has the same general density function as L, and is just a scaled down, reshaped version of $f_L(n)$. To estimate $f_n(n)$ from $f_{n'}(n')$, the cell boundaries in estimating $f_L(L)$ was set so that when $f_{n'}(n')$ is constructed, no cell contains any integer as in interior point.

This is done by prohibiting cells for $f_L(L)$ from containing $(\frac{j}{D})$ as interior point, where $j = 1,2, \ldots$ and hence, $f_n(n)$ is a discretized version of $f_L(L)$ with mass located at n = 1, 2, 3… and the density at each point k equal to $\int_{k-1}^{k} f_{n'}(n')\, dn'$.

When shortage costs are considerably greater than holding costs, the paper has simplified the minimum-cost number of kanbans calculation as follows,

$$f_n(n) = \widehat{D}\, f_{L_{max}}(L_{max})$$

Since in real world scenario, the distribution of lead time is always a finite number, $f_L(L)$ will be finite. The paper stated, when 100 observations are taken over a period, the density function of L_{max} will be a single valued random variable with all its mass at point $\hat{L}_{max}$, which is the maximum of the collected lead times. Thus

$$f_{L_{max}}(L) = \delta(L - \hat{L}_{max})$$

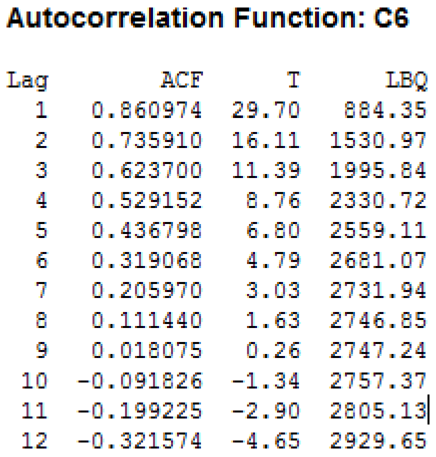
As a result, $f_n(n) = \widehat{D}(\delta(L - \hat{L}_{max}))$

$$= \delta\ (\lceil \widehat{D}L \rceil - \lceil \widehat{D}\hat{L}_{max})]$$

$$= \delta\ (n - \lceil \widehat{D}\hat{L}_{max})]$$

As the equation indicates, the density function of the number of kanbans consists of a single mass at value of n = $[\widehat{D}\hat{L}_{max}]$. Thus, forecasting D and finding the maximum lead time over the measurement period can determine the number of kanbans.

The total cost calculation for 65% utilization at C=10 *and D*=1, is shown in Table 7 when c_h= 1, c_s= 1. The minimum-cost number of kanbans in this case is 3. Similarly, the minimum-cost numbers of kanbans were calculated at various conditions and are listed in Table 8. APPENDIX E lists the cost calculations for all the scenarios.



Autocorrelation Function: C6

```
Lag        ACF      T      LBQ
  1   0.860974  29.70   884.35
  2   0.735910  16.11  1530.97
  3   0.623700  11.39  1995.84
  4   0.529152   8.76  2330.72
  5   0.436798   6.80  2559.11
  6   0.319068   4.79  2681.07
  7   0.205970   3.03  2731.94
  8   0.111440   1.63  2746.85
  9   0.018075   0.26  2747.24
 10  -0.091826  -1.34  2757.37
 11  -0.199225  -2.90  2805.13
 12  -0.321574  -4.65  2929.65
```

Figure 14. Autocorrelation function of lead time at 65% utilization (when C=10 and D=1)

Table 7

Minimum Cost Calculations for 65% Utilization Case (C=10 and D=1) assuming c_h/ c_s= 1

PMF	n	Holding Cost (c_h)	Shortage Cost (c_s)	Total Cost
0.4	1	0	(17*0.03+14*0.14+11*0.19+8*0.04+6*0.11+3*0.04)*1	5.97
0.08	2	(3*0.4)*1	(14*0.03+11*0.14+8*0.19+5*0.04+3*0.11)*1	5.59
0.11	3	(6*0.4 + 3*0.08)*1	(11*0.03+8*0.14+5*0.19+2*0.04)*1	5.56
0.04	4	(8*0.04+5*0.08+ 2*0.11)*1	(9*0.03+6*0.14+3*0.19)*1	5.58
0.19	5	(11*0.4+8*0.11+5*0.11+3*0.04)*1	(6*0.03+ 3*0.14)*1	6.38
0.14	6	(14*0.4+11*0.08+8*0.11+6*0.04+3*0.19)*1	(3*0.03)*1	8.32
0.03	7	(17*0.4+14*0.08+11*0.11+9*0.04+6*0.19+3*0.14)*1	0	11.06

Table 8

Optimal number of kanbans using Histogram Model (Method-2)

No	C	ρ	$\widehat{D}$	*b/h*	K_{series}	$K_{assembly}$
3	1	0.65	1	1	8	9
4	1	0.65	4	1	8	9
1	1	0.9	1	1	18	23
2	1	0.9	4	1	18	23
3	10	0.65	1	1	3	3
4	10	0.65	4	1	3	3
1	10	0.9	1	1	4	4
2	10	0.9	4	1	4	4

No	C	ρ	$\widehat{D}$	b/h	K_{series}	$K_{assembly}$
3	1	0.65	1	10	9	11
4	1	0.65	4	10	9	11
1	1	0.9	1	10	23	30
2	1	0.9	4	10	23	30
3	10	0.65	1	10	3	3
4	10	0.65	4	10	3	3
1	10	0.9	1	10	5	5
2	10	0.9	4	10	5	5

Method-3: Cost minimizing model method. This method was proposed by Askin et al (1993) to determine the number of kanbans in multi-item JIT Systems with an objective to minimize the holding cost and back order cost. A stochastic model was formulated and the steady state conditions were derived for few or many part-types. Shortage cost is assumed to be proportional to the length of the time in a backorder condition. The paper demonstrates the ability of solving different problems at each workstation treating them independently. The problem of minimizing the holding and backorder cost was solved by the below equation:

$$minimize\ E\left(\frac{cost}{time}\right) = \sum_{i=1}^{m}\{h_i \sum_{x=0}^{k_i} x\, P_i(x) + \ b_i \sum_{x=-\infty}^{-1} P_i(x)\} \qquad (7)$$

Where,

m represents number of part types

$P_i(x)$ represents probability of x full containers in inventory for part type *i*

h_i is the holding cost for part type *i*

b_i is the back order cost for part type *i*

$P_i(x)$ is determined by using the steady-state balance equations for the workstation. For more than one part type model, the paper suggested to consider number of jobs in the production queue while calculating the number of kanbans for a part type. The paper recommended introducing the term L_{-i} for writing the balance equation to indicate the expected number of kanbans in the production queue excluding part type i. For the simulation model, the steady state balance equations are:

Rate Out = Rate In

$$\lambda_i p_i(x) = \frac{\mu}{L_{-i}+1} P_i(x-1), x = K_i$$

$$=> P_i(K_i - 1) = \frac{\lambda_i(L_i+1)}{\mu} P_i(K_i) \tag{8}$$

$$\left(\lambda_i + \frac{(K_i-x)\mu}{L_{-i}+K_i-x}\right) p_i(x) - \lambda_i P_i(x+1) = \frac{(K_i-x)\mu}{L_{-i}+K_i-x} P_i(x-1), 0 < x < K_i$$

The above equation can be rewritten as:

$$\left(\lambda_i + \frac{(j+1)\mu}{L_{-i}+j-1}\right) p_i(K_i - j + 1) = \lambda_i P_i(K_i - j + 2) + \frac{j\mu}{L_{-i}+j} P_i(K_i - j), 0 \leq j \leq K_i$$

$$=> P_i(K_i - j) = \frac{(L_{-i}+j)}{j\mu}\left[\left(\lambda_i + \frac{(j-1)\mu}{L_{-i}+j-1}\right)\frac{\lambda_i(L_i+1)}{\mu} P_i(K_i) - \lambda_i P_i(K_i)\right] \tag{9}$$

$$\left(\lambda_i + \frac{K_i\mu}{L_{-i}+K_i}\right) p_i(x) = \lambda_i P_i(x+1) + \frac{K_i\mu}{L_{-i}+K_i} P_i(x-1), x \leq 0 \tag{10}$$

Using the relation,

$$\sum_{-1}^{\infty} P(x) = 1, \tag{11}$$

The equations from (2) - (4) can be generalized in the below form:

$$P_i(K_i - j) = a_j P_i(K_i)$$

Where, $a_j = \frac{\lambda_i(L_{-i}+j)}{j\mu}\left[\left(\lambda_i + \frac{\mu}{L_{-i}+1}\right)\frac{(L_i+1)(j-1)}{\mu} - 1\right]$

λ_i = Demand arrival rate of part type *i*

μ = Average server time

K_i = Kanban numbers for part type i.

L_{-i} = Expected number of kanbans in the production queue excluding part type i.

Finally, the objective function $E\left(\frac{cost}{time}\right)$ was calculated for each possible *x* value and the corresponding *x* value of least objective function *E* was considered to be the optimal kanban number for the simulation model. Figure 15 shows the optimal number of kanbans for the model for various *b/h* ratios excluding workload of part type *i*. In the figure, with an increase in the number of kanbans, the b/h ratio increases and it is also observed that at lower utilization, more number of kanbans are required for higher *b/h* ratio than low b/h ratio. The optimal kanban numbers at various conditions for models of two part type is listed in Table 9. For serial structure the expected number of kanbans is eliminated from the state probabilities balance equations.

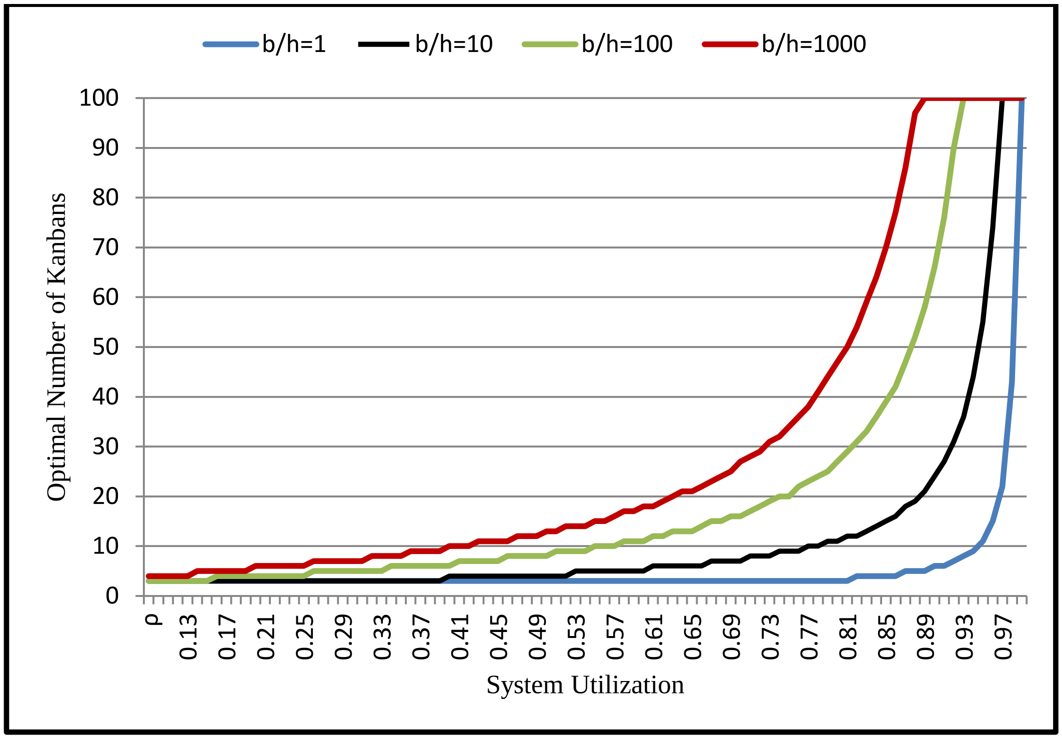


Figure 15. Kanban numbers for two part type model for various *b/h* ratios

Table 9

Optimal number of kanbans using Cost Minimization Model (Method-3)

No.	C	ρ	λ	b/h	K_{series}	$K_{assembly}$
1	1	0.65	1	1	7	9
2	1	0.65	4	1	7	9
3	1	0.9	1	1	11	23
4	1	0.9	4	1	11	23
5	10	0.65	1	1	3	3
6	10	0.65	4	1	3	3
7	10	0.9	1	1	4	4
8	10	0.9	4	1	4	4
9	1	0.65	1	10	9	11
10	1	0.65	4	10	9	11
11	1	0.9	1	10	18	30
12	1	0.9	4	10	18	30
13	10	0.65	1	10	3	3
14	10	0.65	4	10	3	3
15	10	0.9	1	10	5	6
16	10	0.9	4	10	5	6

Research Procedure & Simulation Results

At time = 0, the system has maximum inventory. The simulation was set to run for one month time period. Three shifts per day and six days work week have been considered. Each shift is eight hours long. The calculated number of kanbans had been configured in the simulation. A total of ten replications were used to record the measure of performance parameters. Hence, the simulation was set to run for 34560 minutes for each replication. The simulation was run for various scenarios of container capacity, utilization factor, demand arrival rate, and backorder and holding cost ratio. Table 10 to Table 15 summarize the results of the simulation run of serial and assembly product structure for each method. The results are obtained from Arena Process Analyzer.

