Improving Inventory and Production Control in an Electronic Company: Capacity Planning, Base Stock Policy, and Kanban System

By

Youqun DONG

B.Eng., Mechanical Engineering
Wuhan University, 2008

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING IN MANUFACTURING

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2009

Signature of Author ______________________________
Department of Mechanical Engineering
August 18, 2009

Certified by______________________________
Stanley B. Gershwin
Senior Research Scientist of Mechanical Engineering
Thesis Supervisor

Accepted by______________________________
David E. Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Chairman, Department of Committee on Graduate Students

Improving Inventory and Production Control in an Electronic Company: Capacity Planning, Base Stock Policy, and Kanban System

By

Youqun DONG

Submitted to the Department of Mechanical Engineering
on August 18, 2009 in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering in
Manufacturing

Abstract

This research developed improved methods of inventory and production control in an electronic manufacturing company, which faces fluctuating seasonal demands and is categorized as a multiple part type production system with mixed low and high volume manufacturing.

In the first stage of the project, the daily operation in the factory was examined systematically, and it was observed that the factory's original methodologies in demand analysis, capacity planning, material flow control, and production and inventory control were heuristic, and have been introducing confusion and extra uncertainty into the factory. In the second stage of the project, an integrated approach was introduced to the factory. A long-term capacity planning optimization framework was developed for the systematic capacity planning during peak season; ANOVA was applied to identify the demand seasonality; operational changes were made to smooth the material flow in the factory, and a base stock inventory control policy was adopted to improve the inventory and production control at individual stages in the factory. Lastly, a Kanban production control system was developed based on the chosen base stock policy.

Using current factory data, the performances of the chosen base stock policy at a single production stage were studied with a simulation model. It was observed that the new inventory control policy could achieve a 17% cost reduction at the studied stage, and even bigger cost reduction for the whole production line.

Key words: capacity planning, base stock policy, inventory control, production control, Kanban system design

Disclaimer: The content of the thesis is modified to protect the real identity of the attachment company. Company name and confidential information are omitted.

Thesis Supervisor: Stanley B. Gershwin
Title: Senior Research Scientist of Mechanical Engineering

Acknowledgement

I would like to thank my thesis supervisor, Dr. Stanley B. Gershwin, for his academic guidance during this project. His sensitivity to details and dedication to excellence have motivated me to learn more and think deeper during the project. I also want to express my thanks to Dr. Stephen C. Graves for his generous help with explaining the inventory policy we adopted in this project.

Next, I would like to thank my colleagues in the attachment company. I want to thank Mr. Yan Mun Tjun, our company supervisor, for his patience and continuous guidance for us all through the project despite his hectic schedule. The knowledge and wisdom he shared with us will benefit me for my whole career. Thank Mr. Tai Soon Wah for his help in data collection and discussion. Thank Ms. Ng Ah Soon for her logistics supporting all through the project. My thanks also go to Mr. Koh Choon Hoe for his help with explaining the production processes.

I want to thank Dr. Brian W. Anthony for visiting us in Singapore frequently, coordinating activities for us, and his suggestions to our projects. At the same time, I would like to thank Ms. Jennifer L. Craig for her great help with my thesis writing.

I would like to give my respects and thanks to my teammate, Zhong Yuan. This project could not be finished smoothly without his talent and consistent input. I also want to thank the other two teammates Xiaoyu Zhou and Zia Rizvi for their support all through the project.

Lastly, I would like to thank my parents for all their love to me during my study.

Table of Content

List of Figures

List of Tables

Chapter 1. Introduction

This chapter briefly introduces PDAP Electronics Singapore, including its products classification, production process flow, and demand management process. At the end of this chapter, the M.Eng. project is introduced, and the project roadmap is described to provide an overview of the whole project.

1.1 Company Background

PDAP Electronics Singapore, the project attachment company, is one subsidiary company under RP Electronics organization. It dedicates in one product of the organization. Recently, the organization headquarter management has initiated the implementation of a system analogous to Toyota Production System and encourages the facilities to operate in a LEAN environment. PDAP Electronics Singapore is one of the few chosen factories that are included in the pilot project. Since the factory management is committed to embark on the LEAN production journey, it has set goals for reducing wasteful activities and controlling inventory lying along the production lines.

1.2 Product Classification

The products of this factory are seasonal consumer products. All the products manufactured in this factory can be classified into Class-A and Class-B product categories based on their target markets and technical specifications.

There are 3 product families in Class-A product category, and 6 product families with a total of 10 product models in Class-B product category. Each product family and model has further variants and the whole product portfolio has over 50 stock keeping units (SKU) at the finished goods level. The product classification tree is shown in Figure 1-1. In Figure 1-1, there are four product category levels, namely class level, family level, model level, and SKU level. Class A and Class B are on the class level, MR, D, ND, SR, BA, LE, CP, and SY are on the family level, and SR-AZ and its peers are on the model level. The SKU level classifications are not shown in Figure 1-1.

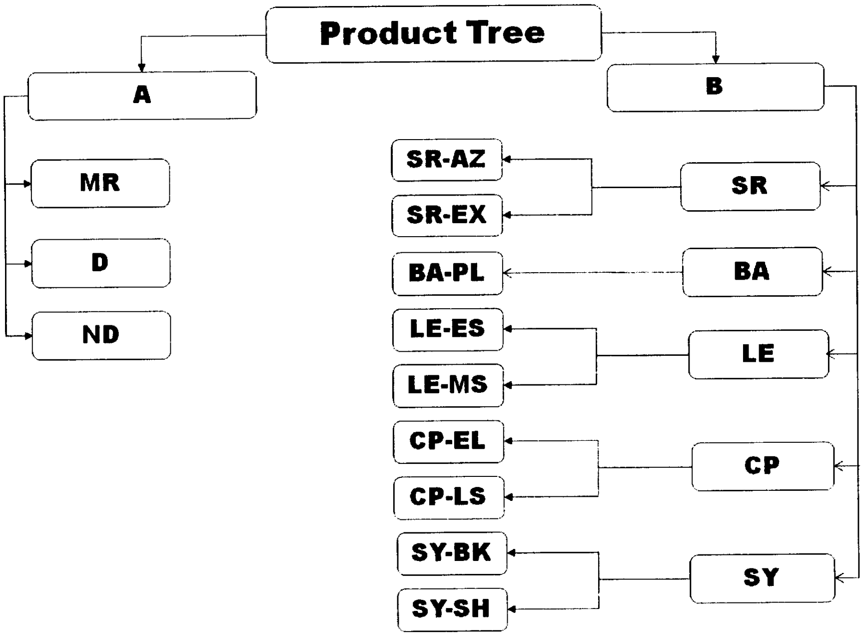


Figure 1-1.Product classification

1.3 Production Process Flow

There are 7 main production stages in PDAP Singapore factory as shown in Figure 1-2. Not all products go through the same processes. All products share stage 1 and 2 initially in their manufacturing processes. After the first two processes, Class-A products are routed to their dedicated production stage 4, and Class-B products are routed to stage 3 before they enter stage 4. After stage 4, some products enter finished goods inventory directly, some products go to stage 5 and stage 7 in sequence for further processing, and others go through all the remaining stages shown in Figure 1-2.

1.4 Demand Management Process

The head quarter of RP organization provides monthly demand forecast to PDAP for the coming year by the end of November of the current year. Every month, the demand forecast is updated for the current month and the remaining months of the year within the first week. It also provides a weekly rolling demand orientation values for the next 52 weeks with rough estimates for the weeks in the following year.

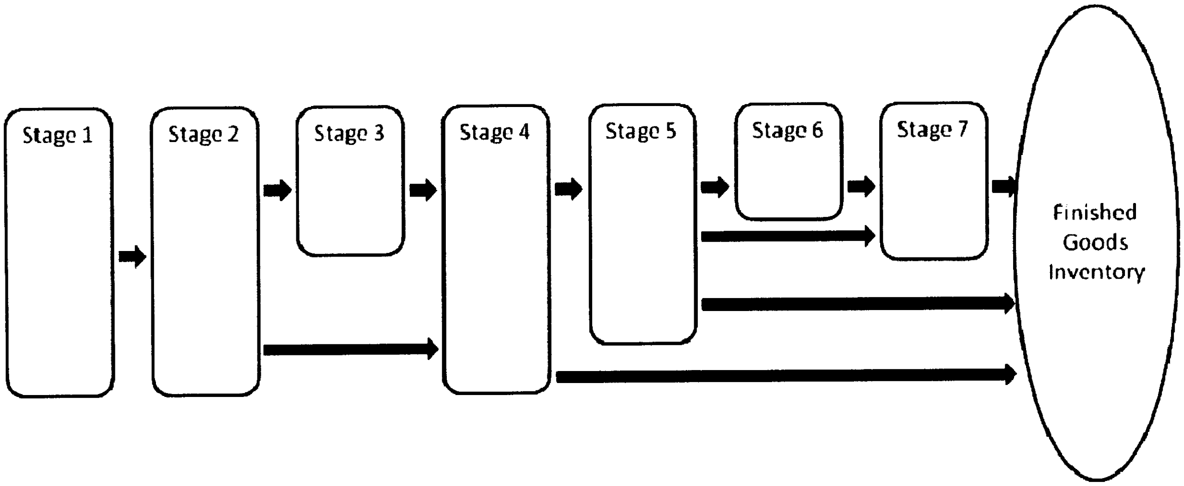


Figure 1-2.Process flow

After the factory receives the forecast, the demand management process begins as shown in Figure 1-3. There are three key people in this process, production planner, factory planner, and commercial planner. The production planner mainly develops the Weekly Production Schedule (WPS), and the commercial planner makes the Monthly Production Schedule (MPS) with the factory planner. The demand management process is elaborated as follows.

First, the commercial planner prepares the MPS at finished goods level (only) based on the monthly forecast from the head quarter. During this process, the production planner provides a weekly constraint list to the factory planner based on his anticipated stock values for the coming week, and the factory planner inform the capability for each product model to the commercial planner. The commercial planner finalizes the MPS based on this information.

Second, the WPS is finalized based on the finalized MPS. The production planner converts the finalized orders sent by the commercial planner and the factory planner into a locked WPS for the next week and a tentative WPS for the second next week.

During the development of the MPS, if the factory planner finds out the demand will exceed the total capacity of the factory, he will shift the excess demand forward to make sure these demands are fulfilled, and this process is called stock building plan development.

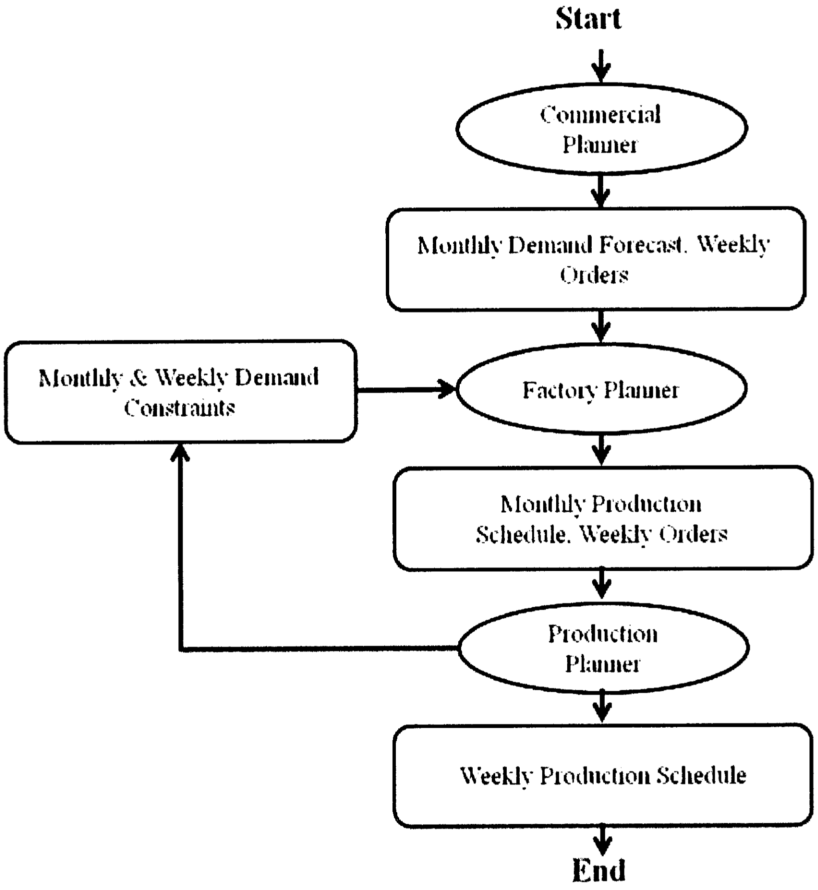


Figure 1-3.Demand management process

1.5 Project Introduction

This project is an M.Eng. project done by a group of M.Eng. students from Massachusetts Institute of Technology. There are four members in this group, Yuan Zhong, Xiaoyu Zhou, Zia Rizvi, and Youqun Dong, the author of this thesis.

To facilitate the LEAN transformation initiated by the company recently is the overall project objective for this M.Eng. project. This project mainly focuses on the operational problems in this factory, and the specific project objectives are:

1. Propose a proper inventory control policy. This inventory control policy is to help the factory to set up interstage inventory buffers (in this thesis, this is called supermarket) to control the work in process inventory along the production line.

2. Propose a production control policy to help trigger production along the production line and set up daily production targets for different production stages.

3. Smooth the material flow to reduce the waste caused by the mismatch of material handling batch sizes along the production line.

After examining the daily operation in the factory systematically, it was observed that the factory's original methodologies in demand analysis, capacity planning, material flow control, and production and inventory control were heuristic, and have been introducing confusion and extra uncertainty into the factory.

To study and solve the problems effectively, the project team was divided into two sub groups with different focuses. Yuan Zhong and the author were in the same sub group focusing on the upstream production line in this factory, while Xiaoyu Zhou and Zia Rizvi were in the other sub group focusing on the downstream production line in this factory.

In this thesis, I mainly focus on the long-term capacity planning methodology in demand management, the material flow smoothing methodology, and the single-stage simulation for the chosen inventory control policy. The detailed project scope for this thesis will be described in section 2.2. My partner Yuan Zhong concentrates on the demand seasonality analysis and the single-stage inventory calculation based on the chosen inventory control policy. In the other sub group, Xiaoyu Zhou focuses on the short-term production leveling in demand management, and the multi-stage inventory calculation based on the chosen inventory policy; Zia Rizvi focuses on a capacited shipment methodology and the multi-stage simulation for the chosen inventory control policy. Please refer to Yuan Zhong[1] Xiaoyu Zhou[2] and Zia Rizvi[3] to know the detail of their work.

1.6 Project Roadmap

The whole project was carried out by stages as shown in Figure 1-4. In Figure 1-4, the rectangular shapes represents the project stage, the oval represents the tasks or targets of the corresponding project stage, and the arrows represent the sequence of the project.

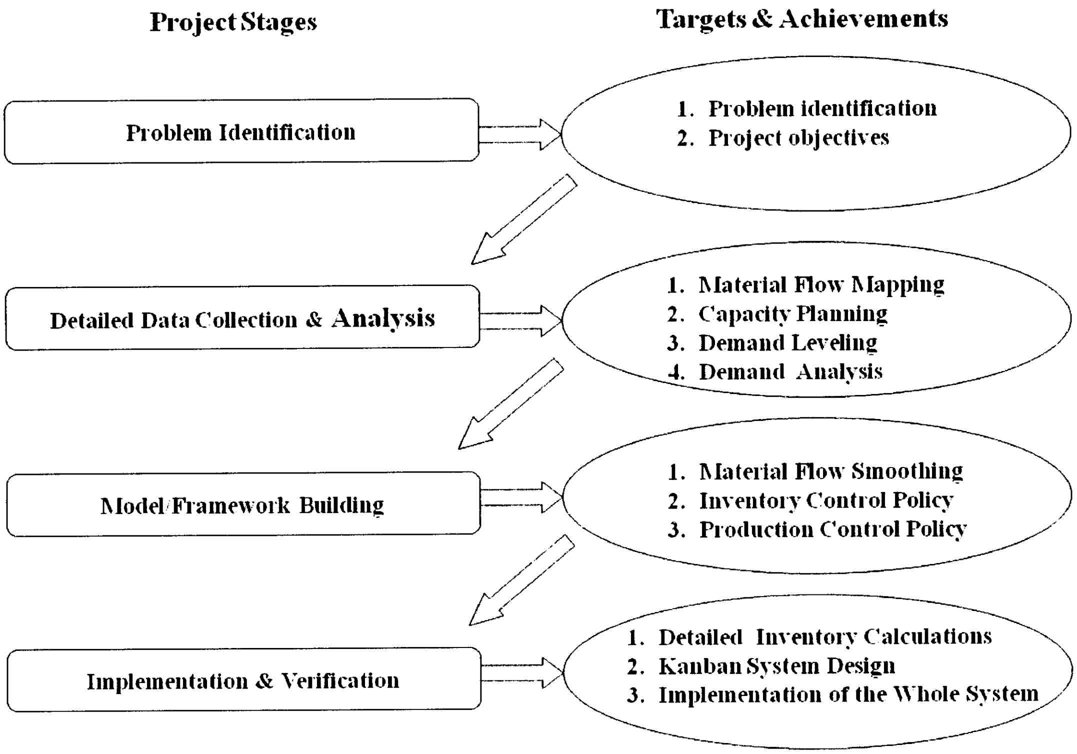


Figure 1-4.Project roadmap

The project started with the problem identification stage. Targets set by the management were briefed first, and then the preliminary data of the production line was collected to identify the potential obstacles to the targets set by the management. Based on the interviews with line supervisor and the study of the production line, potential problems of this system were identified and will be discussed in section 2.1.

To solve the problems, relevant data were collected. First, historical demand data and production plan data were collected for demand management investigation and capacity planning analysis. Then factory parameters such as production cycle time, production rate, line capacity, production batch size, yield, MTTF, MTTR, inventory holding cost, and unit product cost were collected to help us understand the factory, and propose corresponding solutions. At the same time, some factory performance indexes were defined to evaluate the effect of the solutions from this project, including the inventory level at each production stage and the internal and external customer service level

After the data collection stage, the solutions to solve problems discussed in Chapter 2 were proposed, and an inventory and production control framework was built up.

At last, the proposed methodologies were simulated and analyzed with a simulation model, based on which recommendations were made to the factory. Then the methodologies were implemented on some trial products at some production stages, and the performance data is being collected.

Chapter 2. Problem Statement and Thesis Outline

This chapter first provides a description of the problems identified from this system, and then discusses the scope of this thesis. At last, it lists the outline of this thesis.

2.1 Problem Statement

This section describes the main problems unveiled from the current PDAP production system, which can be categorized into two major categories. Problems in areas such as demand analysis, production and inventory control, material flow coordination all belong to operational problems. Problems with company culture and business environment are categorized as business environment problems. In this section, 2.1.1 to 2.1.4 describes 4 main operational problems, and section 2.1.5 discusses a few existing cultural or business environment problems. Though this thesis focuses on solving the operational problems, it provides some insights and recommendations on the business environment problems in this chapter and Chapter 6.

2.1.1 Demand Management Problem

(1) Capacity Planning Problem

The aggregated annual production capacity in this factory is bigger than the aggregated annual demand, however, during the peak demand season, the demand will exceed the capacity of certain production stage. As described in section 1.6, if this happens, the company will make a stock building plan to shift the excess demand to the low demand season before peak season. Sometimes this stock building plan is only developed for the last production stage, which triggers the planning process for the upstream production stages. But they neglected one important fact that building up stock at the last production stage may be more expensive than building up the stock at the upstream stages. Furthermore, the factory only considers the capacity constraints when making the stock building plan, but they neglected the fact that the value of different products may be different, and there should be priority during the stock building process. Because building up the expensive products earlier will increase the inventory holding cost. So a new perspective for the stock building process is needed.

(2) Demand seasonality analysis

This factory plans its operation according to the projected demand pattern during a year. Different operating strategies are used during different seasons, e.g. capacity planning, inventory building targets etc. Hence, being able to reliably determine the demand seasonality is important. Normally this is done by the factory planner's judgment. Based on past experience, the management characterizes the demand into alternating high and low seasons. The high season starts from the middle of the year to around October or November. The low season spans from the end of the year through the first half of the next year. However, the results from this heuristic methodology are not stable or reliable, and there have not been any statistical methods to help the factory determine the seasonality reliably.

2.1.2 Production Control Problem

The current production control process is: the production planner conducts a daily meeting with production stage supervisors to follow up on production targets and shipments. The production plan developed by the production planner serves as the benchmark for each production stage during the current week. However, it is discovered that the factory planner does not plan for stage 3 because of some authority issues left from the company history. Stage 3 has to trigger its own production based on the supervisor's judgment of the upstream work-in-process inventory level, its own stock level and the available capacity. This production control process is shown in Figure 2-1. In this figure, the block horizontal arrows represents the general material flow direction, the line arrows represent the planning signal sent from the production planner to the individual production stages, and the curved arrow depicts the self-planning process of stage 3.

This production control and planning system cannot provide stage 3 with clear production targets, and it involves a great deal of human judgment that leads to arguments and confusion during production. These characteristics of the current production control system results in the unstable interstage customer service level, and the deviation from the production target for the whole production system. This makes the whole production system unstable and hard to control. So a new production control system is needed.

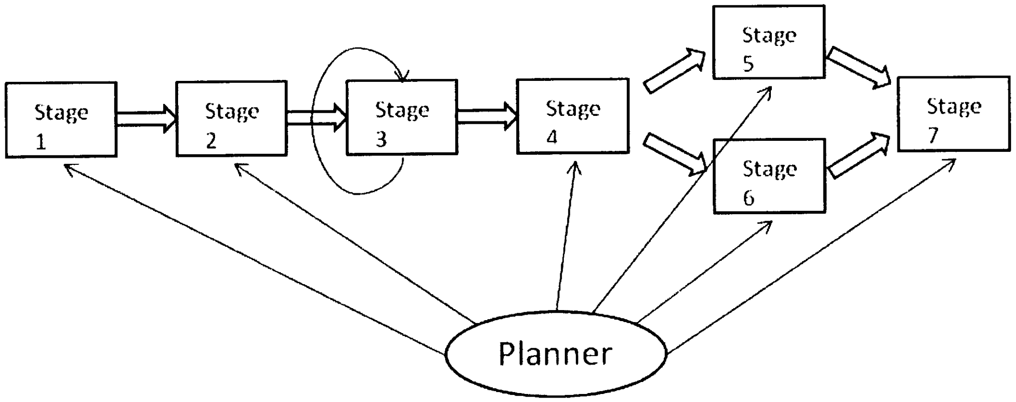


Figure 2-1.Illustration of the original production control mechanism

2.1.3 Inventory Control Problem

This production system has heavy resources sharing phenomenon as already explained in the production process flow description in section 1.3. For instance; stage 3 is a single line stage which supplies five downstream lines in stage 4. So stage 3 is subjected to simultaneous demand of multiple products that needs to be processed on downstream lines, which causes problems with determining the inventory mix after stage 3.

At the same time, the production control problem discussed in section 2.1.2 also causes inventory control problems. For example, if there is difficulty in executing the unsynchronized production plan for some product, the line supervisors tend to keep the lines running on any other available raw materials and try to maximize the line utilization, even these material are not required from downstream. This results in over production and unnecessary inventories along the line.

Careful investigation of all this problems leads us to the conclusion that there is currently no effective inventory control policy integrated with the current production system. The supervisors' subjective judgment causes desynchronized production planning and unreasonable inventory levels along the production line. Hence, a more effective inventory control framework is needed.

2.1.4 Material Flow Problem

In this factory, materials are transferred in batches along the production line, and most of the production stages produce following the same batch size. Different production stages adopt different batch sizes as shown in Figure 2-2 (only 5 stages are illustrated in the figure). The batch size mismatch along the production line causes unnecessary extra material flowing into the downstream production stages from the upstream production stages, and also distorts the demand to upstream stages from downstream stages.

For example, the batch size flow for one product is 300, 900, 840, 200, and 600 as shown in Figure 2-2. When the demand is 1100pcs for stage 7, it has to produce 1200pcs (2 pallets), and transfer 6 trolleys from stage 4. So stage 4 has to transfer 1680pcs (2 trolleys of 840) from stage 3, and stage 3 has to transfer 1800pcs (2 containers) from stage 2. At last, stage 2 has to transfer 1800pcs from stage 1. We can see that to fulfill a demand of 1100pcs, there are 1800pcs products released into this production line from stage 1, and there are 700pcs extra products along the line with the locations shown in Figure 2-3. We can see that the extra material is mostly kept at the downstream lines, where the inventory holding cost is higher. So it is necessary to look into his problem and reduce the waste caused by the mismatch of the current batch sizes.

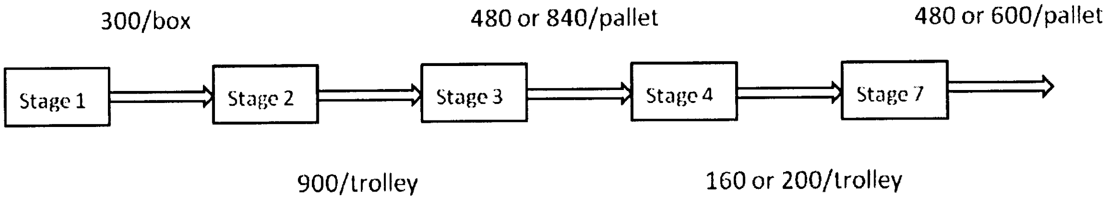


Figure 2-2.Batch size along the production line

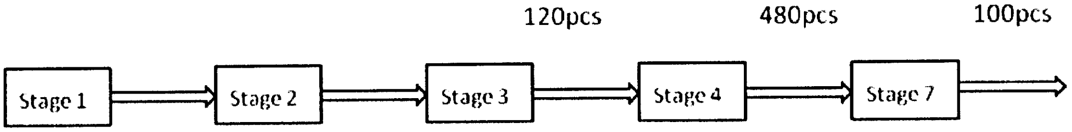


Figure 2-3.Demonstration of the waste

2.1.5 Cultural Problems

The LEAN movement has just been initiated lately in this factory as described in Chapter 1. Just as any revolution, the original culture and business concepts may be challenged by this LEAN concept during the LEAN movement. It will be better to look at the potential problems at the beginning of the revolution.

This LEAN revolution challenges the experience based culture in this company. For some departments in the company, the employees have been working on the same position for one or two decades. There is no job rotation or sharing of new knowledge in this company. There are a few limitations of this. First, some basic underlying assumptions of the current system have never been checked because the employees are too familiar with their own job to discover any problems. Second, the labor force is dedicated and cannot be utilized in other jobs without a high training cost, which actually reduce the potential utilization of the labor force. Lastly, it has developed a company culture that is reluctant to change and evolve.

Besides, the communication between different departments is not effective. For example, there were some jobs done by engineering department which will improve the performance of manufacturing department. However, these achievements were stacked into the files in the engineering department and never transferred or shared with the manufacturing department. So the knowledge in the whole system is not open, but constrained in independent departments.

2.2 Individual Project Scope

The author's sub group focused on production stage 3 in this project. Production stage 3 is a single line production stage. All Class B products, which are 70% of the total demand for this factory, have to go through this stage. As described in section 2.1, there is no production plan for stage 3, and it is hard for it to decide the reasonable inventory mix or set up reasonable production target. So it is important to study stage 3 and help the company to set up the inventory and production control framework for this stage.

Besides this common objective of the sub group, I focused on the capacity planning framework development for the factory, material flow smoothing along the production line, and the simulation of the chosen inventory control policy at production stage 3 to help the company make decisions such as the proper batch size to choose, and the proper inventory level to keep at stage 3.

2.3 Thesis Outline

Chapter 1 introduces the attachment company, including the company background, product category, and demand management process. At the end, it introduces the M.Eng. project briefly.

Chapter 2 describes problems identified from the current factory, including the operational problems and cultural problems. After this, it presents the scope of this thesis and thesis outline.

Chapter 3 reviews literatures related to the studied problems to help understand and solve the problems identified.

Chapter 4 analyzes the problems identified in Chapter 2 in detail, and develops methodologies to solve them, including methodologies in long-term capacity planning, demand seasonality analysis, material flow smoothing, implementation and simulation of the base stock policy, and Kanban system design.

Chapter 5 presents and discusses results from the implementation of the methodologies developed in Chapter 4 with the help of a simulation model.

Chapter 6 summarizes the whole thesis and proposes recommendations to the factory. At the end, current project is criticized, and potential future work is discussed.

Chapter 3. Literature Review

In this chapter, literatures relative to the problems described in chapter 2 were reviewed and criticized, including previous theses done in this factory, and literatures in manufacturing systems, inventory control policies, production control, and visual management techniques.

3.1 Long-Term Capacity Planning

Hua Xia [4] described a long term capacity planning methodology for a multi-product production stage in the same attachment company based on lead capacity planning strategy. The basic concept of her method is to identify the stock building period under the capacity constraint of the studied stage. In her method, the major products at the studied stage were identified first, and then the total excess demand for each product during peak season was calculated. After this, the weekly spare capacity of the studied stage was calculated, based on which the stock building plan was developed. The method she proposed would help the company to avoid unnecessary labor cost and provided the company with a framework to plan the capacity for a single production stage.