Table 10

Simulation results using Method-1 derived kanban numbers for all the instances of serial structure

#	Scenarios	K	Total Order fulfillment	Immediate order fulfillment	Backorder fulfillment	Total Average Inventory	Avg. Order fulfillment Time in minute
1	$C = 1,\ \rho = 65,\ \lambda = 1\ \&\ b/h = 1$	3	34530	29379	5152	9.1	0.117
2	$C = 1,\ \rho = 65,\ \lambda = 1\ \&\ b/h = 10$	3	34530	29379	5152	9.1	0.117
3	$C = 1,\ \rho = 65,\ \lambda = 4\ \&\ b/h = 1$	3	138139	117467	20671	9.1	0.03
4	$C = 1,\ \rho = 65,\ \lambda = 4\ \&\ b/h = 10$	3	138139	117467	20671	9.1	0.03
5	$C = 1,\ \rho = 90,\ \lambda = 1\ \&\ b/h = 1$	7	34529	25697	8832	16.6	1.006
6	$C = 1,\ \rho = 90,\ \lambda = 1\ \&\ b/h = 10$	7	34529	25697	8832	16.6	1.006
7	$C = 1,\ \rho = 90,\ \lambda = 4\ \&\ b/h = 1$	7	138138	102006	36132	16.6	0.272
8	$C = 1,\ \rho = 90,\ \lambda = 4\ \&\ b/h = 10$	7	138138	102006	36132	16.6	0.272
9	$C = 10,\ \rho = 65,\ \lambda = 1\ \&\ b/h = 1$	2	34530	33993	537	61.9	0.015
10	$C = 10,\ \rho = 65,\ \lambda = 1\ \&\ b/h = 10$	2	34530	33993	537	61.9	0.015
11	$C = 10,\ \rho = 65,\ \lambda = 4\ \&\ b/h = 1$	2	138139	135792	2347	61.9	0.004
12	$C = 10,\ \rho = 65,\ \lambda = 4\ \&\ b/h = 10$	2	138139	135792	2347	61.9	0.004
13	$C = 10,\ \rho = 90,\ \lambda = 1\ \&\ b/h = 1$	3	34530	33557	973	86.2	0.111
14	$C = 10,\ \rho = 90,\ \lambda = 1\ \&\ b/h = 10$	3	34530	33557	973	86.2	0.111
15	$C = 10,\ \rho = 90,\ \lambda = 4\ \&\ b/h = 1$	3	138139	133757	4382	86.0	0.033
16	$C = 10,\ \rho = 90,\ \lambda = 4\ \&\ b/h = 10$	3	138139	133757	4382	86.0	0.033

Table 11

Simulation results using Method-1 derived kanban numbers for all the instances of assembly structure

#	Scenarios	K	Total Order fulfillment	Immediate order fulfillment	Backorder fulfillment	Total Average Inventory	Avg. Order fulfillment Time in minute
1	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	3	34529	29378	5151	23.257	0.117
2	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	3	34529	29378	5151	23.257	0.117
3	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	3	138135	117465	20671	23.306	0.03
4	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	3	138135	117465	20671	23.306	0.03
5	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	7	34528	25697	8831	41.218	1.006
6	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	7	34528	25697	8831	41.218	1.006
7	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	7	138135	102004	36131	41.162	0.272
8	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	7	138135	102004	36131	41.162	0.272
9	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	2	34529	33993	537	156.348	0.015
10	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	2	34529	33993	537	156.348	0.015
11	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	2	138136	135788	2347	156.418	0.004
12	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	2	138136	135788	2347	156.418	0.004
13	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	3	34529	34529	0	251.534	0
14	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	3	34529	34529	0	251.534	0
15	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	3	138136	133754	4382	214.264	0.033
16	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	3	138136	133754	4382	214.264	0.033

Table 12

Simulation results using Method-2 derived kanban numbers for all the instances of serial structure

#	Scenarios	K	Total Order fulfillment	Immediate order fulfillment	Backorder fulfillment	Total Average Inventory	Avg. Order fulfillment Time in minute
1	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	8	34530	34452	78	32.791	0.002
2	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	9	34530	34497	33	37.78	0.001
3	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	8	138139	137762	377	32.8	0.001
4	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	9	138139	137966	173	37.787	0
5	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	18	34530	33834	696	65.782	0.08
6	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	23	34530	34306	224	90.445	0.027
7	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	18	138139	134886	3253	65.418	0.024
8	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	23	138139	137069	1070	90.021	0.008
9	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	3	34530	34530	0	111.193	0
10	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	3	34530	34530	0	111.193	0
11	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	3	138139	138137	2	111.156	0
12	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	3	138139	138137	2	111.156	0
13	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	4	34530	34432	99	134.939	0.012
14	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	5	34530	34518	12	184.81	0.001
15	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	4	138139	137632	507	134.526	0.004
16	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	5	138139	138081	58	184.358	0

Table 13

Simulation results using Method-2 derived kanban numbers for all the instances of assembly structure

#	Scenarios	K	Total Order fulfillment	Immediate order fulfillment	Backorder fulfillment	Total Average Inventory	Avg. Order fulfillment Time in minute
1	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	9	34529	34496	33	92.069	0.001
2	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	11	34529	34526	4	116.052	0
3	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	9	138136	137962	173	92.086	0
4	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	11	138136	138102	34	116.064	0
5	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	23	34529	34306	224	218.462	0.027
6	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	30	34529	34480	50	302.135	0.005
7	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	23	138136	137066	1070	217.444	0.008
8	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	30	138136	137889	247	301.057	0.002
1	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	3	34529	34529	0	274.543	0
2	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	3	34529	34529	0	274.543	0
3	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	3	138136	138134	2	274.461	0
4	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	3	138136	138134	2	274.461	0
5	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	4	34529	34431	99	331.55	0.012
6	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	5	34529	34517	12	451.22	0.001
7	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	4	138136	137629	507	330.573	0.004
8	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	5	138136	138078	58	450.145	0

Table 14

Simulation results using Method-3 derived kanban numbers for all the instances of serial Structure

#	Scenarios	K	Total Order fulfillment	Immediate order fulfillment	Backorder fulfillment	Total Average Inventory	Avg. Order fulfillment Time in minute
1	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	7	34530	34350	181	27.818	0.004
2	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	9	34530	34497	33	37.78	0.001
3	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	7	138139	137313	826	27.83	0.001
4	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	9	138139	137966	173	37.787	0
5	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	11	34530	31000	3529	32.808	0.403
6	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	18	34530	33834	696	65.782	0.08
7	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	11	138139	122800	15339	32.651	0.114
8	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	18	138139	134886	3253	65.418	0.024
1	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	3	34530	34530	0	111.193	0
2	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	3	34530	34530	0	111.193	0
3	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	3	11993	11993	0	111.075	0
4	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	3	11993	11993	0	111.075	0
5	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	4	34530	34432	99	134.939	0.012
6	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	5	34530	34518	12	184.81	0.001
7	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	4	138139	137632	507	134.526	0.004
8	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	5	138139	138081	58	184.358	0

Table 15

Simulation results using Method-3 derived kanban numbers for all the instances of assembly Structure

#	Scenarios	K	Total Order fulfillment	Immediate order fulfillment	Backorder fulfillment	Total Average Inventory	Avg. Order fulfillment Time in minute
1	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	9	34529	34496	33	92.069	0.001
2	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	11	34529	34526	4	116.052	0
3	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	9	138136	137962	173	92.086	0
4	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	11	138136	138102	34	116.064	0
5	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	23	34529	34306	224	218.462	0.027
6	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	30	34529	34480	50	302.135	0.005
7	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	23	138136	138102	34	116.064	0
8	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	30	138136	137889	247	301.057	0.002
1	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	3	34529	34529	0	274.543	0
2	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	3	34529	34529	0	274.543	0
3	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	3	138136	138134	2	274.461	0
4	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	3	138136	138134	2	274.461	0
5	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	4	34529	34431	99	331.55	0.012
6	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	6	34529	34529	0	571.177	0
7	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	4	138136	137629	507	330.573	0.004
8	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	6	138136	138127	9	570.094	0

Test of Statistical Significance

A full factorial design was designed and analyzed in order to assess the effects of various system variables on the measure of performance of the system. Table 16 lists the various factors with two different levels. The full factorial design combinations are shown in Table 17.

Table 16

Various Factors at different levels for the factorial design

Factor	Low level Setting	High level Setting
Container Capacity	1	10
Utilization Factor	65%	90%
Mean Demand Arrival	1	4

Table 17

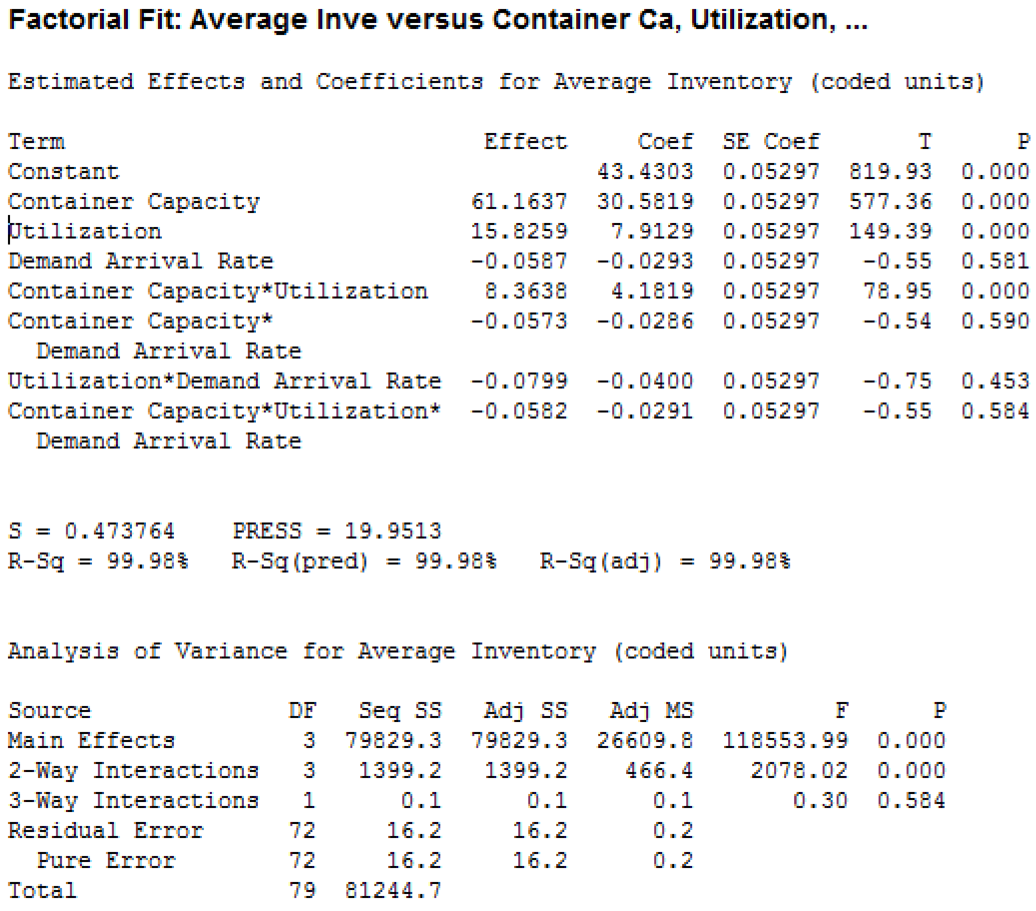
Full factorial design

Exp	Container Capacity	Utilization	Mean Demand Arrival
1	1	65	1
2	1	65	4
3	1	90	1
4	1	90	4
5	10	65	1
6	10	65	4
7	10	90	1
8	10	90	4

For Method-2 and Method-3, the shortage and holding cost ratio (*b/h*) was considered for two levels (1 and 10) in addition to above three factors. Hence, for those two methods, it was a two level and four factorial design and 2^4 possible combinations are designed for full factorial design.

Using these factorial designs the simulation was run and measure of performances were obtained. The model was fit to simulation results and effects are evaluated. Total effects included are three main effects, three two way interactions and one three way interaction.

Significance levels (*P* value) of all estimated effects are obtained using a 5% type-1 error (α = 0.05). The statistical results obtained for Average Inventory are shown in Figure 16.