Though the method worked well under the scenario she discussed in her thesis, there are two limitations of this method:

First, the value difference of the stock building products was not considered. In her method, only capacity constraints were considered. In reality, the stock building products may change every year with new products entering the market and end-of-life products eliminated from the market, and the values of them will also change most likely. This value difference will affect the extra inventory cost encountered during the stock building period, and there should be a strategy to help the factory to develop the right stock building plan with production priority concerning the value difference of the stock building products.

The second limitation is that, Hua Xia assumed that the operation of the studied production stage is not constrained by the upstream and downstream stations in the production system, and she did not evaluate the impact of the stock building plan on the upstream production stages. But in reality, the capacity of the upstream stages may be exceeded because of the stock building plan at downstream stages.

3.2 Manufacturing Systems

3.2.1 Push Production System

A push production system builds up its inventory according to long-term demand forecasts [5].It works well when the demand is steady and predictable, during ramp-up phase, or for predictable seasonal demand [6]. However, due to the innate forecast errors, such a system is prone to product shortages and over production when the demand fluctuates. To buffer against such risks, large inventories are typically kept, especially towards the upstream of the production line. The large inventory buffer renders the system highly inflexible in face of uncertainty.

3.2.2 Pull Production System

In essence, a pull production system only produces what the demand asks for, without relying on demand forecasts to guide its operation. Ideally, production is identical to demand, eliminating the risk of over production. In a pull system, the material flow and information flow travel in opposite directions. There are generally three typical ways of realizing pull production in a factory, namely:

(1) Supermarket pull system

(2) Sequential pull system

(3) Mixed supermarket and sequential pull system [7]

In the supermarket pull system, a safety stock is kept for each product, from which the downstream processes could directly pull. The process upstream of the supermarket is only responsible for replenishing whatever is withdrawn from the supermarket. This arrangement enables short production lead-time when demand arrives. The inventories in the supermarket could also be used to help level production.

A sequential pull system converts customer orders into a "sequence list" which directs all processes to complete the orders. The production schedule is placed at the first stage of the production line. Then each process works sequentially on the items delivered to it by the previous process. As a result, there is no need for large system inventories. Yet, this may lead to longer production lead time and requires high system stability to perform well. A mixed system of the above two could be applied to reap their distinct advantages.

In a mixed system, the supermarket pull system and sequential pull system could operate in parallel on different products or on different part of the production system.

3.2.3 Push-Pull System

In practice, pure pull system may not always be possible. In some occasions, a combined push-pull system is constructed to exploit the benefits of both. Usually, push is adopted at the back end of the system to cut production lead time, while the front end is operated by a pull strategy to limit inventory levels.

3.2.4 Customer Service Level

Customer service level is a crucial measure of production system performance. It measures the system's ability to satisfy the demand delivered to the system in a timely manner. Although its actual definition may vary, two definitions are commonly used [8]:

Type I customer service level: Probability of stock out when there is an order.

Type II (fill rate) customer service level: Percentage of demand met from inventory.

3.2.5 Mean-time-to-failure (MTTF) and Mean-time-to-repair (MTTR)

MTTF and MTTR are important process parameters in a manufacturing system. MTTF is the average time passed by before a machine goes down, whereas MTTR refers to the average time required to repair a machine after it is down [9].

3.3 Inventory Control Policies

There are lots of literatures about inventory control policies. MIT course 15.762[7] discusses two inventory control policies for stochastic demand in general, one is continuous review policy (Q-R policy) and the other is periodic review policy (base stock policy).

3.3.1 Continuous Review Policy (Q-R Policy)

The Q-R policy continuously reviews the inventory level and releases new materials when it falls too low. The main parameters for this policy are the reorder point R and reorder quantity Q. Once the inventory level hits the reorder point, a fixed reorder quantity will be released to the factory floor. This policy is suitable for dedicated high volume production lines. Basic equations and parameters for this policy are shown below.

1) Reorder point R

$$R = \mu L + z\sigma L^{1/2} = \text{expected lead} - \text{time demand} + \text{safety stock} \qquad \textbf{Eq.3-1}$$

2) Average inventory level throughout the time window E[I],

$$E[I] = \left(E\left[I^-\right] + E\left[I^+\right]\right)/2 = \frac{Q}{2} + z\sigma L^{1/2} = \text{cycle stock} + \text{safety stock} \qquad \textbf{Eq.3-2}$$

Notations in the equations:

Q: reorder quantity

μ : demand rate

r: review period in days

z: safety factor

б: standard deviation of demand

L: lead time for replenishment

3.3.2 Periodic Review Policy (Base Stock Policy)

Base stock policy reviews the inventory level according to a fixed review period and tops up the inventory to a predetermined base stock level. The main parameters are the base stock level and the review period. The inventory level is reviewed once after every review period. If it is below the base stock level, production order will be released to the factory floor to replenish the inventory back to the predetermined level. This policy is suitable for production lines shared by multiple products. Basic equations and parameters are shown below.

1) Base stock B,

$$B=\mu(r+L)+z\sigma(r+L)^{1/2} \quad \textbf{Eq.3-3}$$

2) Average inventory level throughout the time window E[I],

$$E[I]=\frac{\{E[I(r+L^{-})]+E[I(r+L^{+})]\}}{2}=\frac{\mu r}{2}+z\sigma(r+L)^{1/2}=\text{cycle stock}+\text{safety stock} \quad \textbf{Eq.3-4}$$

r: fixed review period

The other parameter notations are the same as in the Q-R policy.

3.3.3 Discussion of the Inventory Control Policies

The Q-R policy is suitable for dedicated production lines, whereas the production system studied in this thesis has production resources with heavy resource sharing. This can lead to competing replenishment signals in the system. As a result, manual product prioritization is required and will be the determining factor of policy performance.

Base stock policy may be a better choice for this case where replenishment of individual model inventories can be carried out according to a preset review schedule. Yet, there are also some limitations.

Conventional base stock policy assumes an infinite production capacity with a fixed and deterministic replenishment lead time for each product. Based on this lead time, it derives the required base stock level to cover the demand within a review period. This might be a good approximation for products processed by a machine with little queuing, as the processing time is fixed by machine specifications. Nevertheless, actual production capacity is usually limited, forcing orders to queue up for a long time in front of the machine before processing. This is especially true when the machine processes many types of products, like the stage 3 in PDAP.

When demand levels of different products change, the waiting times fluctuate as well. This will significantly affect the production lead time and the corresponding requirement for safety stock.

However, the base stock policy discussed above has not provided any specific ways of calculating the projected lead times. The lead time values are completely subjective to user judgment. Hence, an improved model which provides mathematical ways of calculating production lead time under capacity constraints is needed.

3.4 Dr. Stephen Graves' Base Stock Policy

3.4.1 Model Introduction

Base stock model published by Dr. Stephen Graves in 1988 [10] deals with the limitations of conventional base stocky policy for shared resources discussed in section 3.3. This model takes the capacity constraint of the production line into account. It works well in smoothing daily production of a multi-item machine using a linear production rule, and determining each model's individual inventory level (Bi).

Some of the key equations and parameters of this model are listed as follows:

1) Proposed lead time by considering machine flexibility to expedite production and demand variations

$$n=(k^2\sigma^2+\chi^2)/2\chi^2 \qquad \textbf{Eq.3-5}$$

k : parameter that is associated with customer service level

б: standard deviation of weekly demand

χ: excess capacity

2) Daily leveled production

$$P_t=\frac{W_t}{n}=\frac{D_t}{n}+\frac{(n-1)P_{t-1}}{n} \qquad \textbf{Eq.3-6}$$

t: time period index

P: daily production quantity

D: daily demand quantity

W: work in process inventory at current production stage

3) For individual model (s) ‘i’:

raw material released exactly equals to the demand on day ‘t’

$$R_{it} = D_{it} \tag{Eq.3-7}$$

R: material release quantity

4) Base-stock calculation for individual model(s)

$$B_i = E[W_{it}] + E[I_{it}] = n\mu_i + k[n\sigma i(2n-1)^{1/2}] \tag{Eq.3-8}$$

μ_i : average demand for item i

3.4.2 Potential Limitation of this Base Stock Policy

There are two potential limitations for implementing this policy in reality. The first one lies in its assumption that this policy does not considering lot sizing effect. The other one lies in its basic material release rule described by Eq. 3-7. In a real manufacturing system, it is difficult to run the system without violating the basic assumptions or the material release rule. And the author did not discuss the possible impacts on the model if these two were violated. These two potential limitations of the model will be discussed in Chapter 5 with the help of a simulation model.

3.5 Visual Management [11]

“Visual management is a method of creating an information-rich environment by the use of visually stimulating signals, symbols and objects.” In simple word, it is the use of signs, lights, notice board, bright or contrasting painted equipment and graphic displays to catch people’s attention and to communicate important information. The goals of visual management are generating meaningful signals, and facilitating people in a factory to access information about what their tasks quickly and accurately, especially for those who do not hold any knowledge of the logic behind.

RAG (Red, Amber, and Green) (or traffic light system) system is “one type of the visual management system. It is a method of highlighting where attention is needed and avoiding attention where it is not needed on the factory floor.” [12]. Usually, this system uses a traffic light color-coding scheme. It works as follows, Red represents "needs urgent action" (out of control, shortage imminent); Amber represents "going out of control" (on the borderline, needs reordering); and Green represents "no problem" (within acceptable limits).

The concept behind this RAG system is actually a colorized priority indicating system. It is usually incorporated into a Kanban system to indicate the priority of actions should be taken.

Chapter 4. Methodology

In this chapter, methodologies developed to solve the problems identified in chapter 2 are described in detail, including methodologies in capacity planning, demand seasonality analysis, material flow smoothing, inventory and production control, and Kanban system design.

4.1 Long-Term Capacity Planning

Because of the limitations of Hua Xia[4]'s method explained in chapter 3, a new capacity planning method was developed in this section. The lead strategy capacity planning was also applied in the new method, and some results were adopted from Hua Xia's results. For example, stock is only built for the high runners, and the reasons were explained in Hua Xia's thesis.

4.1.1 Long-Term Capacity Planning Procedure

In this section, a new stock building framework is proposed and discussed.

The new method is a 7 step stock building framework. It evaluates the capacity of the whole system to identify the process bottleneck for capacity planning, and it takes product value difference and upstream capacity constraint into account when developing the stock building plan. The result of this process is a stock building plan with the lowest extra inventory cost.

Step 1 Capacity evaluation

Analyze the demand for each production stage to evaluate the capacity of each stage, and identify the bottleneck stage, where the lead strategy capacity planning will be applied.

Step 2 Identify the high runners

Apply Pareto chart method to identify the major products at the bottleneck stage. The products with demand over 10% of the total demand at the bottleneck station are considered as high-runners, and those with a proportion lower than 10% are categorized as low runners. The stock building plan will build stock only for high runners.

Step 3 Calculate the total excess demand from the demand forecast data

According to the factory's historical demand data, it is found out that the excess demand usually shows up during week 26 to week 50 in a consecutive pattern. This period was called "peak season" for the bottleneck stage. To calculate the total excess demand, the weeks with excess demand were identified, and the aggregated excess demands were calculated for these weeks following Eq.4-1.

$$\text{Excess demand in week } i = \text{aggregated demand in week } i - \text{capacity in week } i \qquad \textbf{Eq.4-1}$$

Then the total excess demand is calculated with Eq.4-2.

$$\begin{aligned} &\text{Total Excess Demand} \\ &= \sum (\text{Weekly excess demand of week } i) \qquad \textbf{Eq.4-2} \\ &= \sum (\text{aggregated demand of week } i - \text{capacity in week } i) \end{aligned}$$

Step 4 Calculate the excess demand for each high runners

In this step, first the demand proportion of each high runner during the peak season was calculated, and then the aggregated excess demand was allocated to the high runners with the calculated proportion. This provides the excess demand for each high runner, which will be fulfilled with cumulative spare capacity calculated in the next step.

Step 5 Calculate the spare capacity before the peak season

The weekly spare capacity for weeks before the peak season was calculated with Eq.4-3.

$$\text{Weekly spare capacity} = \text{weekly capacity} - \text{weekly aggregated demand} \qquad \textbf{Eq.4-3}$$

Step 6 Identify the stock building period

The objective of the stock building plan is to build up stock needed for the excess demand during peak season with shortest time. So it is necessary to identify the right stock building period. The following algorithm is followed.

Set n as the last week before peak season, and m is any week before week n, which is the start of the stock building period. Then,

$$\textit{Accumulated spare capacity from week m to week n} \geq \textit{total excess demand for the peak season}$$
$$\textit{Accumulated spare capacity from week } (m+1) \textit{ to week n} \leq \textit{total excess demand for the peak season}$$

Then week m to week n is the stock building period.

Step 7 Develop the stock building plan

Here the stock building plan is developed with an optimization algorithm described below.

Parameter notation

C_t: Total extra cost encountered during the stock building period
E_{ij}: Aggregated excess demand of item j in week i
S_i: Spare capacity in week i
S_{upi}: Spare capacity of upstream stage in week i
P_{ij}: Stock building quantity of item j in week i
R: Weekly inventory cost rate
V_j: Value of item j after the studied stage

(1) Calculate C_t

The total extra cost encountered in this stock building plan is only the inventory cost. The changeover cost will not be considered as extra cost, because the stock building plan changes the quantity of each production changeover, but not the production changeover times. So there should be no extra changeovers cost.

The stock building period is from week m to week n as identified in step 6.

In week i ($i \in [m,n]$), the total inventory cost of the high runners is the cost to keep the inventory produced in week i till the end of the stock building period, which is

$$\mathbf{C_{ti} = \sum_j P_{ij} * V_j * R * (n - i + 1)} \quad \textbf{Eq.4-4}$$

The total inventory cost during the stock building period is

$$C_t = \sum_{m}^{n} C_{ti} \quad \textbf{Eq. 4-5}$$

(2) Objective: Minimize total inventory cost

$$
\begin{aligned}
& Min(\mathrm{C_t}) \\
& = Min(\sum_{m}^{n} C_{ti}) \\
& = Min(\sum_{m}^{n} \sum_{j} P_{ij} * V_j * R * (n-i+1))
\end{aligned}
$$

(3) Constraints

i. Stock building quantity constraints: the total stock built quantity during the stock building period should be equal to the total aggregated excess demand during the peak season

$$\sum_i \sum_j \mathrm{P_{ij}} = \sum_i \sum_j \mathrm{E_{ij}} \qquad \textbf{Eq.4-6}$$

ii. Current production stage capacity constraint: the stock planned to be built in week i should be less than the spare capacity of week i for the current production stage.

$$\sum_j \mathrm{P_{ij}} \le \mathrm{S_i}$$

iii. Upstream production stage capacity constraint: the stock planned to be built in week i should not exceed the upstream spare capacity of week i at the same time.

$$\sum_j \mathrm{P_{ij}} \le \mathrm{S_{upi}}$$

iv. Non negative constraint: the stock building for product j during week i should be non negative numbers.

$$\mathrm{P_{ij}} \ge 0$$

This optimization can be done with **Excel Solver** [13]. The Excel cells contain the algorithm described above is shown in Appendix IV, and one example of how to use this method is demonstrated in Chapter 5.

4.1.2 Implementation Consideration

The demand forecast is updated monthly as described in chapter 1, so the weekly aggregate demand is expected to change after each forecast update. Consequently, the weekly excess demand and the weekly spare capacity should be updated following Eq.4-1, 4-2, 4-3 on a monthly basis. Thus, Step 3 to 7 should be performed on a monthly basis. After the capacity planning, the demand pattern of the bottleneck stage and upstream stages should be revised based on the stock building plan.

To compare the method describe above and the method proposed by Hua Xia, please refer to reference 4.

4.2 Demand Analysis Methodology

In this section, a general demand management and analysis method is proposed for individual production stage. This method is consisted of 3 major elements.

(1) Demand pooling

Risk pooling theory suggests that demand variability is reduced if demands are aggregated across different end products, because as we aggregate demand across different products, it becomes more likely that high demand for one product will be offset by low demand for another. This reduction in variability allows a decrease in safety stock and therefore reduces average inventory.

This concept can be introduced to upstream production stages where the product customization is not obvious, such as stage 3 in this factory. Because stage 3 is not the end process section, so some of the SKUs are the same products at stage 3, and they only differentiate from each other during the downstream processes. So we proposed to aggregate the demand for different SKUs sharing the same product at stage 3 into a new product level, which is called SP level, and design the supermarket after stage 3 based on the SP level. For example, SKU A, B and C are different at stage 4, but they are the exact the same product at stage 3 named SP1. So we can aggregate the demand for these three SKUs into the demand for SP 1, and stage 3 can keep inventory for SP 1 based on this aggregated demand instead of keeping inventory separately for SKU A, B and C. It becomes more likely that high demand for one product, like SKU A, will be offset by low demand for another, such as B or C. This reduction in variability allows a decrease in safety stock for these three SKUs and therefore reduces average inventory for SP 1.

(2) Choose major products

After the capacity planning and demand pooling, the demand pattern and product structure are fixed for individual production stage. The next step will be to identify the high runners that should be involved in inventory calculation.

Pareto Ratio Chart was applied to the demand data to identify the high runners for certain production stage. According to the factory's historical data, the high runners will most probably remain as major product all through the year, so this process can be done once a year.

In the Pareto analysis, products with a daily demand higher than 10% of the total daily demand are called high runner, which is worthy of storing. Those products with a daily demand lower than 10% will be considered as low runner and will not be stored in the designed supermarket.

However, the chart cannot tell the whole story. The high runners should be chosen based on both this Pareto analysis and the production process consideration. First, some products have much longer lead time than the other products, which makes it important to store this kind of products even their demand rate is low. Second, there are also products with low demand rate and high standard deviation, which also have to be stored to cover their demand fluctuation.

(3) Demand seasonality analysis

As mentioned in section 1.3, there are two product categories of this factory, Class-A and Class-B products. Class-A product is about 30% of the total demand, and Class-B product is about 70% of the total demand. Because Class-B products are mostly sold in America and Europe, and holidays in these region, such as Christmas and New Year, have heavy impacts on the demand of Class-B products, which forms the seasonality for Class-B product. For Class-A product, because they are sold mostly where the holiday effect is not so influential, so the demands for Class-A products are stable and consistent throughout the year comparably, and Class A product is not the focus of this thesis.

Identifying the season will help the company to understand their demand pattern better and prepare the production system for the demand better. This seasonality analysis will also make it convenient to implement the new base stock policy discussed in the flowing section, because the company will not have to calculate the reasonable inventory level or production settings on a monthly basis or quarterly basis, but on a seasonality basis, which is more reasonable.

Analysis of variance (ANOVA) was applied to the demand data to identify the demand seasonality for individual stage. In this analysis, each month is taken as a sample group, and the daily demand for the whole year is regarded as the population. To compare and verify the seasonality, a few different seasonality grouping combinations were analyzed and compared. Finally, the seasonality is chosen based on the F value and P value from ANOVA. The combination provides the highest F value and lowest P value is chosen. Yuan Zhong [1] describes this method in detail, please refer to reference 1 to know more about this method and the results discussion.

4.3 Material Flow Smoothing Methodology

As described in chapter 2, batch size mismatch along the production line introduces lot sizing effect into the system, and causes waste of materials. So the material flow in this factory was studied, and a method to smoothen the material flow along the production line was proposed as follows.

(1) Batch size coordination based on product categorization

It is found out that there are two thickness categories for all products and the batch sizes along the line can be categorized according to this shape characteristic. Here the two categories are called Size K product and Size N product. Size K product is thicker, which is packed in 480pcs/pallet at the finished goods level. Size N product is thinner, which is packed in 600pcs/pallet at the finished goods level. The batch size flows for these two product categories are shown in Figure 4-1 and 4-2.

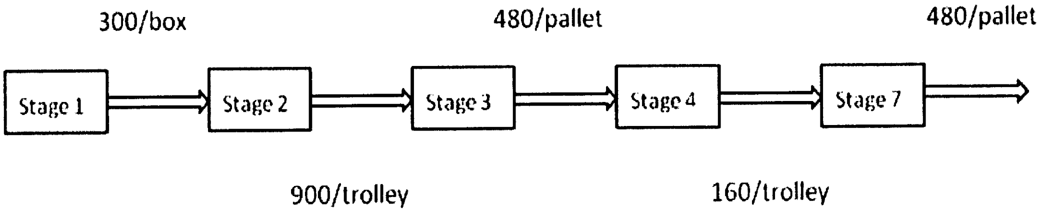


Figure 4-1.Size K product batch size demo

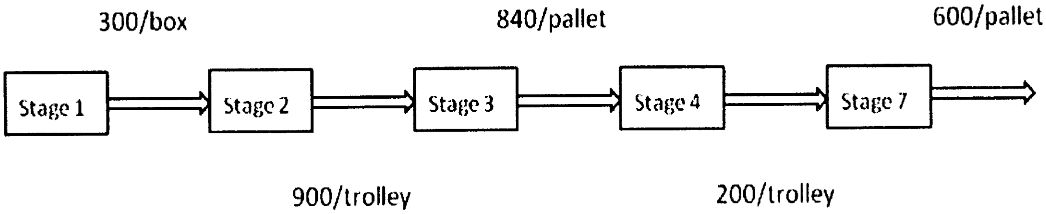


Figure 4-2.Size N product batch size demo

From Figure 4-1, we can see that for size K product, there will be no waste except for stage 2. From 4-2, we can see that for size N product, there will be no waste except for stage 3. From this analysis, we can see the root cause of this material flow problem actually lies in the batch size mismatch at production stage 3.

According to the above analysis, we suggested to standardize the batch size at stage 3.The revised batch size flows are shown in Figure 4-3 and 4-4.

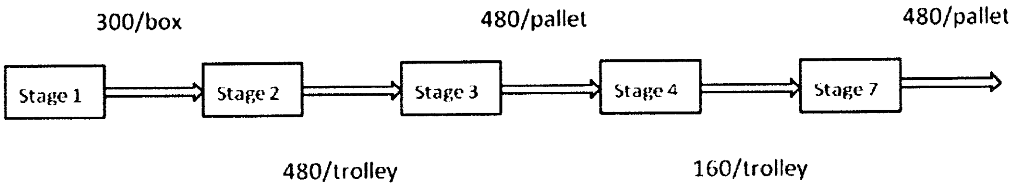


Figure 4-3.Proposed size K product batch size flow

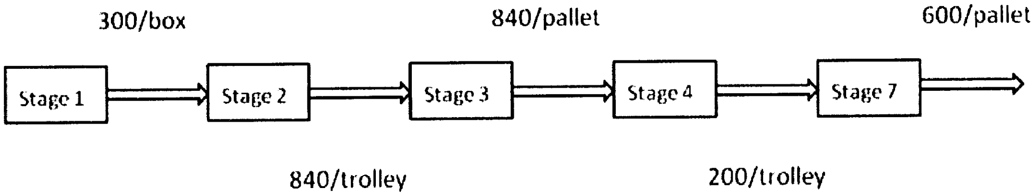


Figure 4-4.Proposed size N product batch size flow

(2) Material flow smoothing between stage 3 and 4

As we can see from Figure 4-4, there is still batch size difference between stage 3 and 4 for size N products. To solve this, we created a material flow temporary buffer (TB) at stage 4.

The extra material released into stage 4 is recorded every material release, and the daily accumulated extra material release at stage 4 is also recorded. This accumulated extra material release is a temporary material buffer. If the accumulated extra material is bigger than the batch size at stage 4, the extra material will be used to fulfill part of or all of the demand for stage 3 directly instead of releasing new material from stage 3. If the extra material at stage 4 is smaller than the demand for stage 3, new material will be released from stage 3. This will control the extra material released into stage 4, and reduce material waste caused by the batch size mismatch.

4.4 Inventory Control Policy

As described in Chapter 1, the production system in this factory is a heavy resource sharing system with multiple products and fluctuating demand. According to these characteristics, the new base stock policy developed by Dr. Stephen C. Graves was adopted to control the inventory and production in this factory. According to the literature review in Chapter 3, this new designed production system will be a supermarket pull production system. In this section, the new base stock policy is described in detail.

(1) Assumption of the new policy

i. Demand is independent identically distributed, and has an infinite history

ii. No lot sizing effect

(2) Model Introduction

Notations of some important parameters of this model are listed below.

- D: Demand
- R: Raw material release quantity
- P: Production quantity
- B: Base stock level, the sum of W and I.
- C: Line capacity
- W: Intrastage inventory (inventory for raw material for the stage)
- I: Interstage inventory (finished goods inventory for the stage)
- t: Time period index
- i: Product type
- n: Planned lead time
- χ: Excess capacity available for certain production stage, which is the difference between total demand and total capacity
- μ: average demand rate
- б: Demand standard deviation
- k: Safety factor

This policy specifies new production control rules and calculates the inventory levels for each product manufactured on the same multi-product line. I_t and W_t are interstage and intrastage inventory at certain production stage during time period t, and they can also be translated as finished goods inventory and raw material inventory at certain production stage. P_t is the production target for certain production stage. R_t is the material release quantities, and D is demand. The random variables I_t, W_t, P_t, R_t are aggregated entities while I_{it}, W_{it}, P_{it}, R_{it} are entities for individual product type.

For example: $$I_t = \Sigma I_{it}$$

I_{it} is the interstage inventory for product I at the start of time period t.

Some important relationships and equations of this inventory control policy are list below.

1) The balance equations for aggregated entities are:

$$W_t = W_{t-1} + R_t - P_{t-1} \qquad \textbf{Eq. 4-7}$$

$$I_t = I_{t-1} + P_{t-1} - D_t \qquad \textbf{Eq. 4-8}$$

2) The material release rule for this policy is:

$$R_t = D_t \qquad \textbf{Eq. 4-9}$$

3) Eq. 4-7 to 4-9 can be easily extended to individual product types:

$$W_{it} = W_{it-1} + R_{it} - P_{it-1} \qquad \textbf{Eq. 4-10}$$

$$I_{it} = I_{it-1} + P_{it-1} - D_{it} \qquad \textbf{Eq. 4-11}$$

4) The material release rule then becomes:

$$R_{it} = D_{it} \qquad \textbf{Eq. 4-12}$$

5) χ and n are calculated by:

$$\chi = C - D \qquad \textbf{Eq. 4-13}$$

$$n = \left(k^2\sigma^2 + \chi^2\right) / 2\chi^2 \qquad \textbf{Eq. 4-14}$$

Assumption: $\chi \leq k\sigma$

Otherwise set n=1.

K is the safety factory, and in this thesis, k is 1.64 for all calculation, which represents a 95% customer service level.

6) The production target for individual model i is set by:

$$R_{it} = D_{it}$$

$$P_{it} = \frac{W_{it}}{n} \qquad \textbf{Eq. 4-15}$$

7) The expected inventory values for individual model i are given by:

$$B_i = E[W_{it}] + E[I_{it}] = n\mu_i + k\left[n\sigma_i / (2n-1)^{1/2}\right] \qquad \textbf{Eq. 4-16}$$

8) For later calculation, E[W_{it}] and E[I_{it}] will be obtained for every important SKU at each production stage with consideration of reasonable demand grouping (pooling). And the floor production will be controlled by Eq. 4-12 and 4-15.

The mechanism of this base stock policy can be illustrated as in Figure 4-5. Demand from downstream stage is fulfilled with the finished goods inventory at upstream stage, and then this finished goods inventory is replenished by the production at upstream stage. From this description, we can see that the "Pull" mechanism is enforced by this inventory policy.

The steps to use this inventory control policy are:

Step 1.Calculate χ and **n** for the target production stage flowing Eq. 4-13, and 4-14. To calculate χ, the aggregated demand parameters for the target production stage should be obtained first.

Step 2.Based on the calculated planned lead time **n**, calculate the expected **W** and **I** with Eq. 4-16. The inventory setup is completed in this step.

Step 3.During daily production, when demand comes, the demand signal will be transferred to all the production stages, and the material release rule described in Eq.4-12 should be followed as shown in Figure 4-5.

Step 4.After material release, **W** and **I** should be updated following Eq. 4-10 and 4-11.

Step 5.Daily production target should be set with Eq.4-15.

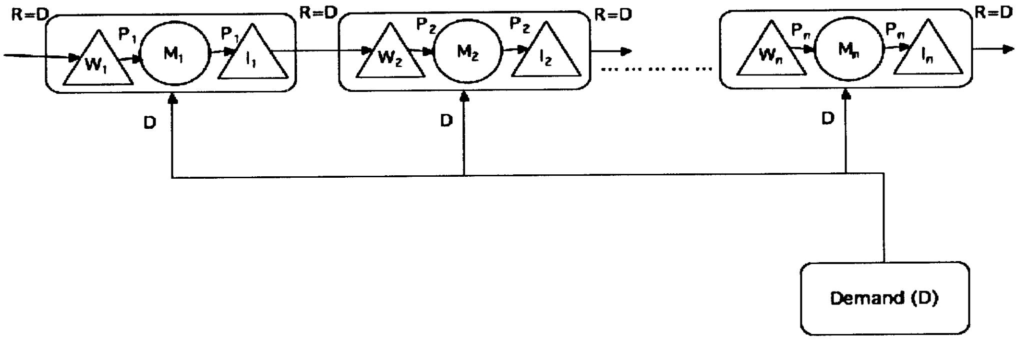


Figure 4-5.Base stock policy mechanism

4.5 Single Stage Simulation

The chosen base stock model was originally developed for single production stage with multiple products. Here a simulation model was developed based on the base stock model described in section 4.4 in **Excel** to simulate the performance of the new base stock policy and verify the operational changes proposed in section 4.3 on single product at single production stage, and in this simulation, production stage 3 was chosen as an example.