Factorial Fit: Average Inve versus Container Ca, Utilization, ...

```
Estimated Effects and Coefficients for Average Inventory (coded units)

Term                                Effect     Coef  SE Coef       T      P
Constant                                    43.4303  0.05297  819.93  0.000
Container Capacity                 61.1637  30.5819  0.05297  577.36  0.000
Utilization                        15.8259   7.9129  0.05297  149.39  0.000
Demand Arrival Rate                -0.0587  -0.0293  0.05297   -0.55  0.581
Container Capacity*Utilization      8.3638   4.1819  0.05297   78.95  0.000
Container Capacity*                -0.0573  -0.0286  0.05297   -0.54  0.590
  Demand Arrival Rate
Utilization*Demand Arrival Rate    -0.0799  -0.0400  0.05297   -0.75  0.453
Container Capacity*Utilization*    -0.0582  -0.0291  0.05297   -0.55  0.584
  Demand Arrival Rate


S = 0.473764    PRESS = 19.9513
R-Sq = 99.98%   R-Sq(pred) = 99.98%   R-Sq(adj) = 99.98%


Analysis of Variance for Average Inventory (coded units)

Source              DF   Seq SS   Adj SS   Adj MS          F      P
Main Effects         3  79829.3  79829.3  26609.8  118553.99  0.000
2-Way Interactions   3   1399.2   1399.2    466.4    2078.02  0.000
3-Way Interactions   1      0.1      0.1      0.1       0.30  0.584
Residual Error      72     16.2     16.2      0.2
  Pure Error        72     16.2     16.2      0.2
Total               79  81244.7
```

Figure 16. Full Factorial Fit for the response: Average Inventory

The p-values of all the effects are less than 0.05 except the main effects of demand arrival rate and the interaction effects containing this factor, which means these effects are significant. A normal probability chart and a Pareto chart of the parameters were used to check which parameters influence the measure of performance most. The Normal Probability Plots for the Average Inventory are shown in Figure 17. The normal probability plot indicates the factors, container capacity, utilization and the interaction between container capacity & utilization, are significant for α = 0.05. Other factor Demand of Arrival Rate is not significant for the model fit. Hence, unimportant effects are screened out and a new full model was fitted using only the effects that were identified as statistically significant.

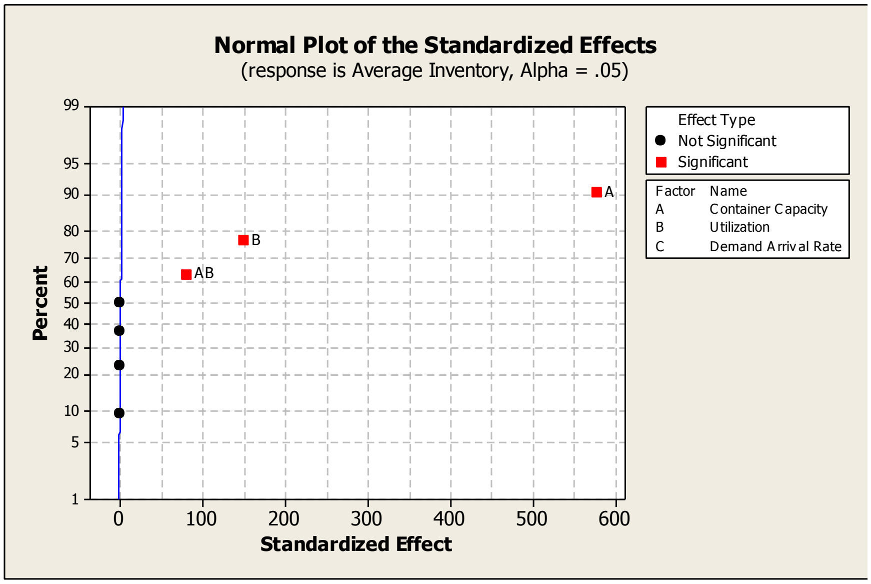
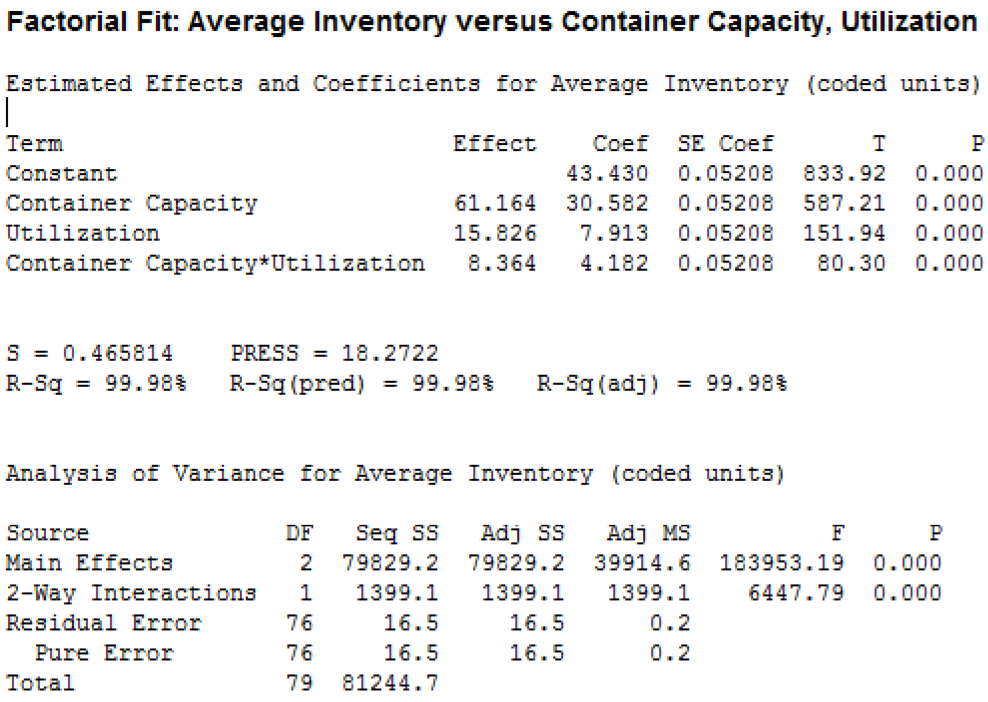


Figure 17. Normal Plot effects for Average Inventory

Several plots were generated to visualize the effects. The reduced model was then evaluated. The P-value of all the terms of the reduced model is less than

0.05, which confirms that the model is good for further exploration and validation. The reduced factorial fit for the response, average inventory against the factors: container capacity and utilization is shown is Figure 18.



Factorial Fit: Average Inventory versus Container Capacity, Utilization

```
Estimated Effects and Coefficients for Average Inventory (coded units)
|
Term                            Effect    Coef  SE Coef       T      P
Constant                                43.430  0.05208  833.92  0.000
Container Capacity              61.164  30.582  0.05208  587.21  0.000
Utilization                     15.826   7.913  0.05208  151.94  0.000
Container Capacity*Utilization   8.364   4.182  0.05208   80.30  0.000


S = 0.465814    PRESS = 18.2722
R-Sq = 99.98%   R-Sq(pred) = 99.98%   R-Sq(adj) = 99.98%


Analysis of Variance for Average Inventory (coded units)

Source              DF   Seq SS   Adj SS   Adj MS          F      P
Main Effects         2  79829.2  79829.2  39914.6  183953.19  0.000
2-Way Interactions   1   1399.1   1399.1   1399.1    6447.79  0.000
Residual Error      76     16.5     16.5      0.2
  Pure Error        76     16.5     16.5      0.2
Total               79  81244.7
```

Figure 18. Factorial Fit for the reduced model

Residual plots are used for further validation. The residual plots did not show any concerns. Hence, the Main effects and interactions effects were set-up to visualize the present effects. Those are shown in Figure 19 for the Average Inventory Response.

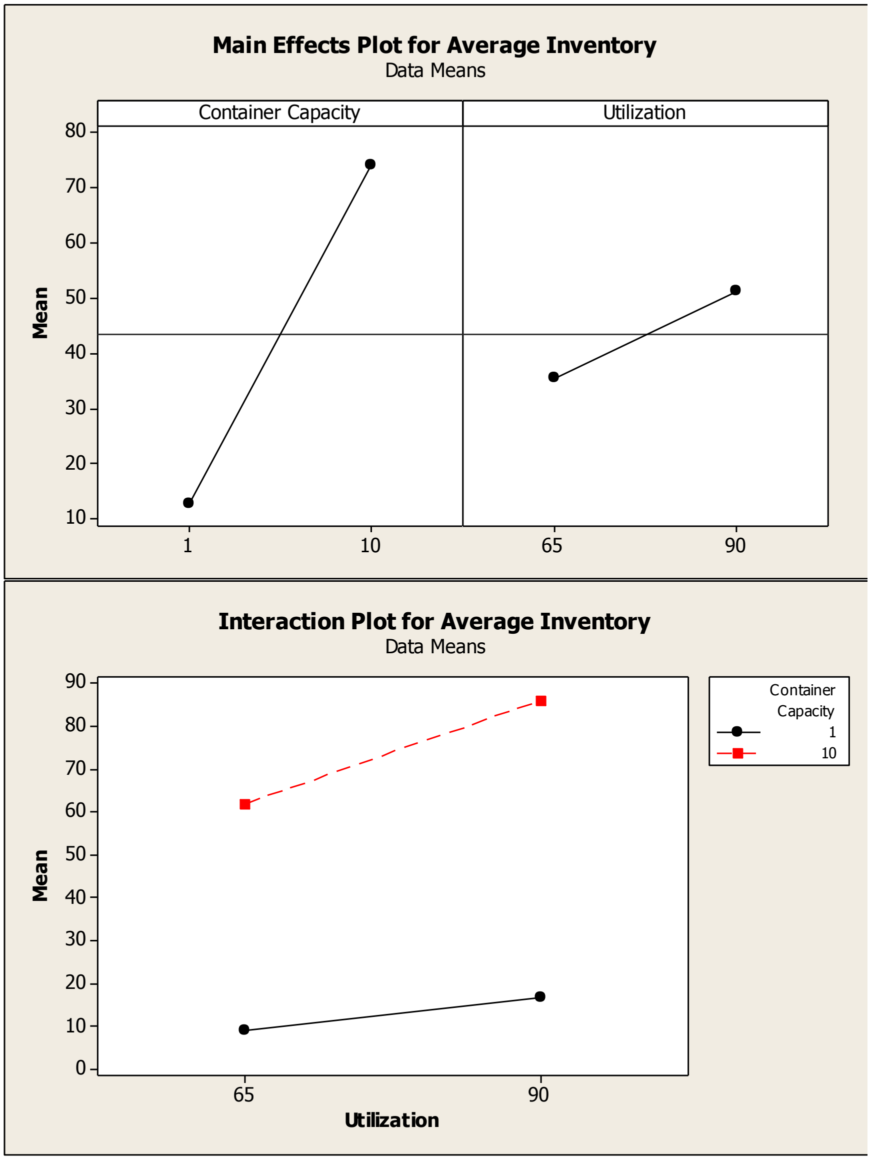


Figure 19. Main Effect and Interaction plot of the reduced model for Average Inventory

The steep slope line of the main effects plot of container capacity indicates that the factor, container capacity, has greater effect on average inventory than system utilization. This means, a small change in container capacity can impact the average inventory largely. The interaction effect can magnify or diminish the main effect. Hence, the interaction effect was evaluated. The average inventories at higher container capacity condition (*C*=10) are greater at both system utilization (ρ=65 and ρ=90) than low container capacity conditions. Also, the difference in responses between runs using *C*=1 and *C*=10 at ρ=90 is higher than the difference in responses at ρ=65. Average inventory increases with increase in container capacity or system utilization.

Similarly analysis of variance was carried out to effects of these factors on measure of performances namely, rate of backorder fulfilled & customer order fulfillment time. The results from the main and interaction effects on each response are:

1. Rate of backorder fulfillment: Container capacity has a larger impact on backorder fulfillment. The rate of backorder fulfilled is low when Container Capacity is high which means, most of the demands are fulfilled immediately. The interaction effect plot shows, rate of backorder fulfilled is low for Container Capacity (*C*=10) than the *C*=1 at both the utilization settings (ρ=90 and ρ=65). Hence to minimize the backorder fulfill rate, *C*=10 and ρ=65setting is preferred.
2. Customer Order Fulfillment time: The factors: container capacity, system utilization and demand arrival rate, has an impact on the order fulfillment rate. At high demand arrival rate, low system utilization and high container capacity, the replenishment time is low. APPENDIX F lists all the statistical significance test results and main effects and interactions

effect plot for all the responses. Results of ANOVA are summarized for all the three measure of performances in Table 18.

Table 18

Summary of Analysis of Variance Results

Factors	Measure of Performances Average Inventory	Rate of backorder fulfillment	Customer Order fulfillment time
Container Capacity (*A*)	x	x	x
Utilization Factor (*B*)	x	x	x
Demand Arrival rate (*C*)	-	-	x
AB	x	x	x
BC	-	-	x
AC	-	-	x
ABC	-	-	x

* x means significant when α=0.05. ** (-) means not significant

Analysis of Results

A comparison study was performed using Arena’s Process Analyzer between various scenarios of serial and assembly structures of all the three methods. Total Inventory cost was calculated for each scenario. Total inventory cost is the sum of backordered cost and holding cost. The holding cost is assumed to be $1 per item per time period for raw material unit and an additional $1 is added to the holding cost per unit per time period for each additional process the raw materials go through to become a finish goods. The holding cost is the product of average inventory of the station per time period and holding cost per item per period at that station. The holding cost of the final shipped item is the sum of the holding cost of the item at each stage of production line. The backordered cost is $1 per item per time period. Table 19 and Table 21 summarize the cost incurred for all methods when backordered cost and holding cost ratio (*b/h*) are 1 and 10 respectively.

Table 19

Comparison Study of various cost incurred for Method-1

		Serial Structure			Assembly Structure		
#	Scenarios	Holding Cost($)	Backordered Cost($)	Total Inventory Cost($)	Holding Cost($)	Backordered Cost($)	Total Inventory Cost($)
1	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	28.08	5152	5180.08	78.627	5151	5229.627
2	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	28.155	20671	20699.2	78.831	20671	20749.83
3	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	48.945	8832	8880.95	137.049	8831	8968.049
4	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	48.78	36132	36180.8	136.623	36131	36267.62
5	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	177.89	537	714.89	525.061	537	1062.061
6	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	177.575	2347	2524.58	524.119	2347	2871.119
7	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	249.42	973	1222.42	198	973	1171
8	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	248.095	4382	4630.1	721.14	4382	5103.14
9	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	28.08	51520	51548.1	78.627	51510	51588.63
10	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	28.155	206710	206738	78.831	206710	206788.8
11	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	48.945	88320	88368.9	137.049	88310	88447.05
12	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	48.78	361320	361369	136.623	361310	361446.6
13	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	177.89	5370	5547.89	525.061	5370	5895.061
14	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	177.575	23470	23647.6	524.119	23470	23994.12
15	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	249.42	9730	9979.42	198	9730	9928
16	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	248.095	43820	44068.1	721.14	43820	44541.14

Table 20

Comparison Study of various cost incurred for Method-2

		Serial Structure			Assembly Structure		
#	Scenarios	Holding Cost($)	Backordered Cost($)	Total Inventory Cost($)	Holding Cost($)	Backordered Cost($)	Total Inventory Cost($)
1	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	101.36	78	179.36	325.755	33	358.755
2	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	101.39	377	478.39	325.797	173	498.797
3	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	200.07	696	896.07	767.967	224	991.967
4	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	198.93	3253	3451.9	764.319	1070	1834.319
5	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	327.82	0	327.82	944.938	0	944.938
6	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 1$	327.49	2	329.49	943.975	2	945.975
7	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	398.65	99	497.65	1143.203	99	1242.203
8	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 1$	397.15	507	904.15	1138.957	507	1645.957
9	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	116.34	330	446.34	409.749	40	449.749
10	$C = 1$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	116.36	1730	1846.4	409.791	340	749.791
11	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	274.28	2240	2514.3	1061.043	500	1561.043
12	$C = 1$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	272.97	10700	10973	1057.227	2470	3527.227
13	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$	327.82	0	327.82	944.938	0	944.938
14	$C = 10$, $\rho = 65$, $\lambda = 4$ & $b/h = 10$	327.49	20	347.49	943.975	20	963.975
15	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$	548.56	120	668.56	1563.021	120	1683.021
16	$C = 10$, $\rho = 90$, $\lambda = 4$ & $b/h = 10$	547.04	580	1127	1558.709	580	2138.709

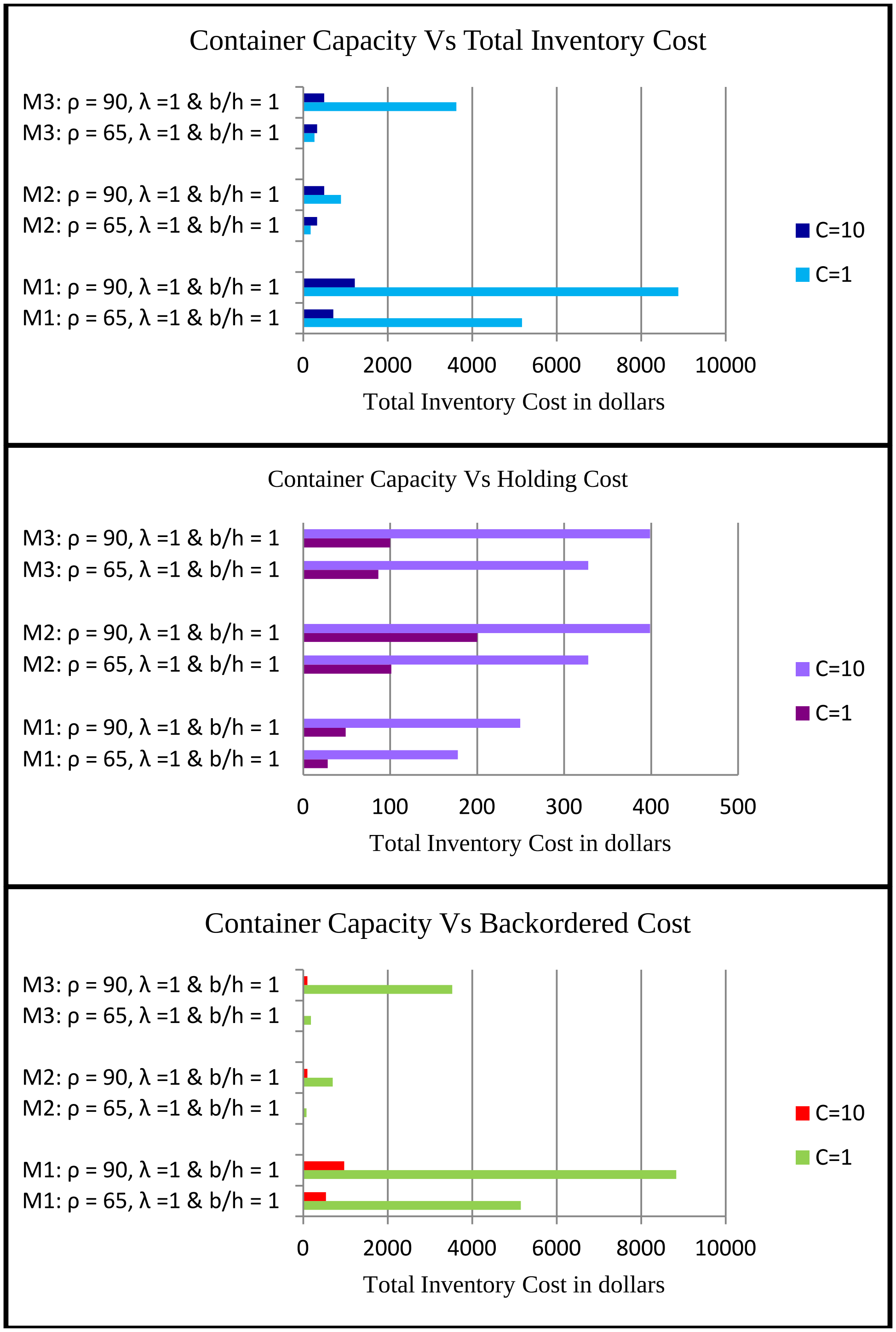
Table 21

Comparison Study of various cost incurred for Method-3

		Serial Structure			Assembly Structure		
#	Scenarios	Holding Cost($)	Backordered Cost($)	Total Inventory Cost($)	Holding Cost($)	Backordered Cost($)	Total Inventory Cost($)
1	C = 1, ρ = 65, λ =1 & b/h = 1	86.4	181	267.4	325.755	33	358.755
2	C = 1, ρ = 65, λ =4 & b/h = 1	86.415	826	912.42	325.797	173	498.797
3	C = 1, ρ = 90, λ =1 & b/h = 1	99.9	3529	3628.9	767.967	224	991.967
4	C = 1, ρ = 90, λ =4 & b/h = 1	99.3	15339	15438	764.319	1070	1834.319
5	C = 10, ρ = 65, λ =1 & b/h = 1	327.82	0	327.82	944.938	0	944.938
6	C = 10, ρ = 65, λ =4 & b/h = 1	327.66	0	327.66	943.975	2	945.975
7	C = 10, ρ = 90, λ =1 & b/h = 1	398.65	99	497.65	1173.194	99	1272.194
8	C = 10, ρ = 90, λ =4 & b/h = 1	397.15	507	904.15	1138.957	507	1645.957
9	C = 1, ρ = 65, λ =1 & b/h = 10	116.34	330	446.34	409.749	40	449.749
10	C = 1, ρ = 65, λ =4 & b/h = 10	116.36	1730	1846.4	409.791	340	749.791
11	C = 1, ρ = 90, λ =1 & b/h = 10	200.07	6960	7160.1	1061.043	500	1561.043
12	C = 1, ρ = 90, λ =4 & b/h = 10	198.93	32530	32729	1057.227	2470	3527.227
13	C = 10, ρ = 65, λ =1 & b/h = 10	327.82	0	327.82	944.938	0	944.938
14	C = 10, ρ = 65, λ =4 & b/h = 10	327.66	0	327.66	943.975	20	963.975
15	C = 10, ρ = 90, λ =1 & b/h = 10	548.56	120	668.56	1983.01	0	1983.01
16	C = 10, ρ = 90, λ =4 & b/h = 10	547.04	580	1127	1978.695	90	2068.695

The results of all the methods indicate that when container capacity is low, it accumulates lot of backorders. Hence, the backordered cost is high when container capacity is low. In the other side, the holding cost is high when container capacity is high due to lots of slack inventories. To further analyze and compare the results, graphs are plotted. Figure 20 plots the scenarios to compare the costs against container capacities. Total Inventory cost is the sum of holding cost and backordered cost. Total inventory cost plot indicates that at higher container capacity the cost is low due to low backordered cost.

Serial Structure and Assembly Structure results indicate that Method-1, The Toyota Production Model, incurs prominently the highest cost among the three methods used to calculated kanban numbers for this research. The total inventory cost for all methods are plotted in Figure 21. Comparison in the chart confirms that the costs are very high for Method-1 when the cost ratio is high. This is due to its inability to adjust the kanban numbers when the backordered cost increases. However, The Histogram method and the cost minimization method both adjust the kanban numbers when the cost factors change, which helps to control the backordered queue. Among these two methods, the histogram method reacts better at low container capacity and high utilization. In other cases, both the methods incur same inventory costs.



(*Notes: M1 – Method-1, M2 – Method-2, M3 – Method-3, C- Container Capacity)

Figure 20. Comparison study of system cost effectiveness at various container capacities for all methods

#	Scenarios	#	Scenarios
1	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	5	$C = 1$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$
2	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	6	$C = 1$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$
3	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 1$	7	$C = 10$, $\rho = 65$, $\lambda = 1$ & $b/h = 10$
4	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 1$	8	$C = 10$, $\rho = 90$, $\lambda = 1$ & $b/h = 10$