4.5.1 Model Introduction

(1) Model Parameters

t : time period
D_t : demand for time period t
W_{it} : work-in-process inventory for item i during time period t
I_{it} : finished goods inventory for item i during time period t
P_{it} :production quantity for item i during time period t
n : planned lead time
b_{in} : inbound batch size
b_{out} : outbound batch size

In this simulation, the time unit is 1 day.

(2) Assumptions

i. There is no starvation to stage 3 from upstream stations.
ii. The demand for stage 3 follows N (μ, σ).
iii. The demand uncertainty is the only uncertainty in this model.
iv. All the parameters represent the status of the stage at the beginning of the simulation time unit. If time period is 1 day, then they represent the status of the stage at the beginning of the day.

(3) Simulation process

i. Input demand data D_t. This D_t is already rounded up according to the batch size at the downstream line of stage 3, which is 600pcs/batch. This demand is then rounded up by the outbound batch size at stage 3, $D_t' = ([D_t / b_{out}] + 1) \times b_{out}$.

ii. Calculate planned lead time n with Eq.4-14.

iii. Calculate the initial value for W_{it} and I_{it}, which are expected values for W and I based on Eq. 4-16. They are rounded up into W_0 and I_0 with b_{in}, b_{out} respectively following the similar procedure as D_t roundup in step **i.**

iv. Calculate the initial production value P_0 with Eq.4-15. P_0 is rounded up based on the outbound batch size at stage 3, which is $P_0' = ([P_0 / b_{out}] + 1) \times b_{out}$. So this P_0'is the actual production quantity used in this simulation. But in the following description, P_0'is still named as P_0. When considering multiple products, there is a capacity constraint on the production value for each product, which is that the total production value for all the products should not exceed the line capacity.

After this step, the initial preparations for the simulation are done.

v. Calculate P, W, I, and B for day 1 after the initial preparation.

Step 1, I_1 is calculated based on Eq.4-11, $I_1 = I_0 + P_0 - D_1'$

Step 2, the material release requirement R_1 is calculated with Eq. 4-12, and R_1 has to be rounded up with the inbound batch size from upstream stage, $R_1' = ([D_1' / b_{in}] + 1) \times b_{in}$.

Step 3, W_1 is calculated based on Eq. 4-10, which is $W_1 = W_0 + R_1' - P_0$.

Step 4, P_1 is calculated with Eq. 4-15. Then all the parameters for day 1 are set.

Step 5, replicate step 1 to 4 to calculate parameters for day 2 to the last day of the simulation time period.

The process described above is the basic simulation model. The excel cells containing the formulations for this basic model are shown in Appendix I.

4.5.2 Single Stage Simulation Experiments

There are four considerations for the implementation of the new base stock policy. First, the current batch size mismatch at stage 3 cannot satisfy the material release rule set by the new base stock policy, and the impact of this violation needs investigation. Second, the effect of TB concept proposed before needs to be verified. Third, the batch size effect on the new base stock policy needs to be studied. At last, the effect of this new base stock policy should be validated. So in this section, experiments are designed to test the four considerations listed above.

These experiments were all carried at production stage 3, and the simulation demand data used in these experiments are the real demand data of product SP21 at stage 3 during Jan-Apr, 2009. Because of the lack of data, there are only 84 data points with a mean of 4295pcs/day, and a standard deviation of 1928pcs. The raw demand data is shown in Appendix II.

(1) Test for the violation of the material release rule

As described before, the batch size mismatch at production stage 3 will violate the material release rule set by the new base stock policy. Two experiments were carried out to test the impact of violating the material release rule as follows.

In the first experiment, the batch sizes were kept as the current factory settings, $b_{in}=900$, $b_{out}=840$, under which Eq.4-12 was not followed. In the second experiment, the batch size setting was changed to $b_{in}=b_{out}=840$ as proposed in section 4.3, under which Eq.4-12 was followed.

Results from these two experiments were compared and discussed to verify the proposals in section 4.3.

(2) Test for TB concept

After the experiments in (1), TB concept proposed in section 4.3 was incorporated into the original simulation model.

The simulation stays the same till step 4 in the original simulation model described in section 4.5.1, (3), v. After step 4, two new parameters were introduced into the model. The first one is daily extra material release from stage 3to stage 4, **DEW**, and the second one is the accumulated extra material release from day 1 onward, **ACW**. And the simulation procedure was also modified. Continuing with the simulation steps described in 4.5.1, (3), v:

Step 5, DEW_1 on day 1 is calculated and recorded.

$$DEW_1 = D_1' - D_1 . \qquad \textbf{Eq.4-17}$$

D_1 is the demand for stage 4 roundup by the batch size of stage 4, and D_1' is the demand for stage 3 roundup by the batch size of stage 3 according to D_1. The difference between them is the extra material that moved from stage 3 to stage 4, which is not required by stage 4.

Step 6, ACW_1 is calculated by add up all DEW before current day. Assume there is no extra material before day 1, so after day 1 there will be one DEW_1, and $DEW_1 = ACW_1$.

Step 7, when day 2 begins, demand D_2 comes. The material handler from stage 4 is required to compare ACW_1 after day 1 with batch size at stage 4. If ACW_1 is bigger than one batch, he is required to compare ACW_1 with D_2, or else skip the following procedure and release all material directly from stage 3.

If D_2 is bigger than ACW_1, subtract the biggest multiple of stage 4 batch size from ACW_1, and from D_2 at the same time, which means that stage 4 will be served with the extra material transferred from stage 3 on day 1. Then both ACW_1' and D_2' are generated. This D_2' will be rounded up into D_2''with the outbound batch size at stage 3, which is the final demand for stage 3 on day 2, then

$$DEW_2 = D_2'' - D_2' \qquad \textbf{Eq.4-18}$$

$$ACW_2 = ACW_1' + DEW_2 \qquad \textbf{Eq.4-19}$$

If D_2 is smaller than ACW_1, it will be served all by ACW_1. So there is no need to release material from stage 3 to stage 4, and the demand for stage 3 in this situation is $D_2'=0$.

$$DEW_2 = 0 \qquad \textbf{Eq.4-20}$$

$$ACW_2 = ACW_1 - D_2 \qquad \textbf{Eq.4-21}$$

Step 8, repeat step 1 to step 7 for day 3 onwards.

This new model is shown in Appendix III. The results from this experiment were discussed and the effect of the TB concept was evaluated in Chapter 5. After this experiment, the simulation model was finalized and validated in the next experiment.

(3) Validation of the simulation model

After the simulation model finalization in the previous experiment, the final simulation model was validated in this experiment. The most important parameters from the chosen base stock policy, namely W, I and B, were taken as the validation index in this experiment. The criterion for this validation is that under the same assumptions, simulated values of these parameters should be the same or close to the theoretical calculation values from the equations of the chosen base stock model.

Because the original base stock policy did not consider the lot sizing effect, so the batch size in this experiment was set to 1pc, and then the simulation was run with the same demand data as in the first few experiments. The value of W, I and B from the simulation were collected and compared to the calculated value.

(4) Verification of the effect of the new base stock policy

Results from the finalized simulation model were collected. Important performance parameters such as the stock out probability, average W and I level, and production fluctuation were monitored and compared with real factory data to verify the effect of the new base stock policy on stage 3.

(5) Batch size effect simulation

As described in section 3.4.2, the chosen base stock policy has its own potential limitations. In the model, Dr. Graves assumed there was no lot sizing effect. But in the studied factory, there is lot size, and its impact on the implementation of the chosen base stock policy should be studied.

Final simulation model was used in this experiment, and the only changing variable in this experiment is the batch size at stage 3.

The following batch sizes were chosen $b_{in} = b_{out} = 1, 56, 112, 168, 224, 280, 560, 840$. Reasons for choosing these batch sizes are:

i. When there is no lot sizing effect, batch size b should be 1. And this scenario is the original scenario set in the chosen base stock model.

ii. The other batch sizes were chosen based on the possible batch sizes the company can have without investing much. Batch size 56 is chosen because the smaller container size in the factory is 56pcs/container. Batch size 112, 168, 224, 280, 560, and 840 are multiples of the smallest container size. And these batch sizes cover all the potential batch sizes that can be adopted in this factory.

(6) Multi-stage simulation and overall financial impact analysis

A multiple stage simulation including all the studied production stages was developed by Zia Rizvi [3] to test the effect of the chosen base stock policy on the whole production line. Two SKUs were chosen to be run with the simulation. Please refer to reference 3 to know the results and discussion on this topic.

Xiaoyu Zhou [2] discussed the overall financial impact of this new base stock policy on the factory. Please refer to reference 2 to know the details.

4.6 Inventory Calculation of Stage 3 for the Peak Demand Season in 2009

After verification, the new base stock model was applied to stage 3 to set up inventory for the peak demand season from Jul to Oct, 2009. Only high runners chosen by Pareto analysis were involved in the calculation.

There are 3 critical parameters needs to be calculated to apply the new base stock policy, and they are excess capacity available for certain production stage χ, average demand rate $\boldsymbol{\mu}$, and demand standard deviation $\boldsymbol{\sigma}$.

χ is calculated by Eq.4-13; $\boldsymbol{\mu}$ is estimated from forecast demand data following the demand pooling strategy; $\boldsymbol{\sigma}$ should be estimated based on the historical data, but for year 2009, the demand for the target months is not real customer demand, but is distorted by human manipulation because of the infrastructure construction in the factory in the second half of 2009, when there will be nearly no production for certain stages. This means that the production is decoupled with the real customer demand, and the historical standard deviation for the demand cannot be used anymore, so the standard deviation from the forecast data was used in the calculation.

Zhong Yuan [1] explains the methods to estimate **μ** and **σ** in detail, and the results from his analysis were applied in this thesis for calculation.

Because there is not enough time to monitor the implementation results, a **Crystal Ball** [14] simulation was carried out to provide insights of the model performance during the peak season.

4.7 Kanban System Design

To facilitate the production control, a Kanban production control system incorporating the new base stock policy was designed.

There are a few major concerns in designing a Kanban system, including designing Kanban Cards, deciding the number of Kanban cards, and developing operation rules for the Kanban system.

(1) Designing Kanban Cards

Since this factory has previous experience on Kanban card design, their current card design was adopted, which contains information such as card ID number, name of the product, model transition number, quantity represented by one card. Xiaoyu Zhou [2] discussed this topic in his thesis. Please refer to reference 2 for details.

(2) Number of Kanban cards for each product

To decide the number of Kanban cards for each product on the Kanban board, first the Kanban level of each product was calculated. The Kanban level is the same as the calculated base stock level needed for that product. The number of Kanban cards was calculated by Eq.4-22.

$$\text{Quantity of Kanban cards for product i} = \frac{\text{Base stock level for one product i}}{\text{Batch size for product i at stage j}} \qquad \textbf{Eq.4-22}$$

(3) Alerting Kanban level

An alerting value for the finished goods inventory should be set to tell the workers on the line that the inventory situation is in danger of shortage because of some reason, and actions are needed. At the same time, this alerting Kanban level should protect the stage from shortage before actions are taken. This Kanban level should be equal to the demand from downstream stage during the reaction time. Here the reaction time was determined by the MTTR for stage 3, and the demand rate was determined by the highest downstream consuming rate, so the demand during reaction time is the product of these two. The number of Kanban cards for the alerting inventory level was calculated as shown in Eq.4-23.

$$\text{Min No. of Kanban cards for product i} = \frac{\text{Downstream demand rate} * \text{Longest MTTR at current stage}}{\text{Batch size of product i at stage j}} \qquad \textbf{Eq.4-23}$$

(4) Operation rule for the designed Kanban system

The operation of the designed Kanban System incorporated the inventory control policy and the RAG concept discussed in Chapter 3. To handle emergency situations during daily production, a red card system was recommended to run in parallel with the proposed Kanban system.

i. Incorporation of the new base stock policy and RAG concept

There are four major parameters in the new base stock policy, namely finished goods inventory I, material release requirement R, work-in-process inventory W, and production target P. To incorporate this policy into the Kanban system, the Kanban board was divided into four major areas correspondingly, namely I area, R area, W area, and P area. Cards in I area represent finished goods; cards in R area represent demand, which is also the material release requirement for upstream production stage; cards in W area represent available raw material at current production stage; cards in P area represent the production target for current stage. The operation of this Kanban system follows the algorithm of the new base stock policy, and will be described in Chapter 5.

The RAG concept was incorporated into the Kanban system design too. R area is the "Green" area, which means the material in this area has the lowest priority in production; W area is the "Amber" area, which means the material in this area needs not to be transformed into finished goods immediately, but the material must be kept for the smoothing of the system, and it has the second highest priority in production; P area is the "Red" area, which means the target set in this area must be achieved as soon as possible, and has the highest priority in production. The areas were colored on the physical Kanban board during implementation.

The detailed operation rules will be shown in Chapter 5.

ii. Red card system

The designed Kanban system only caters for the high runners, so there should be another system to cater for the low runners. So a system named "Red Card System" is used for the production of low runners and emergency situations. When demands for low runners are planned by the factory planner before hand, then they are transformed into number of red cards required on the Kanban board. Productions of the low runners have the highest priority during production because low runners are not stored. And if something emergent happens, this red card system will also tell workers on the line the top priority activity to do.

This red card system does not use "Pull" methodology but "Push" methodology as what the factory is practicing now. After implementing the work done by this M.Eng. group, the factory production system will be a "Push-Pull" system. For the major products, pull mechanism is adopted and applied by the new base stock model; for the low runners, push mechanism is maintained.

Chapter 5. Results and Discussion

This chapter presents the results of the work done by the author in this project, including the demonstration of the long term capacity planning framework, the results from the single stage simulation experiments, and at the end, the Kanban system design and operation.

5.1 Long-Term Capacity Planning Demonstration

The procedure of using the long-term capacity planning framework proposed in Chapter 4 is demonstrated in this section.

(1) The demonstration of the capacity planning framework

In this demonstration, the input demand data is 2008 demand forecast data, and the annual inventory cost rate is 15% of the stock value.

i. Identify the system bottleneck

To identify the bottleneck of the whole production line, system capacity map of this factory is shown in Figure 5-1. In this figure, the rectangular shapes represent the production stage, the arrows represent the general material flow, and the numbers in the rectangular represent the available capacity for each stage.

After analyzing the 2008 demand data, it was discovered that stage 6 is the bottleneck stage that encountered excess demand during the 3rd quarter in 2008. Therefore, the long-term capacity planning methodology should be applied at stage 6 to fulfill the excess demand.