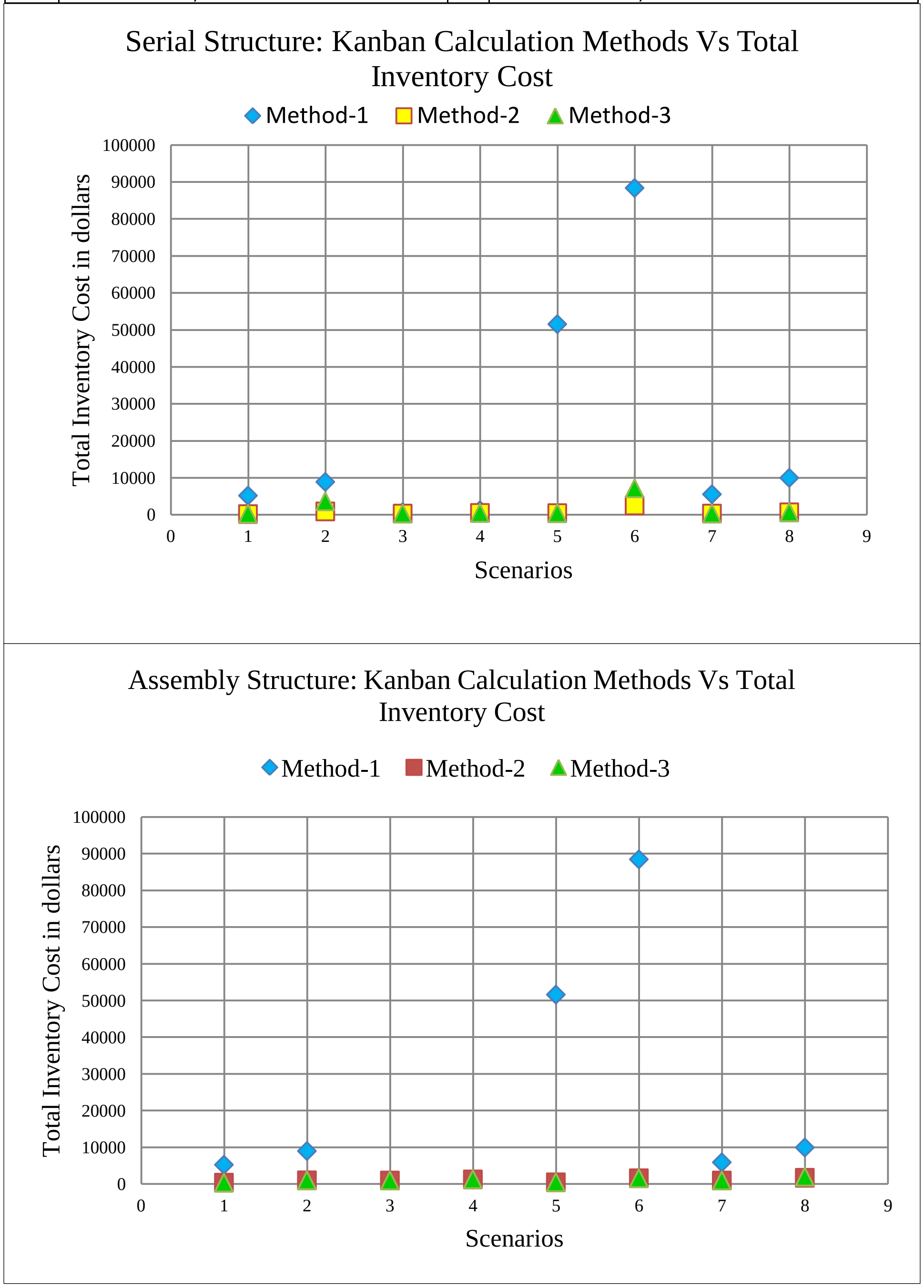
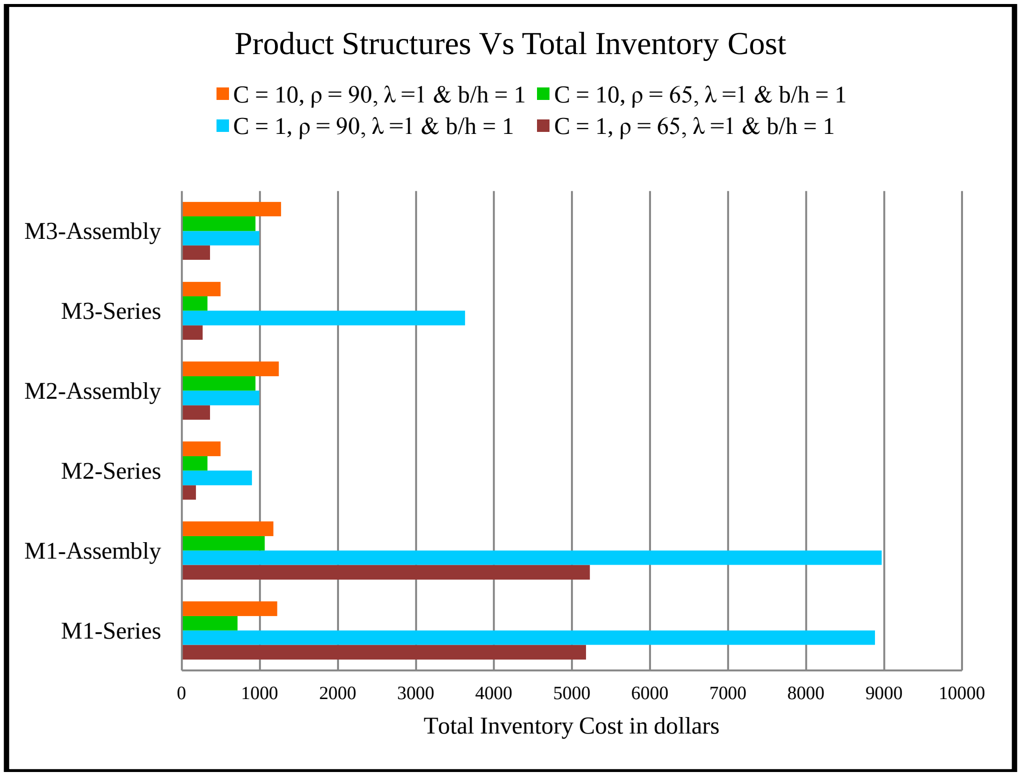


Figure 21. Comparison study of system cost effectiveness for various Kanban calculation methods



(*Note: M1- Method-1; M2 – Method-2 and M3- Method-3)

Figure 22. Comparison study of product structures for various methods

Among serial and assembly product structures, assembly structure incurs more inventory cost than serial structure in two of the methods. Method-1 does not adjust the kanban numbers according to the product structure, hence both incurs same cost for both the product structures. The production queue in assembly structure deals with more than one item. Hence, it is important to adjust the kanban numbers to tackle the bottle necks in the system. Method-2 considers the lead time demand to calculate number of kanbans which helps to control the kanbans. Method-3 considers a factor, an expected number of kanban of other part types excluding that the part type *i*, to accurately calculate the state probabilities. Figure 22 presents the cost differences between product structures at various scenarios. The figure also indicates that the inventory cost is high at higher utilization. The variation in inventory cost, at $\rho = 65\%$ and $\rho=90\%$, is higher in Method-1 than the other two.

Summary of the chapter

This chapter discussed all the methods used in this research to calculate the number of kanbans. The calculated kanban numbers were used in the simulation model and measure of performances were recorded. A statistical significance test was performed in order to assess the effects of various factors on system performances. It was evident that the total average inventory and rate of backordered fulfillment are impacted by main effects of utilization, container capacity and by their interaction effect. With an increase in container capacity, total average inventory increased and the rate of backorder fulfillment decreased. Similarly, with increase in utilization, the average inventory and the rate of backordered fulfillment both increased. The holding cost and backordered cost incurred for each scenario were calculated. The cost tables indicated that a lower container capacity resulted in a high backordered cost which increased the total inventory cost. Various charts were drawn to analyze and compare the experimental results. The results are discussed in Chapter-5 in more detail. The conclusions are drawn based on the analysis of the research questions as outlined in Chapter-1.

Chapter 5

CONCLUSION

Introduction

This chapter discusses results from the data analysis presented in Chapter-4. In addition to providing conclusions to the research questions, this study also provides implications and suggestions for future research. Finally, it summarizes how this research contributes to the greater body of knowledge in the field.

Discussion of Experimental Results

This section discusses the experimental results of the data from the previous chapter in further detail. The data analysis presented is in coherence of the research questions that were outlined in chapter-1.

Effective container size for a particular system. The variability of the container capacity has a greater impact on total inventory cost. The data from Table 10 to Table 15 indicate that when the container capacity is low, it maintains a low average inventory; however, accumulates lots of backorders. In case of larger container capacities, there are lots of slack inventories which help to reduce the backorders. The holding cost, backordered cost and total inventory cost plot in Figure 20 demonstrates that the total inventory cost is high due to high backordered cost when container capacity is low. Total inventory cost is low when container capacity is high due to less backordered cost.

Effective method to set up number of kanbans for the system. The cost comparison study between all the methods indicated that Method-1 (Toyota Product Formula) incurs the highest inventory cost. Method-1 uses alpha factor of 0.1 to calculate the number of kanbans, and accumulates lots of backorders. Method-1 also fails to adjust the kanbans to reduce the shortages as backordered cost increases, whereas, Method-2 and Method-3 have the ability to adjust the Kanban levels when backordered cost increases to reduce shortages. This limitation of Method-1 makes Method-2 and Method-3 more reliable especially when backordered cost is high and container capacity is low. By comparing results of Method-2 and Method-3, it is inferred that, the difference in total inventory cost incurred by both the methods are minimal and system performances are better than Method-1. In some cases especially in low container capacity and high utilization, the histogram method reacts better and adjusts the kanbans to incur less total inventory cost.

Relationship between utilization and customer order fulfillment time. The backorders are high at high system utilization, which increases the time to fulfill a customer order. Experimental result data tables (Table 10 to Table 15) indicate that customer order fulfillment time is low when utilization is low and It increases when utilization increases. Hence, it is inferred that lower the system utilization quicker is the customer order fulfillment time.

Effective system structure between serial and assembly product structure. In assembly product structure, the production queue has more than one part types and it is important to adjust the kanbans in order to deal with the bottlenecks. The number of kanbans calculated by Method-1 fails to adjust the kanbans for assembly product structure. Figure 22 indicates same total inventory costs for both serial and assembly structure of Method-1. However, Method-2 and Method-3 adjust the kanban numbers for assembly product structure which helps to reduce the kanban replenishment time. For these two methods, the backorders are less compare to serial structures but the total average inventory is high, which in turn increases the inventory holding cost. The data from Table 19 to Table 21 illustrate that the holding cost is very high in case of assembly structure for both Method-2 and Method-3 which increases the total inventory cost. Hence, it is inferred that the serial product structure is cost effective than assembly structure for Method-2 and Method-3.

Research Implication

This research provides a systematic approach to decision making process for managers of small sized companies who are looking to implement Kanban system or trying to improve the existing system. It is a valuable tool for assessing the effects of the changes in container capacity, utilization factors, and demand arrival rates. It also provides a comparison of various methods to calculate optimal number kanbans required for a system. In research community, this simulation model can serve as a good reference model to compare against other manufacturing systems. It conceptualizes an alternative way to construct an assembly line model in arena.

Making an accurate simulation study is challenging due to the scale of factors that are present in a real time manufacturing system. It would be beneficial to study a more reliable and a comprehensive simulation model by using any advanced simulation software.

Future Scope

This study is based on many limitations and has a vast scope for future research in the following area:

1. This study has used only two levels of each factor for its factorial design. For accurate conclusion, more levels of each factor can be used.
2. More factors such as waiting time, replenishment time, cycle time etc. can be incorporated to the study to know how these factors influence the system performances.

3. More sophisticated simulation model can be built to better analyze the system.
4. Other advanced simulation software can be used to build a scalable and robust model for future study.
5. Many manufacturing systems have more than two part types processed in their assembly line. Hence, a multi part model using many part types can be simulated and analyzed for future research in this area.

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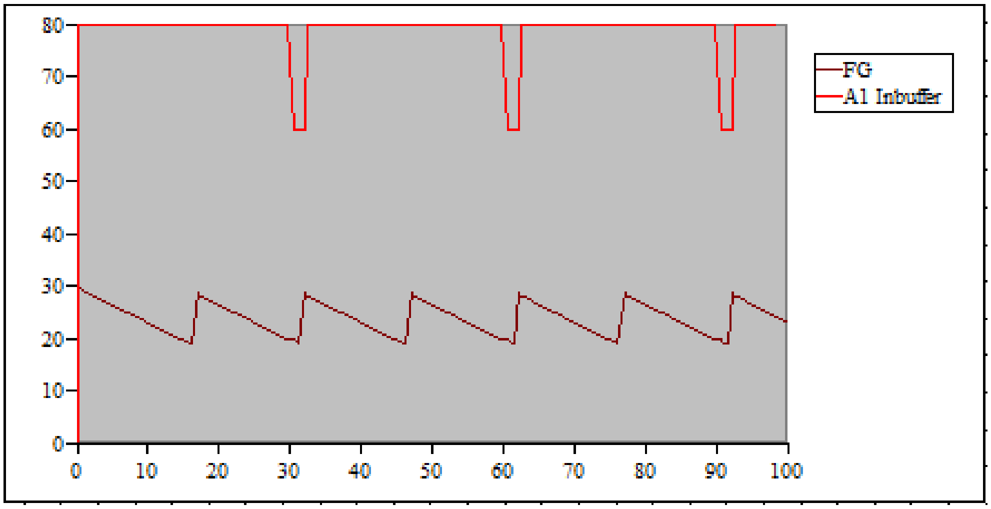
APPENDIX A

GANTT CHARTS FOR ASSEMBLY STRUCTURE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90
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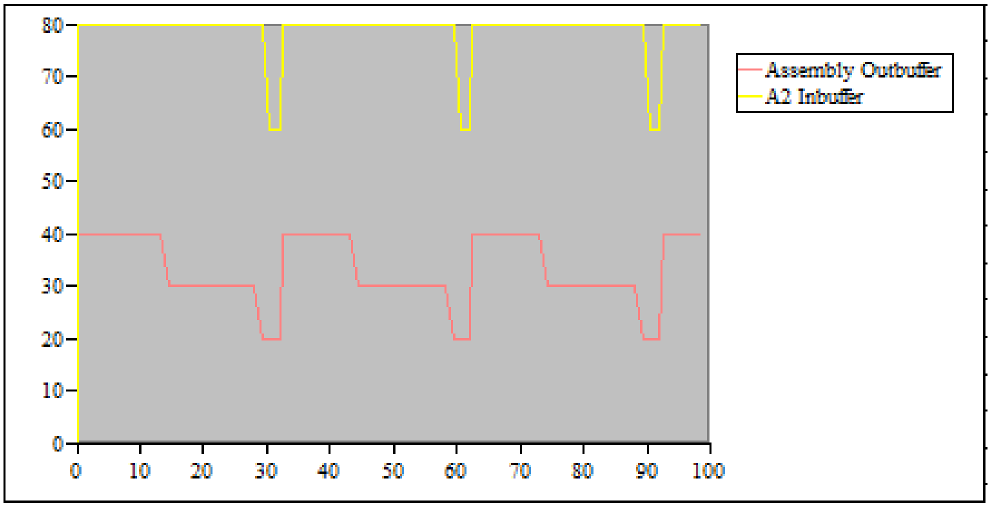
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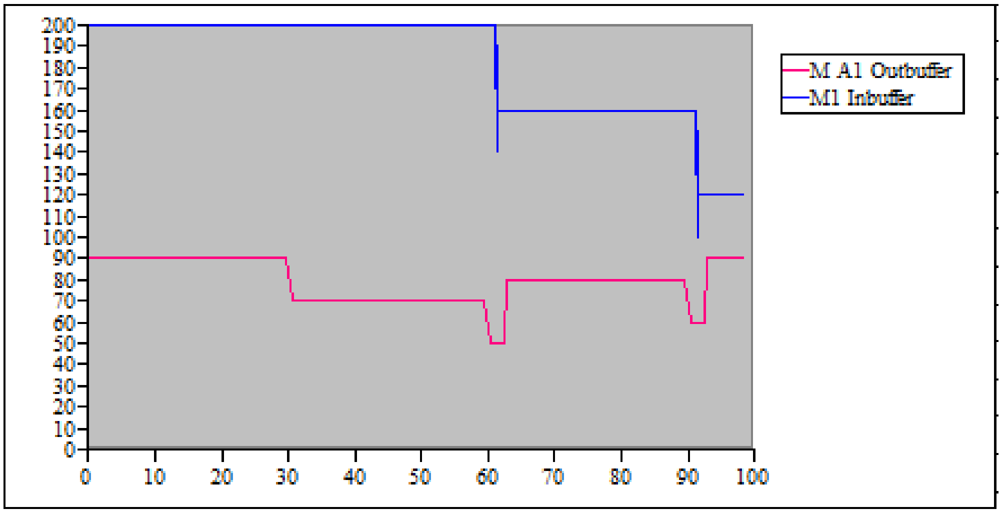
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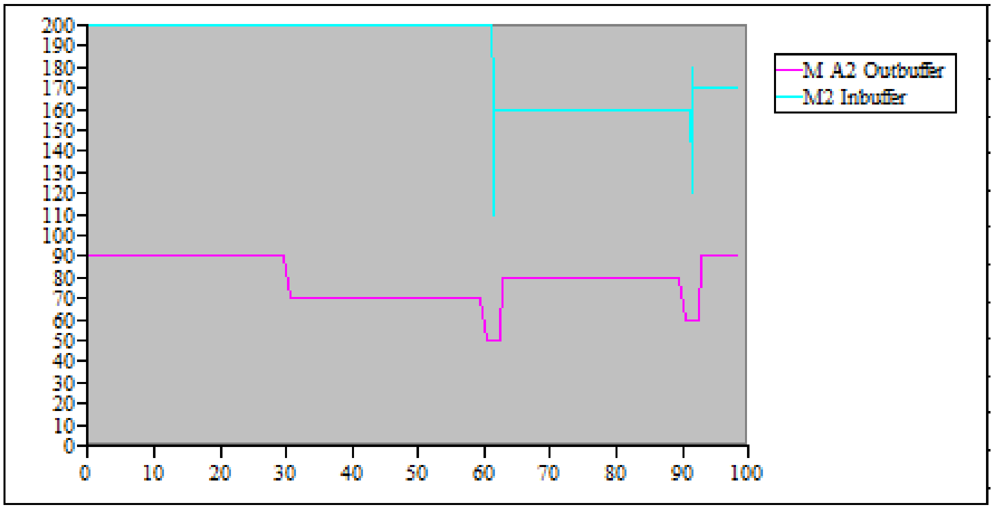
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30
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10
0
0
10
20
30
40
50
60
70
80
90
100

APPENDIX B

PROCESSING TIMES

C	ρ	λ	$1/\mu = C^*(\rho/\lambda)$
1	0.9	1	0.9
1	0.9	4	0.225
1	0.65	1	0.65
1	0.65	4	0.1625
10	0.9	1	9
10	0.9	4	2.25
10	0.65	1	6.5
10	0.65	4	1.625

APPENDIX C

COLLECTED STATISTICS OF LEAD TIMES FROM PREVIOUS SIMULATION RUNS

#	1-65-1*	1-65-4	1-90-1	1-90-4	10-65-1	10-65-4	10-90-1	10-90-4
1	0.65	0.162	0.9	0.225	6.494	1.626	9.009	2.252
2	0.953848	0.237462	1.453848	0.363462	6.494	1.626	9.009	2.252
3	1.158627	0.288157	1.908627	0.477157	6.494	1.626	9.009	2.252
4	1.53839	0.382598	2.53839	0.634598	6.494	1.626	9.009	2.252
5	1.95	0.486	3.378219	0.844555	6.494	1.626	9.009	2.252
6	1.95	0.486	4.137542	1.034385	6.494	1.626	9.009	2.252
7	1.95	0.486	4.912649	1.228162	6.494	1.626	9.009	2.252
8	0.957307	0.235327	2.957307	0.739327	7.053972	1.768494	12.08397	3.020494
9	0.815533	0.199383	3.065533	0.766383	6.494	1.626	9.009	2.252
10	0.65	0.162	2.046001	0.5115	6.494	1.626	9.009	2.252
11	0.65	0.162	1.103303	0.275826	6.494	1.626	9.009	2.252
12	1.158901	0.288725	1.862204	0.465551	6.494	1.626	9.009	2.252
13	0.65	0.162	1.045465	0.261366	6.494	1.626	9.009	2.252
14	0.65	0.162	0.9	0.225	6.494	1.626	9.009	2.252
15	1.178912	0.293728	1.678912	0.419728	6.494	1.626	9.009	2.252
16	1.197975	0.297993	1.947975	0.486993	6.559897	1.644974	11.5899	2.896974
17	1.078699	0.267674	2.078699	0.519674	6.494	1.626	12.99763	3.248658
18	1.37649	0.341622	2.62649	0.656622	6.494	1.626	9.009	2.252
19	1.817745	0.451436	3.317745	0.829436	6.494	1.626	9.009	2.252
#	1.95	0.486	4.018115	1.004528	6.494	1.626	9.065847	2.265962
20	0.65	0.162	1.265221	0.316305	6.494	1.626	9.85109	2.462023
21	0.65	0.162	0.9	0.225	6.494	1.626	9.009	2.252
22	0.65	0.162	0.9	0.225	6.494	1.626	10.359	2.58925
23	0.65	0.162	0.9	0.225	6.494	1.626	12.02322	3.005055
24	0.65	0.162	0.9	0.225	6.494	1.626	11.38016	2.844039
25	0.65	0.162	0.9	0.225	6.494	1.626	9.009	2.252
26	0.65	0.162	0.9	0.225	6.494	1.626	9.009	2.252
27	1.017835	0.253459	1.517835	0.379459	6.494	1.626	11.3932	2.8478
28	1.050073	0.261018	1.800073	0.450018	6.494	1.626	9.009	2.252
29	1.681984	0.418496	2.681984	0.670496	6.494	1.626	9.009	2.252
30	1.95	0.486	3.322547	0.830637	6.494	1.626	10.8458	2.710951
31	1.234203	0.305551	2.734203	0.683551	6.494	1.626	9.623814	2.405204

#	1-65-1*	1-65-4	1-90-1	1-90-4	10-65-1	10-65-4	10-90-1	10-90-4
32	1.35243	0.334608	3.10243	0.775608	6.494	1.626	9.009	2.252
33	0.718459	0.175615	2.718459	0.679615	6.494	1.626	9.009	2.252
34	0.65	0.162	2.544817	0.636204	6.63093	1.662733	11.66093	2.914733
35	1.122539	0.279635	3.267356	0.816839	6.494	1.626	12.99541	3.248102
36	0.65	0.162	2.244138	0.561035	6.494	1.626	14.01981	3.503953
37	0.65	0.162	1.71445	0.428613	6.494	1.626	13.87781	3.468204
38	1.158665	0.288666	2.473115	0.618279	6.494	1.626	12.48818	3.120545
39	0.65	0.162	0.9	0.225	6.494	1.626	12.62014	3.153284
40	0.65	0.162	0.9	0.225	6.494	1.626	13.69459	3.421647
41	0.65	0.162	0.9	0.225	6.494	1.626	9.860527	2.462882
42	0.703302	0.174826	1.203302	0.300826	6.494	1.626	9.009	2.252
43	0.936427	0.232607	1.686427	0.421607	7.306906	1.831727	12.33691	3.083727
#	1.498102	0.372526	2.498102	0.624526	6.494	1.626	9.009	2.252
44	1.761913	0.437978	3.011913	0.752978	8.217398	2.059349	13.2474	3.311349
45	0.65	0.162	0.9	0.225	8.77891	2.202227	16.32391	4.080227
46	0.65	0.162	0.9	0.225	7.866785	1.976696	17.92679	4.480696
47	0.936318	0.233079	1.436318	0.359079	6.494	1.626	15.37738	3.843094
48	0.789012	0.195753	1.539012	0.384753	6.494	1.626	17.12949	4.280872
49	0.65	0.162	0.9	0.225	6.494	1.626	18.42297	4.603992
50	0.713035	0.177258	1.213035	0.303258	6.494	1.626	14.86217	3.713543
51	1.033715	0.256929	1.783715	0.445929	6.494	1.626	14.9673	3.739576
52	0.65	0.162	1.419203	0.3548	6.494	1.626	16.01357	4.000893
53	0.65	0.162	0.9	0.225	6.494	1.626	14.37761	3.591651
54	0.65	0.162	0.9	0.225	6.494	1.626	14.44944	3.609359
55	0.65	0.162	0.994391	0.248598	6.494	1.626	15.89194	3.969735
56	0.65	0.162	1.172551	0.293138	6.494	1.626	11.12875	2.778686
57	0.911627	0.226907	1.684178	0.421045	6.494	1.626	12.93786	3.230715
58	0.65	0.162	1.542235	0.385559	6.494	1.626	10.07043	2.513606
59	0.65	0.162	1.430543	0.357636	6.494	1.626	9.167118	2.287529
60	0.65	0.162	0.9	0.225	6.494	1.626	10.33748	2.57987
61	0.65	0.162	0.9	0.225	6.494	1.626	9.009	2.252
62	0.65	0.162	0.9	0.225	6.494	1.626	10.32475	2.580686

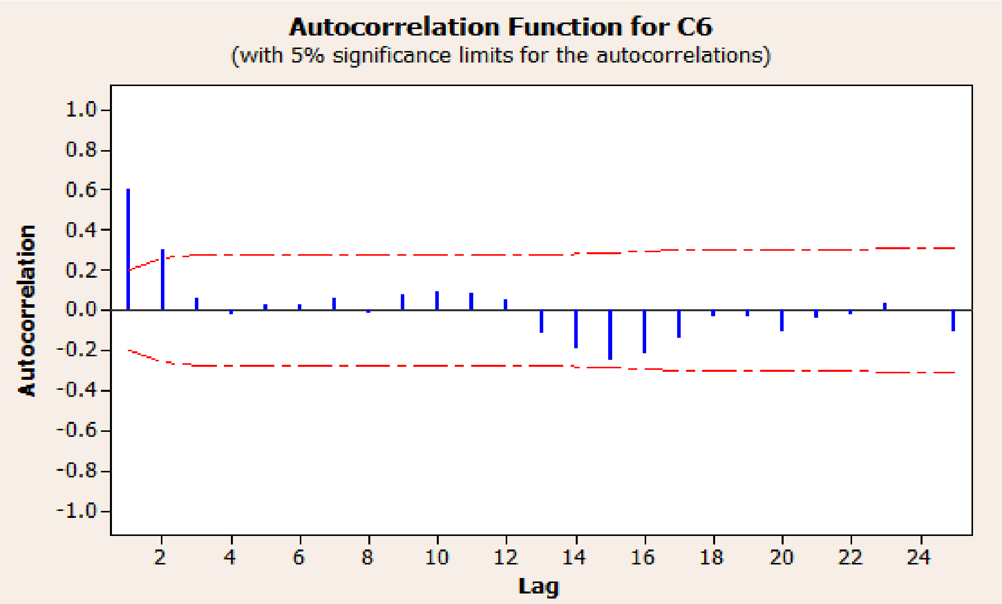
#	1-65-1*	1-65-4	1-90-1	1-90-4	10-65-1	10-65-4	10-90-1	10-90-4
63	0.65	0.162	0.9	0.225	6.494	1.626	10.0928	2.52245
64	1.285607	0.320401	1.785607	0.446401	6.494	1.626	11.74422	2.935055
65	1.581381	0.393845	2.331381	0.582845	6.494	1.626	9.009	2.252
66	1.926502	0.479625	2.926502	0.731625	6.494	1.626	9.009	2.252
67	1.95	0.486	3.209236	0.802309	6.494	1.626	9.272042	2.317511
#	1.851163	0.45979	3.351163	0.83779	6.494	1.626	9.009	2.252
68	1.589628	0.393907	3.339628	0.834907	6.494	1.626	10.2916	2.572401
69	1.797417	0.445354	3.797417	0.949354	6.494	1.626	9.009	2.252
70	1.95	0.486	4.422418	1.105604	6.494	1.626	9.009	2.252
71	1.95	0.486	4.952677	1.238169	6.494	1.626	9.009	2.252
72	1.95	0.486	5.692795	1.423199	6.494	1.626	9.009	2.252
73	1.95	0.486	6.3	1.575	6.494	1.626	9.009	2.252
74	1.95	0.486	6.3	1.575	6.494	1.626	9.009	2.252
75	1.95	0.486	6.3	1.575	6.494	1.626	9.009	2.252
76	1.95	0.486	6.3	1.575	6.494	1.626	9.009	2.252
77	1.95	0.486	6.3	1.575	6.494	1.626	9.009	2.252
78	1.95	0.486	6.3	1.575	6.494	1.626	9.009	2.252
79	1.95	0.486	6.3	1.575	8.809062	2.207266	13.83906	3.459266
80	0.65	0.162	4.234169	1.058542	6.494	1.626	12.8006	3.199399
81	1.12498	0.280245	4.959149	1.239787	6.494	1.626	13.76867	3.441169
82	0.65	0.162	4.677272	1.169318	6.494	1.626	14.47342	3.617106
83	1.034731	0.257682	5.312003	1.328	6.494	1.626	11.01349	2.751872
84	0.65	0.162	3.098667	0.774666	6.494	1.626	10.15347	2.536617
85	0.65	0.162	0.9	0.225	6.494	1.626	9.009	2.252
86	0.800382	0.199095	1.300382	0.325095	6.659624	1.669906	11.68962	2.921906
87	0.65	0.162	0.9	0.225	6.749083	1.694771	14.29408	3.572771
88	1.056873	0.263219	1.556873	0.389219	6.494	1.626	14.77682	3.693206