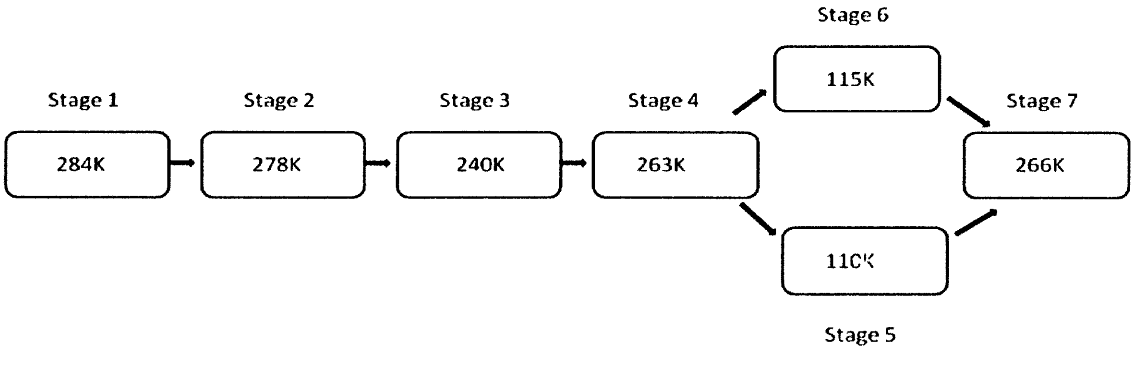


Figure 5-1.System capacity map

ii. Identify high runner products

The Pareto analysis was applied to 2008 demand forecast data as shown in Figure 5-2. As can be seen in the figure, there are three products with demand more than 10% of the total demand at stage 6, namely product 7, 10, and 12 (their names are CP-EL3, SR-AZ44, and SR-AZ46 respectively), which are the high runners at stage 6. The values of these three products are $5, $4, and $5 respectively.

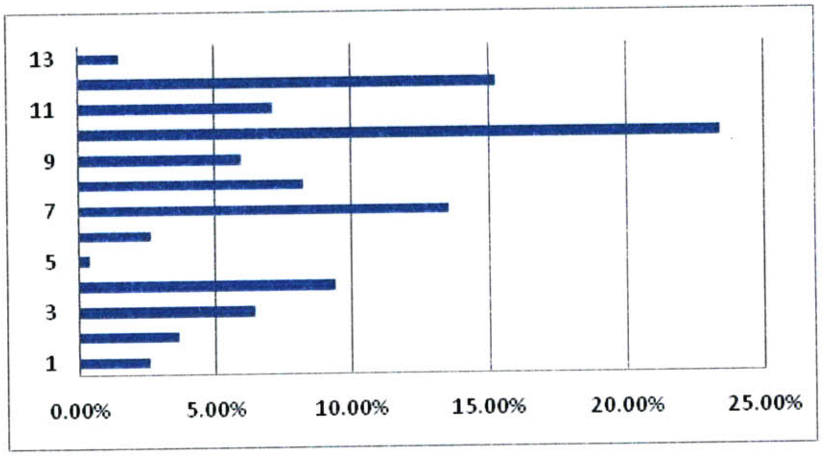


Figure 5-2.Pareto chart for long term capacity planning

iii. Calculate the total excess demand

To calculate the total excess demand, first, the peak season for stage 6 was identified as shown in Appendix V. The cells in red are the weeks with excess demand. Then the total excess demand was calculated based on Eq.4-1 and Eq.4-2, and the result is 274,773pcs as shown in Appendix V.

The demand of the three high runners during the peak seasons were identified, Then the proportions of the high runners relative to each other were calculated. At last, the stock building quantity for each of the products was calculated respectively as shown in Table 5-1.

Table 5-1.Summary for the high runners

Product	Peak Season Demand	Percentage of each Product	Planned Stock Qty	Value/pc
SR-AZ44	250442	23%	63317.24	5
CP-EL3	485090	45%	122641.4	4
SR-AZ46	351292	32%	88814.34	5
Total	1086824			

iv. Identify the stock building period

The spare capacities at stage 6 for the nearest 10 weeks prior to the peak season were calculated based on Eq.4-3 and listed in Table 5-2.

Table 5-2.Extra capacity before the peak season

Week	18	19	20	21	22	23	24	25	26	27
Spare Capacity	61591	36887	39443	54719	45102	55750	34654	35827	19977	3697

The accumulated spare capacity from week 21 to week 27 is 249,726pcs, and the accumulated spare capacity from week 20 to week 27 is 289,169pcs. From the previous step, the total excess demand is 274,773pcs, and 249,726 ≤ 274,773 ≤ 289,169, so based on the criteria set in the methodology part, the stock building period should be from week 20 to week 27.

v. Develop the stock building plan with optimization

Following the algorithm developed in section 4.1.1, the optimization was run and the results are shown in Appendix VI. To verify the effect of this capacity planning method, demand patterns before and after capacity planning are drawn in Figure 5-3.

In Figure 5-3, the horizontal axis is time, the vertical axis is quantity. The red line represents the original demand pattern, the green line represents the demand pattern after capacity planning, and the black dash line represents the capacity limit at the bottleneck stage.

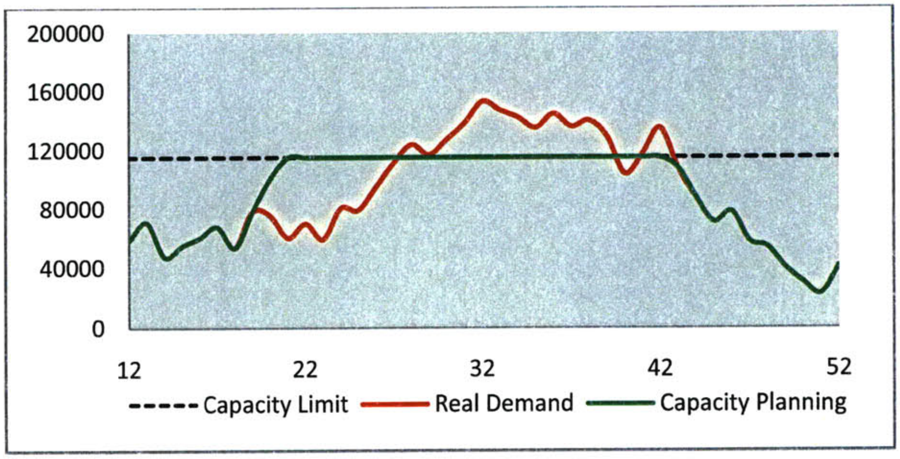


Figure 5-3.Capacity planning effect demonstration

From Figure 5-3, it can be observed that the red line exceeds the black dash line from 28 to week 42, which means the capacity was exceeded during this time period. It also can be observed that there is no green line exceeding the limit of the black dash line, which means the capacity planning algorithm shifts the excess demand to the low demand season, so that all the demand are within the capacity limit of stage 6 after the capacity planning.

(2) Comparison with the method proposed by Hua Xia [4]

When the value differences between the stock building products are small, the two methods give almost the same results. When the value difference is bigger, the advantage of the proposed method in this thesis is obvious. For example, if the values for the high runners were \$5, \$4, and \$7 instead of the original value discussed in (1), the total inventory cost during the stock building period would be \$22,412 based on Hua Xia's method, and \$19,640 based on the new method in this thesis. There is a 12.4% inventory cost reduction with the new method. (Please refer to the Appendix of reference 4 to know the calculation details of her method.)

Because the values of products at stage 6 vary from \$2 to \$7, so it is important to incorporate the value difference between products when developing the stock building plan.

This method should be applied to the forecast demand data at the beginning of the year. By far, this method has received positive feedback from the factory planner, and they are trying to apply this planning framework to next years' demand orientation.

5.2 Choose High Runner Product

The Pareto analysis was applied to the 2009 demand forecast data as shown in Figure 5-4.

From the chart, the high runners were identified as SP 12, 13, and 21. But as discussed before, the quantity criterion is not the only criteria. After discussion with the management, a few other products were added into the supermarket calculation because of process lead time and other considerations. So the products involved in the supermarket calculation are SP5, SP11, SP12, SP 13, SP14, SP16, SP21, and SP24.

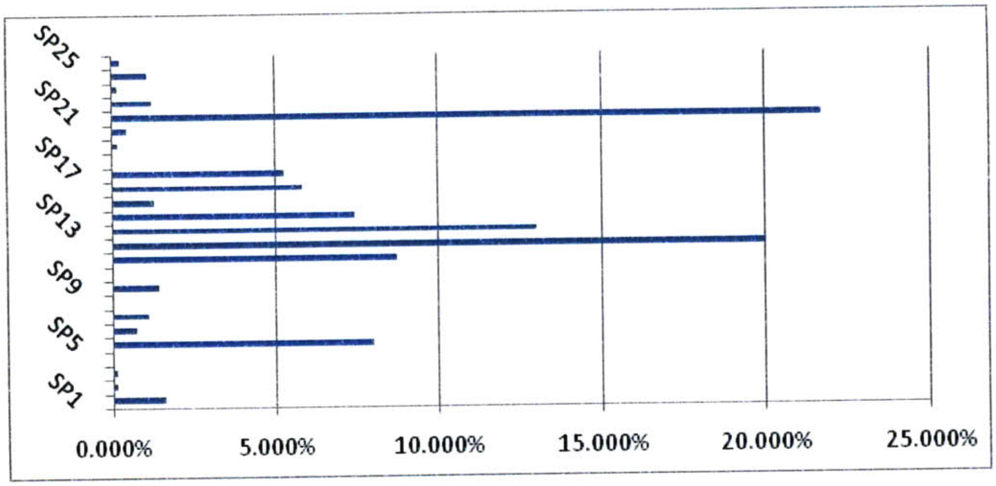


Figure 5-4.Pareto chart for choosing the high runners

5.3 Single Stage Simulation Experiment Results

In this section, the results for the single stage simulation experiments are presented and discussed. Demand parameters used in this section are shown in Table 5-3.

Table 5-3.Demand parameters

Product	SP21
Mean	4295
Standard Deviation	1928
Aggregated Mean	16209
Aggregated Std	6458

5.3.1 Test Results for the Violation of Material Release Rule

(1) Experiment results

As discussed in section 4.5, the batch size setting in the first experiment is $b_{in}=900$, $b_{out}=840$, under which the material release rule "R=D" is not satisfied. The batch size setting in the second experiment is $b_{in}=b_{out}=840$, under which the material release rule "R=D" is satisfied. The initial values for this experiment were calculated following the algorithm described in section 4.5.1, and are listed in Table 5-4. Table 5-5 summarizes the results from these two experiments. Figure 5-5 shows the inventory structures at stage 3 from these two experiments and theoretical calculation.

Table 5-4.Initial value for the first simulation

n	1.06
W_0	5040
I_0	3360
P_0	5040
B	8400

Table 5-5.Comparison of the W, I, and B

Average Value	R≠D	R=D	Calculated
Wt	5291	5060	5400
It	18900	3370	3360
Pt	5420	5060	5880
B	24191	8430	8760

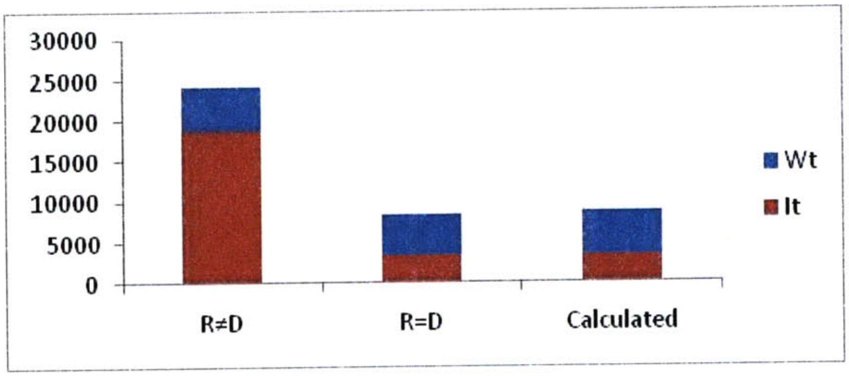


Figure 5-5.Inventory structure before and after the batch size coordination

(2) Observations and discussion

From Table 5-5, it is observed that in the first experiment, the finished goods inventory level at stage 3 is much higher than that in both experiment 2 and theoretical calculation. The reason for this is that, when the material release rule is not satisfied, the material release quantity to stage 3 will always be bigger than its demand. This will release extra work in process inventory to stage 3. According to Eq.4-15, the extra work in process inventory results in overproduction at stage 3, which increases the finished goods inventory level at stage 3. In the second experiment, the simulated values for W, I, and B are almost the same as in the theoretical calculations. And there is no extra material transferred into stage 3 during material transferring caused by batch size mismatch.

According to the results in these two experiments, it can be concluded that the violation of the material release rule set by the new base stock model will results in high finished goods inventory level at stage 3, which is not preferable because the finished goods inventory is more expensive. So we suggest that the factory standardize the batch size at stage 3 to satisfy the material release rule as described in section 4.3. At the same time, the simulation model was modified so that the inbound batch size at stage 3 equals to the outbound batch size for the following experiments.

5.3.2 Test Results for TB concept

(1) Experiment results

In the second experiment described in section 5.3.1, it was observed that there were 38,040pcs extra products released from stage 3 to stage 4 because of the batch size mismatch between these two stages. The experiment in this section incorporated TB concept into the model as discussed in section 4.5.2. The results from this experiment are shown in Table 5-6. Figure 5-6 shows the inventory structures before and after the implementation of the TB concept, as well as the structure from the theoretical calculations.

Table 5-6.Comparison of the results before and after TB concept

Average Value	Before	After
Wt	5060	4610
It	3370	3820
Pt	5060	4610
B	8430	8430
Stock out probability	1.19%	1.19%
Accumulate Extra to PA	38040	240

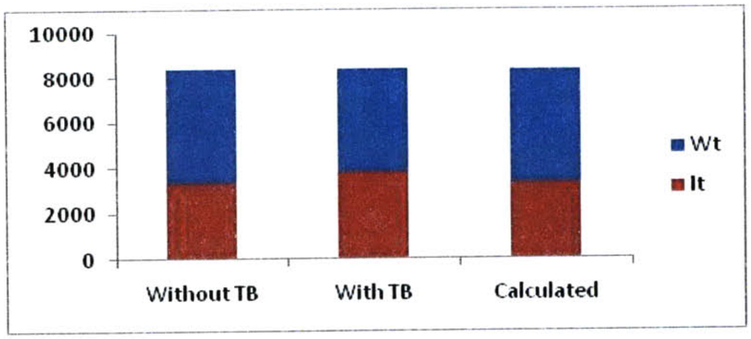


Figure 5-6.Inventory structure before and after the implementation of TB

(2) Observations and discussion

From the highlighted cells in Table 5-6, it can be observed that there is a 37,800 reduction in extra material release from stage 3 to stage 4 after TB concept was incorporated. From Figure 5-6, it can be observed that TB concept has little impact on the inventory structure.

It is also observed that the I value from simulation is bigger than the I value from theoretical calculation, and the W value from simulation is smaller than the W value from calculation. This is caused by the batch size effect on the production value. In the simulation, the calculated production value is always rounded up according to the production batch size at stage 3, so there will be always overproduction (less than one batch), which will reduce the calculated W value and increase the calculated I value.

According to this experiment, it can be concluded that the TB concept can reduce the waste caused by batch size mismatch between stage 3 and 4. So we suggest that the factory follow the TB concept wherever there is a batch mismatch along the production line. At the same time, we can tell that the best way to eliminate waste on the line and smooth the material flow is to standardize the batch size along the whole production line.

5.3.3 Simulation Model Validation

In this experiment, the batch size was set to 1pc/batch to eliminate the batch size effect. The simulated values of W, I and B were collected and compared with the theoretical values in Table 5-7.

Table 5-7.Validation of the simulation model

Parameter	Simulated Value	Calculated Value	Difference
W	4884	4541	7.55%
I	2897	3186	-9.07%
B	7780	7727	0.69%

B is the most important parameter controlled by this inventory policy, and from Table 5-7, it can be seen there is almost no difference between the simulation value and the theoretical value for B, which means that this simulation model can provide comparably accurate information about the performance of stage 3. So the simulation model used in this experiment is validated, and it is the final simulation model used in the following experiments.

5.3.4 Single Stage Base Stock Policy Verification

(1) Experiment results

The simulation model in section 5.3.2 has been validated, so the simulation results from section 5.3.3 provides the best estimations on the performance of stage 3 after implementing the new base stock policy. The simulation results were collected and compared to the actual factory data as shown in Table 5-8. Figure 5-7 shows the inventory structure from the simulation and from the real factory data.

Table 5-8.Single stage verification of the new base stock policy

Batch size:840	Actual Data	Simulation
W	468	4610
I	8425	3820
P	NA	4610
B	8893	8430
B($)	29823.45	26980
Decrease of B	NA	9.53%
Stock out	7.69%	1.19%

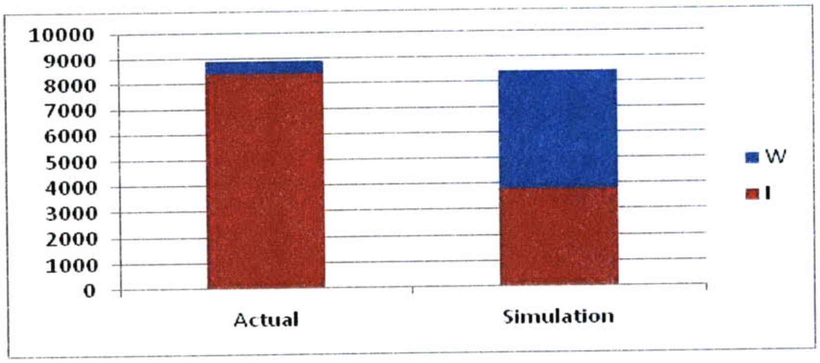


Figure 5-7.Inventory structure comparison

To observe the performance of the new base stock policy on inventory and production control, the time series plots of W, I, B and P at stage 3 are drawn in Figure 5-8 and Figure 5-9. Figure 5-8 show the behavior of W, I, and B after implementing the new base stock model, and Figure 5-9 shows the time series plot of production quantity and demand quantity at stage 3. In Figure 5-8, the blue line represents W level, the red line represents I level, and the green line represents B level. In Figure 5-9, the blue line represents daily demand for stage 3, and the red line represents daily production quantity at stage 3.

(2) Observations and discussion

From Table 5-8, it can be observed that the stock value at stage 3 would decrease by 9.53% if the new base stock model was implemented during the simulation period. At the same time, the customer service level will increase by 6% (from 3 days out of 84 days to 1 day out of 84 days).

From Figure 5-7, it can be observed that the new base stock model changes the inventory structure at stage 3. In the simulation, the work in process inventory is higher than the real factory work in process inventory, and the finished goods inventory is lower than what has currently been kept after stage 3 in the factory. Because the work in process inventory is cheaper than the finished goods because there is no value added activity performed on it, so this inventory structure change leads to the reduction in total stock value at stage 3 as observed in Table 5-7.

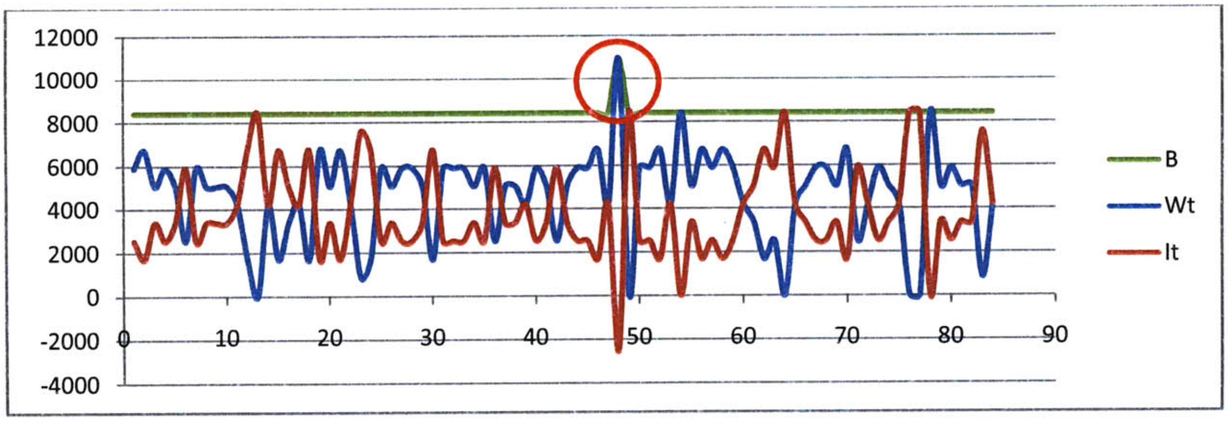


Figure 5-8.Performance of W, I and B

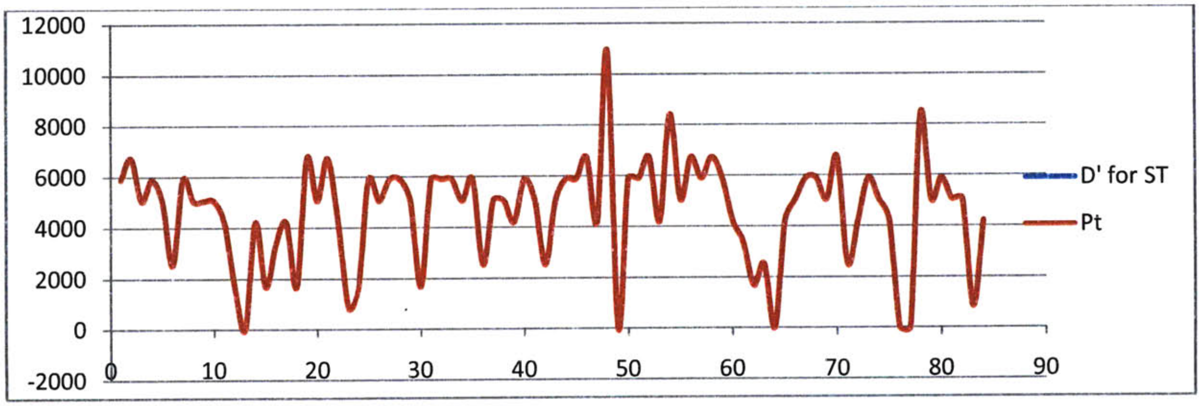


Figure 5-9.Daily production vs. daily demand

As can be seen from Figure 5-8, parameter B is stable except for a spike on day 48 as cycled in red on Figure 5-8. After studying the real demand data, it is discovered that there is a demand of 10,529pcs on day 48 as highlighted in Appendix II. This demand is out of (μ+3σ) demand interval, which means that the probability of encountering this demand is less than 0.3%. Though there is a demand outlier, the policy works well and recovers within two days as shown in Figure 5-8.

Figure 5-8 also shows that parameter W and I are comparably stable during the simulation period except for the time period around day 48. This means that the new base stock policy can control the inventory well.

It is observed from Figure 5-9 that the daily demand curve and the daily production curve overlap with each other. This is because the calculated planned lead time is so close to 1 that the difference between the daily demand and daily production cannot be differentiated. The detailed derivation for this observation is shown below.

i. Notation in the derivation

P_t: production value on day t

W_t: work in process inventory on day t;

R_t : material release quantity on day t;

D_t : demand quantity on day t.

ii. Derivation

Based on Eq.4-15, $P_{t-1} = 0.94W_{t-1}, P_t = 0.94W_t$

Based on Eq.4-10, $W_t = W_{t-1}+R_t-P_{t-1}$

Based on Eq.4-12, $R_t = D_t,$

So

$$W_t = 0.06\ W_{t-1} + D_t$$

So

$$P_t = 0.94W_t = 0.94*(0.06\ W_{t-1} + D_t) = 0.056W_{t-1} + 0.94\ D_t.$$

It can be seen from this derivation that P_t and D_t are so close that they cannot be differentiated in Figure 5-9.

When n is bigger than 1 and not close to 1, a production smoothing effect would be observed based on the base stock policy, and this effect will be presented and discussed in section 5.4.

From the results and discussion above, it can be seen that with the help of the operational changes in material handling, the new base stock policy can control the inventory and production well at a single production stage.

5.3.5 Batch size Effect Study

(1) Experiment results

In this experiment, parameters such as W, I, B, stock value B($), cost saving, and stock out probability were collected and summarized in Table 5-9.

Table 5-9.Simulation results under different batch sizes

Batch size	Batch Size	W	I	B	B($)	Percentage of decrease in B($)	Stock out probability
Real Situation	840	468	8425	8893	29823.45	NA	7.69%
Batch size =1	1	4883	2897	7780	24705.56	17.16%	3.57%
Batch size =56	56	4855	2979	7835	24896.55	16.52%	3.57%
Batch size=112	112	4827	3061	7888	25085.17	15.89%	3.57%
Batch size=168	168	4788	3146	7934	25253.3	15.32%	3.57%
Batch size=224	224	4781	3320	8101	25819.28	13.43%	1.19%
Batch size=280	280	4797	3357	8153	25990.89	12.85%	2.38%
Batch size=560	560	4620	3813	8433	26987.01	9.51%	1.19%
Batch size=840	840	4610	3820	8430	26980	9.53%	1.19%

(2) Observations and Discussion

i. Stock out probability

The stock out probability under different batch sizes was plotted in Figure 5-10. There are two observations from the figure. First, the stock out probability decreases as the batch size increases, and smaller batch sizes have higher stock out probabilities. Second, the stock out probability has two main values: 3.57% (3 out of 84 days) for batch sizes under 200pcs, and 1.19% (1 out of 84 days) for batch sizes over 200pcs.

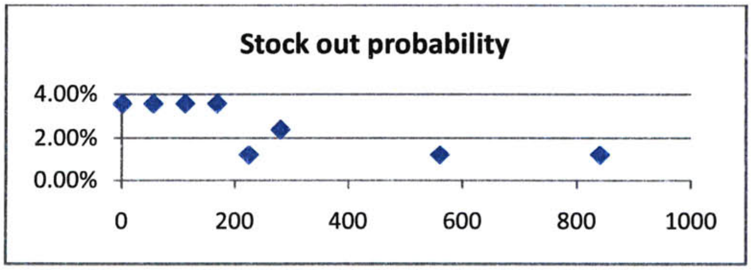


Figure 5-10.Stock out probability vs. batch size

After studying the simulation results, it is discovered that the 3 stock-out days for batch sizes under 200 are day 48, day 54, and day 78; and the 1 stock-out day for batch size over 200 is day 48. There is one common day for these two categories, which is day 48. As mentioned before, there is a demand outlier on day 48, so it is reasonable to encounter a stock out on day 48 under all batch sizes. So the difference between two stock-out probabilities lies in whether there are stock-outs on day 54 and day 78 under different batch sizes.

As can be seen from Figure 5-10, there are no stock-outs on day 54 and 78 under batch sizes over 224pcs, and there are with batch sizes under 224pcs, which can be explained as follows. When the demand comes, part of the demand will be served by the extra material transferred into from stage 3 to stage 4 as described in section 4.3. And this is called TB effect. This TB effect will reduce the demand for stage 3, so the stock out probability will be reduced too.

On day 54 and day 78, batch sizes under 224pcs cannot generate TB effect that is big enough to reduce the demand for stage 3 and avoid stock out. But when the batch size increases, there will be more extra material released into stage 4 from stage3, and the TB effect will increase at the same time. So when the batch size is over 224pcs, the TB effect is big enough to reduce the demands to that can be satisfied with the stock and production at stage 3, so there will be no stock outs on these two days. So there will be no stock outs for batch sizes over 224pcs on day 54 and 78.

It can be seen from this experiment that a batch size of 200pcs may be the stock out probability threshold: When the batch size is over 200, the stock out probability will be around 2%, otherwise, the stock probability is around 4%.

ii. Performance of I, W, and B

Figure 5-11 shows the change of I, W, and B with the change of batch sizes. It can be seen that base stock level B increase slightly with the batch size increase. It is also observed that W decreases and I increases with the batch size increase. To explain this observation, average extra material released to stage 4 from stage 3 under different batch sizes is plotted in Figure 5-12, revised demand for stage 3 from stage 4 after TB effect under different batch sizes is plotted in Figure 5-13, and average daily production value under different batch sizes is plotted in Figure 5-14.