#	1-65-1*	1-65-4	1-90-1	1-90-4	10-65-1	10-65-4	10-90-1	10-90-4
89	0.875332	0.217333	1.625332	0.406333	6.494	1.626	12.17774	3.043184
90	0.65	0.162	0.9	0.225	6.494	1.626	11.03905	2.758263
91	0.981136	0.244283	1.481136	0.370283	6.494	1.626	9.009	2.252
#	1.204097	0.299524	1.954097	0.488524	6.494	1.626	10.739	2.68425
92	0.65	0.162	1.563463	0.390865	6.494	1.626	11.87774	2.968686
93	0.965402	0.240351	2.128865	0.532216	6.494	1.626	9.009	2.252
94	0.65	0.162	0.9	0.225	7.50996	1.88249	12.53996	3.13449
95	0.65	0.162	0.9	0.225	8.904707	2.233677	16.44971	4.111677
96	0.65	0.162	0.9	0.225	8.440627	2.120157	18.50063	4.624157
98	0.65	0.162	0.9	0.225	6.494	1.626	9.009	2.252
99	0.953848	0.237462	1.453848	0.363462	6.494	1.626	9.009	2.252
100	1.158627	0.288157	1.908627	0.477157	6.494	1.626	9.009	2.252

*Note: [x-y-z] notation in the table represents [container capacity, utilization factor, and demand arrival rate].
Eg: [1-90-1] means, at a scenario when container capacity =1, utilization factor=90% and demand arrival rate = 1

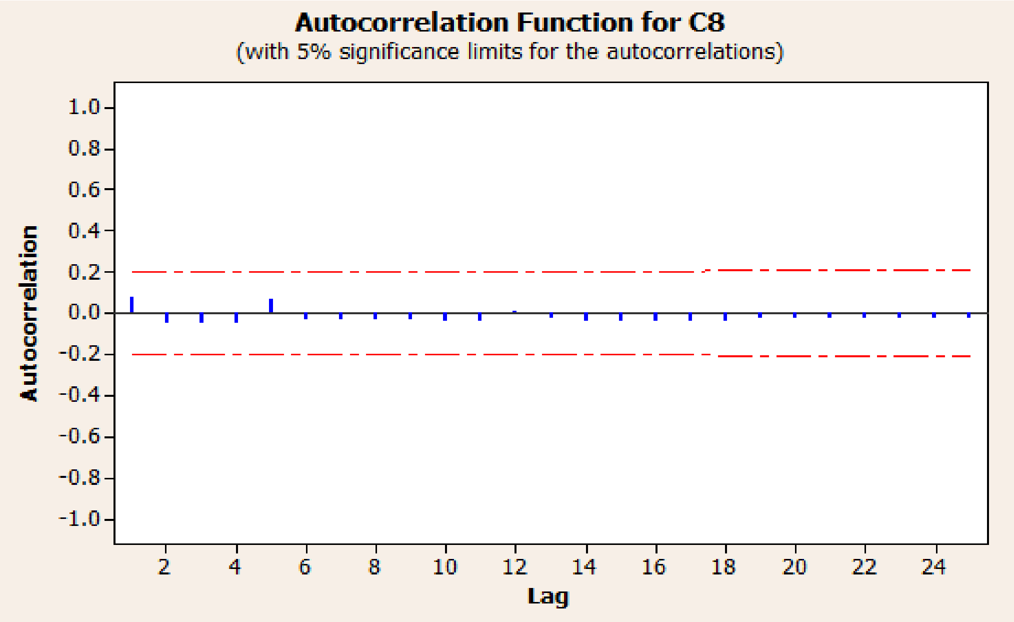
APPENDIX D

AUTOCORRELATION FUNCTIONS



Autocorrelation Function for C6
(with 5% significance limits for the autocorrelations)
Autocorrelation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2
4
6
8
10
12
14
16
18
20
22
24
Lag

10-90-4



Autocorrelation Function for C8
(with 5% significance limits for the autocorrelations)
Autocorrelation
1.0
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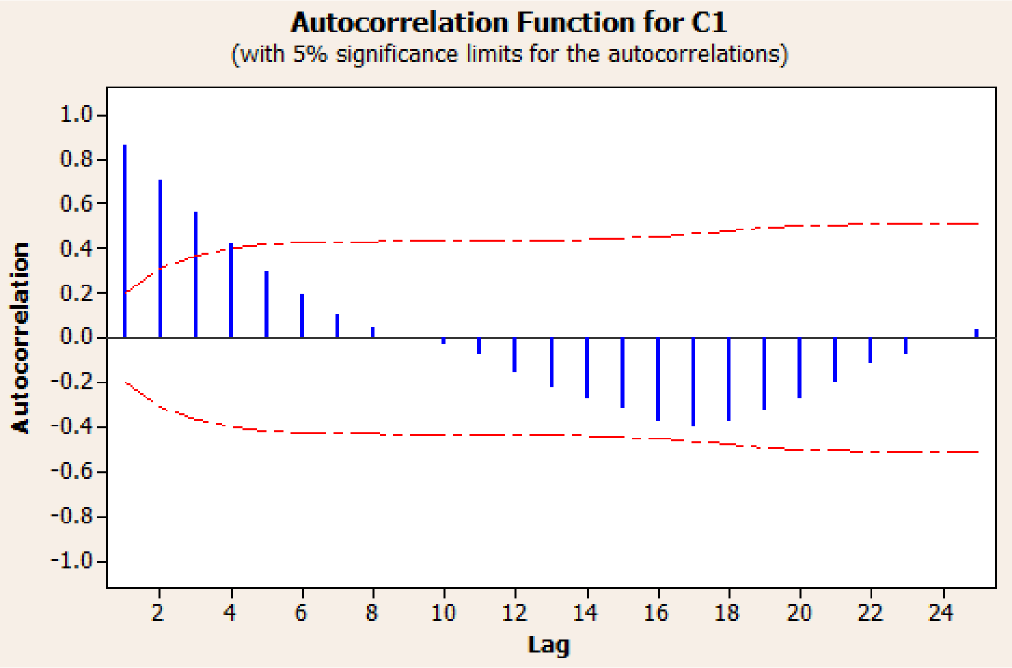
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2
4
6
8
10
12
14
16
18
20
22
24
Lag

10-65-4


Autocorrelation Function for C1
(with 5% significance limits for the autocorrelations)
Autocorrelation
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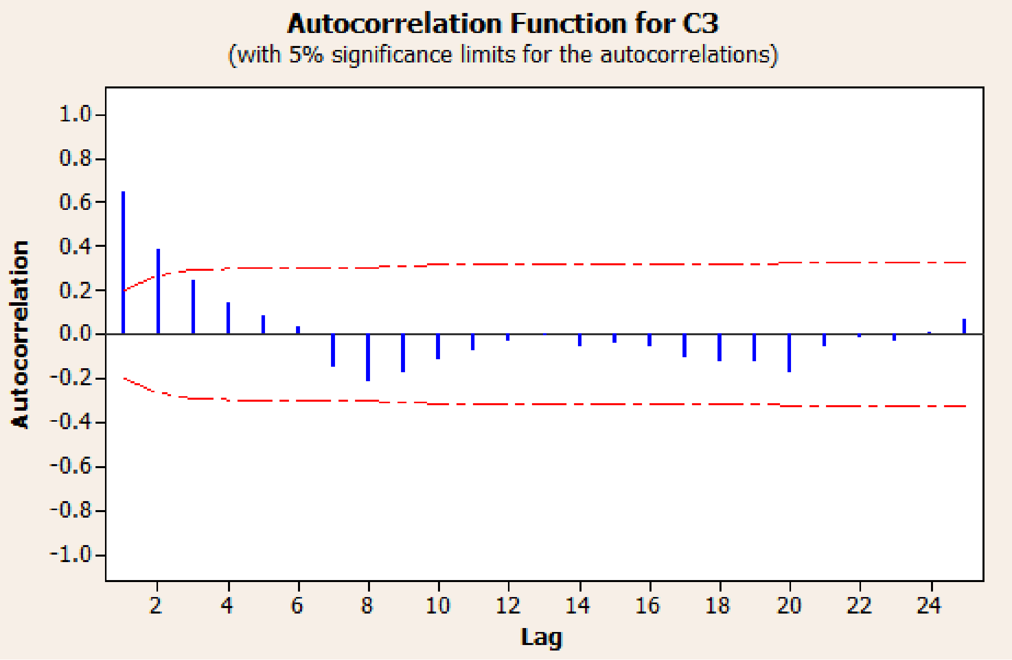
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2
4
6
8
10
12
14
16
18
20
22
24
Lag

1-90-1


Autocorrelation Function for C3
(with 5% significance limits for the autocorrelations)
Autocorrelation
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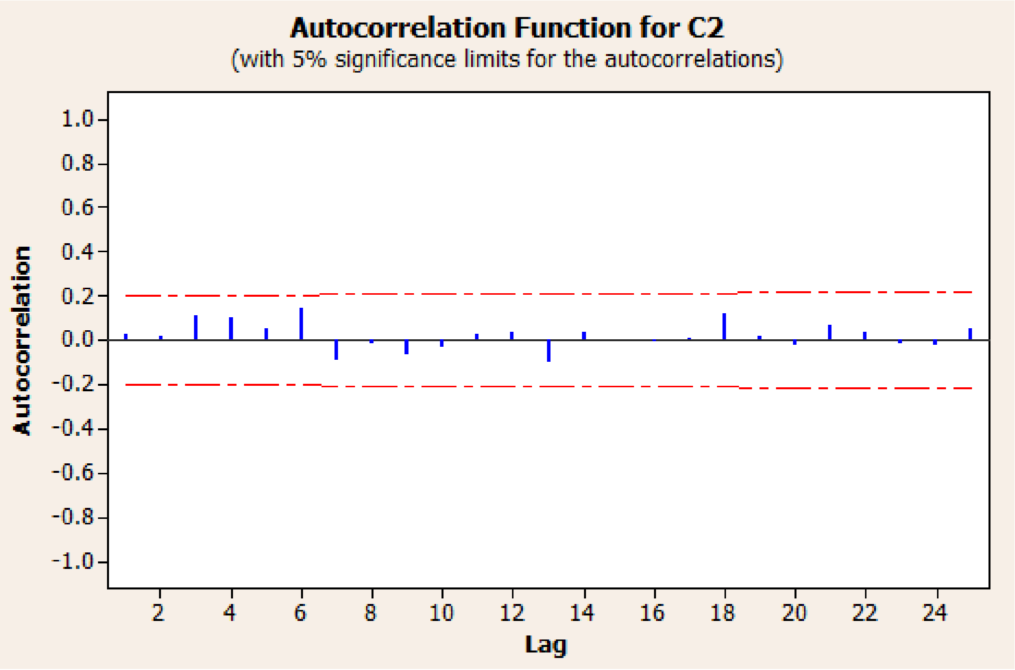
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2
4
6
8
10
12
14
16
18
20
22
24
Lag

1-65-1


Autocorrelation Function for C2
(with 5% significance limits for the autocorrelations)
Autocorrelation
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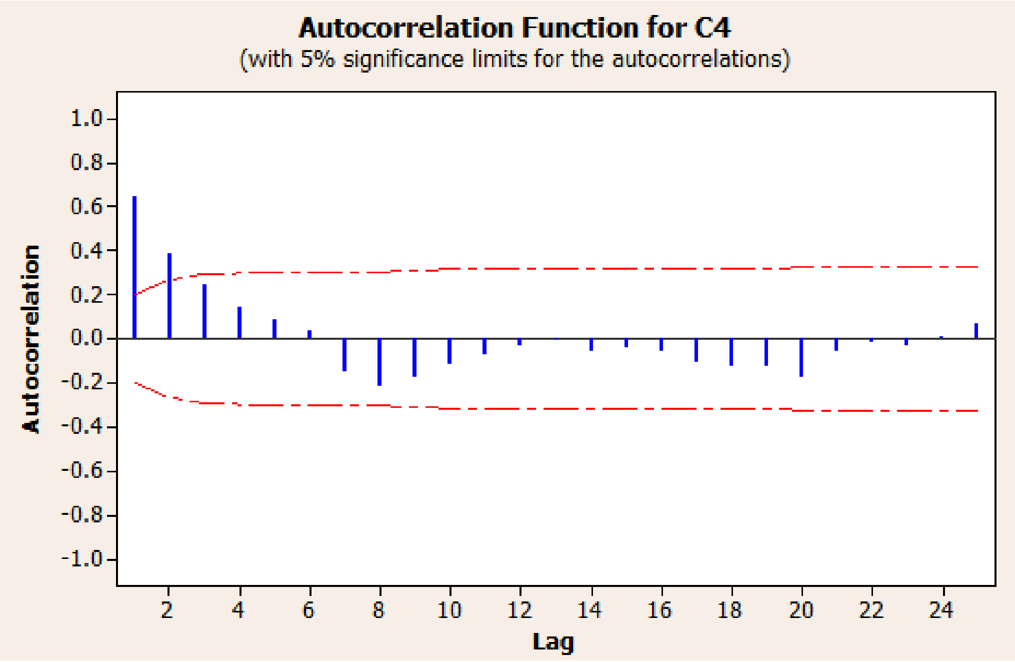
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2
4
6
8
10
12
14
16
18
20
22
24
Lag

1-90-4


Autocorrelation Function for C4
(with 5% significance limits for the autocorrelations)
Autocorrelation
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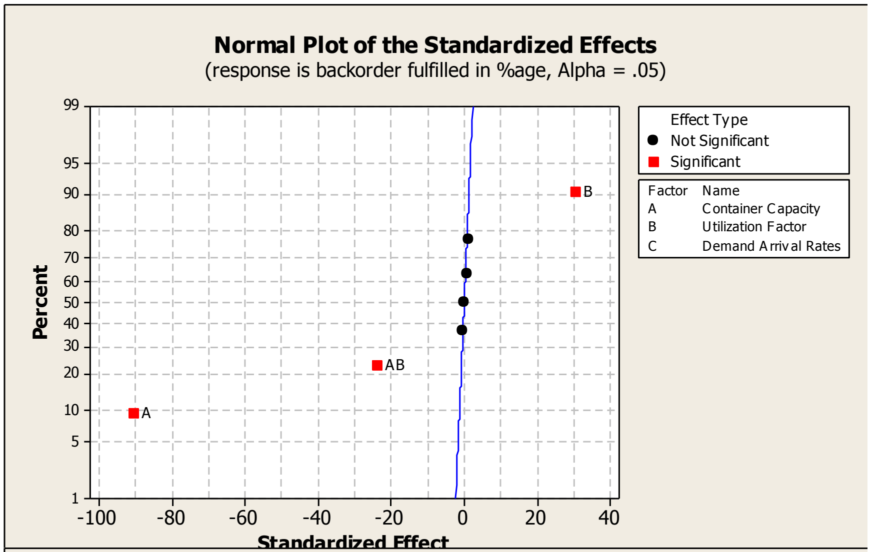
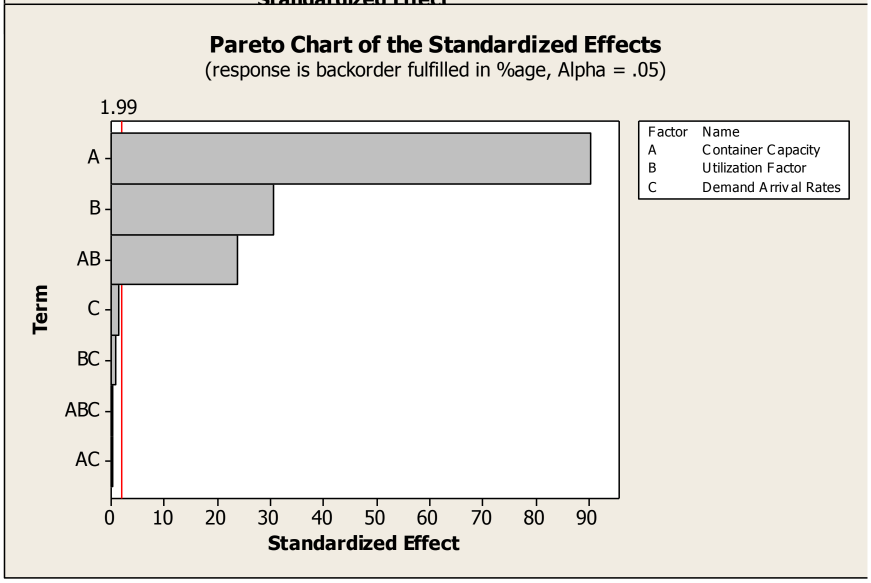
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
2
4
6
8
10
12
14
16
18
20
22
24
Lag

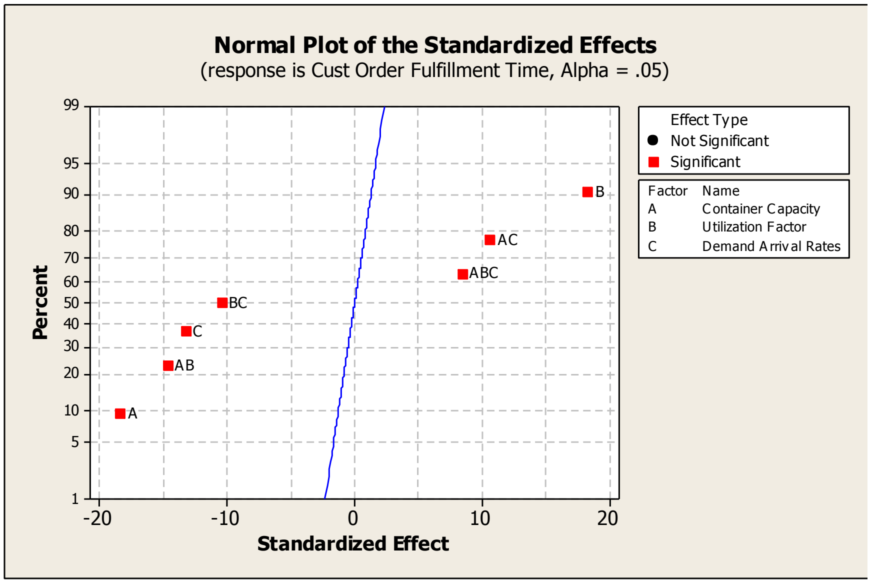
1-65-4

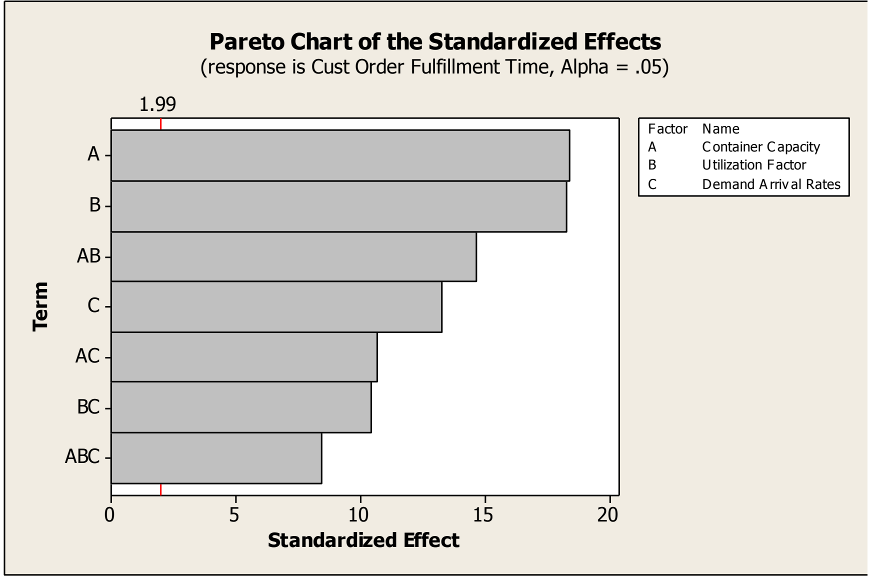
APPENDIX E

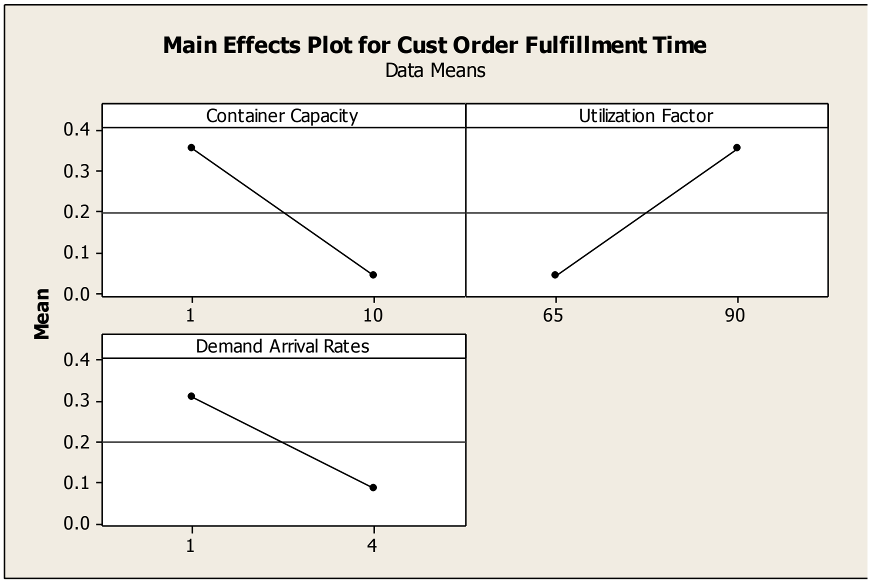
MAIN EFFECTS AND INTERACTION EFFECT PLOTS

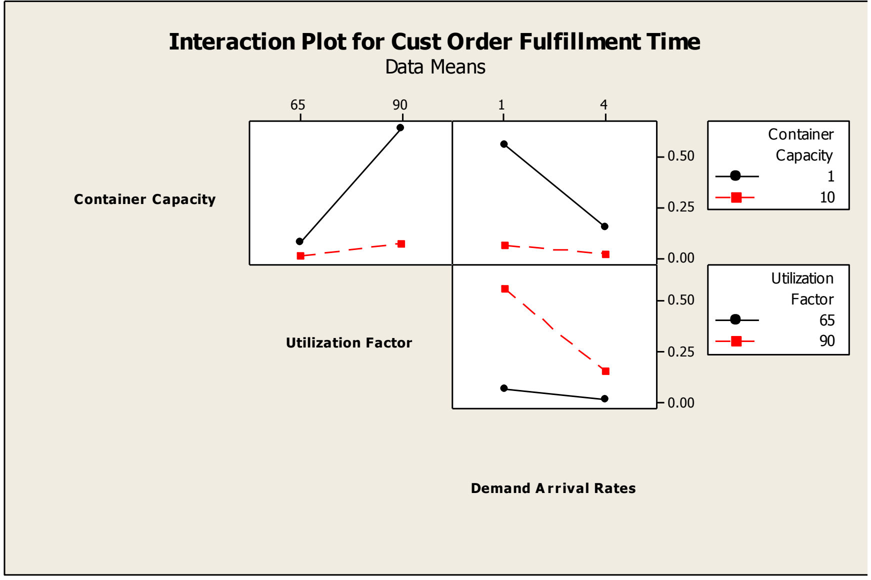

Normal Plot of the Standardized Effects
(response is backorder fulfilled in %age, Alpha = .05)
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-100
-80
-60
-40
-20
0
20
40
Standardized Effect
B
AB
A
Effect Type
● Not Significant
🟥 Significant
Factor Name
A Container Capacity
B Utilization Factor
C Demand Arrival Rates


Pareto Chart of the Standardized Effects
(response is backorder fulfilled in %age, Alpha = .05)
1.99
Term
A
B
AB
C
BC
ABC
AC
0
10
20
30
40
50
60
70
80
90
Standardized Effect
Factor Name
A Container Capacity
B Utilization Factor
C Demand Arrival Rates


Normal Plot of the Standardized Effects
(response is Cust Order Fulfillment Time, Alpha = .05)
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-20
-10
0
10
20
Standardized Effect
A
AB
C
BC
ABC
AC
B
Effect Type
● Not Significant
🟥 Significant
Factor Name
A Container Capacity
B Utilization Factor
C Demand Arrival Rates


Pareto Chart of the Standardized Effects
(response is Cust Order Fulfillment Time, Alpha = .05)
1.99
Term
A
B
AB
C
AC
BC
ABC
0
5
10
15
20
Standardized Effect
Factor Name
A Container Capacity
B Utilization Factor
C Demand Arrival Rates


Main Effects Plot for Cust Order Fulfillment Time
Data Means
Container Capacity
Utilization Factor
Demand Arrival Rates
Mean
0.0
0.1
0.2
0.3
0.4
1
10
65
90
1
4


Interaction Plot for Cust Order Fulfillment Time
Data Means
65
90
1
4
Container Capacity
Utilization Factor
Demand Arrival Rates
0.00
0.25
0.50
Container Capacity
1
10
Utilization Factor
65
90