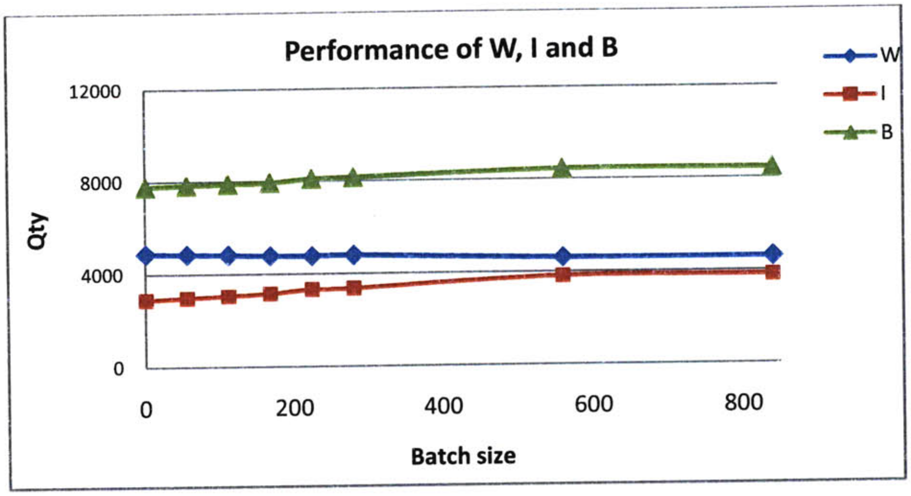


Figure 5-11.Behavior of W, I and B under different batch sizes

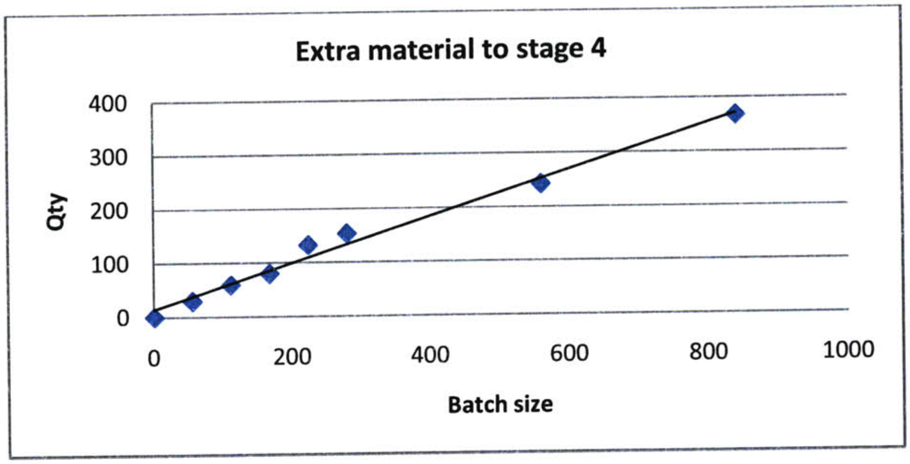


Figure 5-12.Behavior of extra material released to stage 4

Figure 5-12 proves that there will be more material released into stage 4 from stage 3 as the batch size increases. Figure 5-13 shows that actual demand for stage 3 decreases with the increase of batch sizes, which is caused by the increase of TB effect as discussed in **i**. According to the material release rule "R=D", when demand decreases, material released into stage 3 will decrease too. So W will decrease with batch size increase as was observed from Figure 5-11.

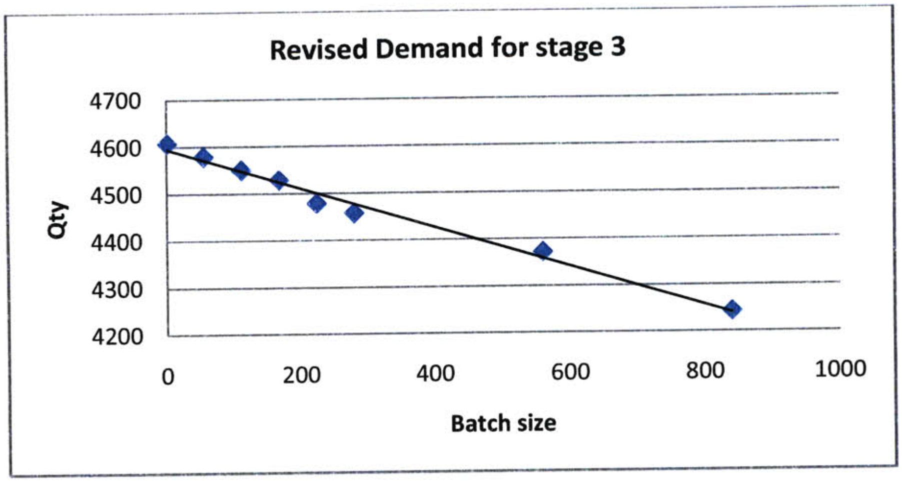


Figure 5-13.Behavior of demand for stage 3

It can be seen from Figure 5-14 that production value is stable under different batch sizes. Based on Eq.4-11, when demand from downstream decreases and production value stays the same, the finished goods inventory will increase. Because when batch size increases, B increases, W decreases, and I increases as shown in Figure 5-11, it can be concluded that I increases faster than W decreases base on Eq.4-16, and batch size has a more significant effect on finished goods inventory.

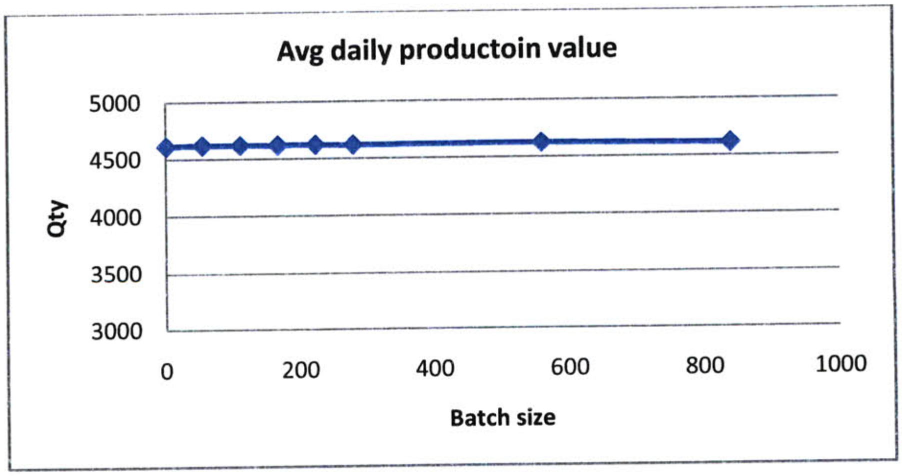


Figure 5-14.Behavior of production value under different batch sizes

From the analysis above, it is concluded that bigger batch size results in higher I and lower W. It is clear that this will increase the stock value at stage 3, so small batch size is more preferable for stage 3.

iii. Cost saving analysis

As discussed in **ii**, batch size change will change the inventory structure at stage 3, which will change stock value at stage 3. And the cost reduction from the new base stock policy is plotted with the batch size change in Figure 5-15.

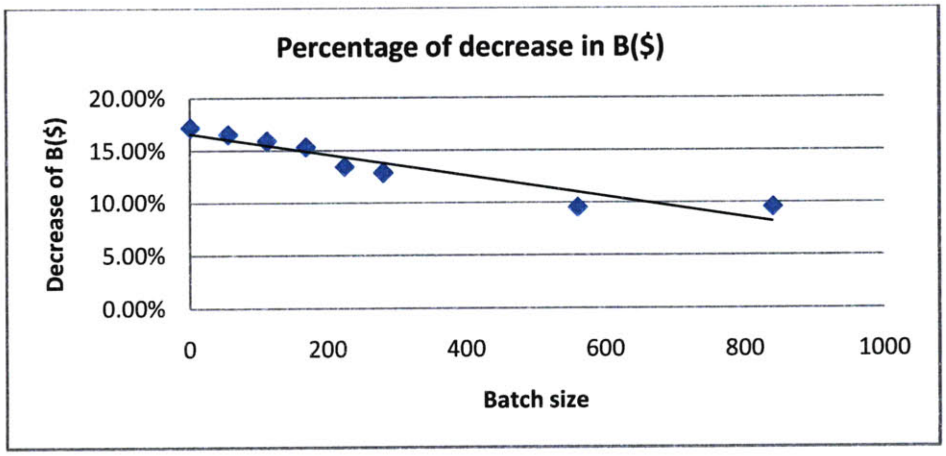


Figure 5-15.Behavior of stock value under different batch sizes

It can be seen from Figure 5-15 that the new base stock policy can achieve a 17% cost reduction when there is no batch size effect (batch size is 1pc). As the batch size increases, the cost reduction decreases. With the current batch size settings in the factory, 840pcs/batch, the cost reduction from the implementation of the new base stock policy is 9%.

In conclusion of all the analysis in this section, it is discovered that batch size has a significant impacts on the implementation of the new base stock model at single production stage. On one hand, small batch size provides higher cost reductions for the factory; on the other hand, big batch size achieves lower stock out probability (higher customer service level). Combine these two considerations, a batch size of 224pcs is recommended, which provides highest customer service level with a 13.4% cost reduction.

5.4 Inventory Setup Calculation and Simulation for the Peak Season in 2009

In this section, the inventory setup for the coming high demand season from Jul to Oct in 2009, is calculated and one of the major products was simulated with the simulation model finalized in section 5.3.

(1) Inventory setup calculation

The high runners were chosen as described in section 5.2. The demand parameters were calculated followed methods discussed by Yuan Zhong [1]. And the calculation results are shown in Appendix VI (Data has been disguised).

To provide insights on the performance of stage 3 in this trial implementation, a simulation was run with the peak season demand data in **Crystal Ball** on one trial products at stage 3.

(2) Simulation with peak season demand data

i. Statistical results

The initial parameters for this simulation are listed in Table 5-10.

Table 5-10.Initial parameters

Demand Mean	6590
Demand Std	1713
n	3.46
W	23520
I	4200
P	7560
B	27720

Crystal Ball was run 1000 times with a time horizon of 120 days. After the simulation, parameters, such as W, I P, B, and stock out probability, were collected and the average values of these parameters are listed in Table 5-11.

Table 5-11.Simulation results

W	22457
I	5276
P	6895
B	27734
Stock out probability	1.10%

It can be seen from Table 5-10 and 5-11 that the simulated I value is higher than calculated I value, and simulated W value is smaller than calculated W value. This is caused by the batch size effect on production value. When the batch size is bigger than 1, the simulated production value will be rounded up with the batch size, so there will be always overproduction than the calculated production value based on Eq.4-15. So more material will be transformed from W into I in the simulation, so W will be smaller in simulation, while I will be bigger.

It is also discovered from Figure 5-16 that the probability distribution of stock-outs seems to be exponentially distributed with an average of 1.4 days. And from Figure 5-17, it can be observed that the base stock level at stage 3 during the peak demand season will fall within the [27720, 27800] interval with a probability higher than 0.9, which means the base stock level is comparably stable.

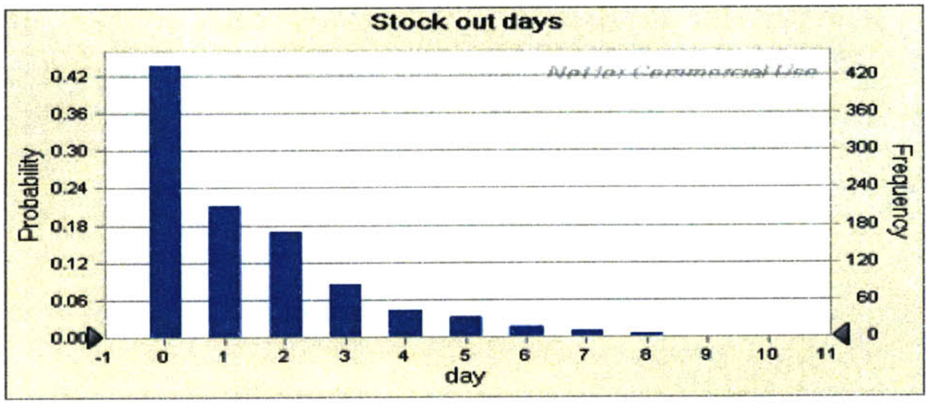


Figure 5-16.Probability distribution of the number of stock outs

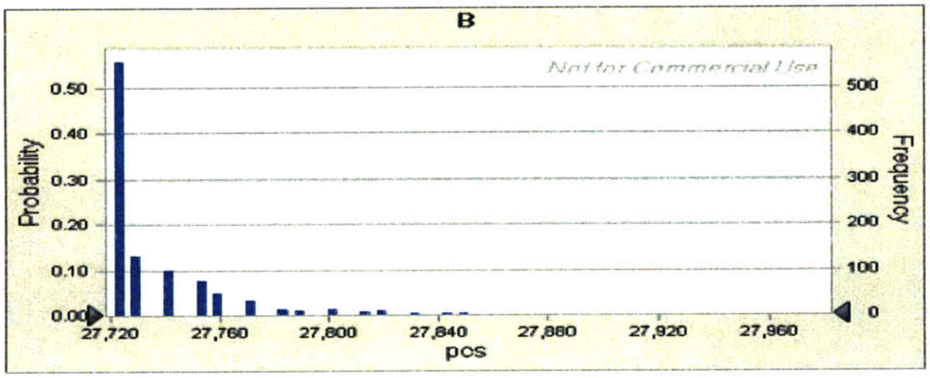


Figure 5-17.Probability distribution of base stock level

ii. Results from individual trial

Besides the statistical results presented above, the individual simulation trials are also monitored to study the production control effect of the chosen base stock model.

Figure 5-18 shows an obvious production smoothing effect which helps stage 3 avoid the highest demand and reduce the demand fluctuation. The reason for the production smoothing effect is: for the peak demand season, the calculated planned lead time n is 3.45 days, which is bigger than 1. This creates a production smoothing effect according to Eq.4-16, which enables the system not to follow the demand tightly, balances the production capability through the planned lead time, and creates stable demands throughout the production system.

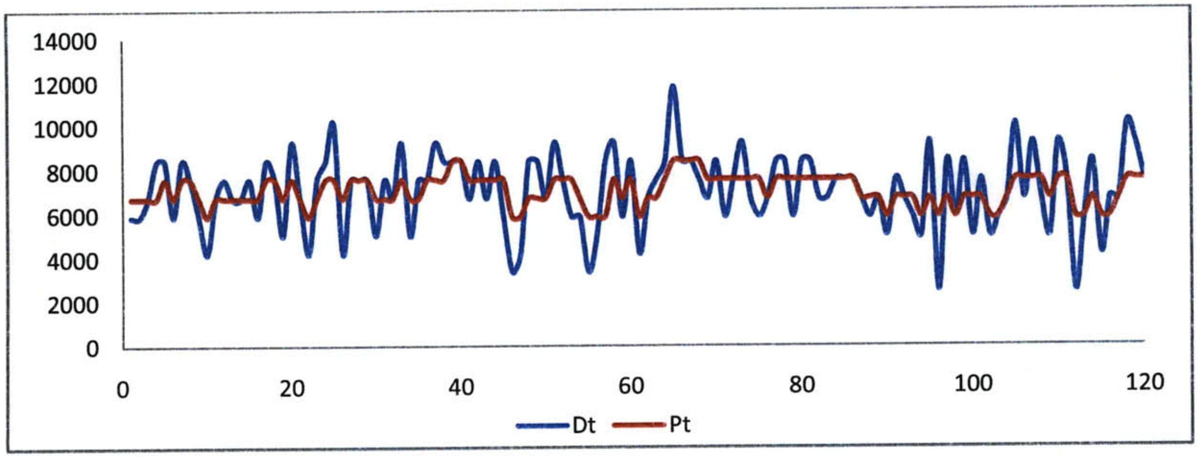


Figure 5-18.Daily production vs. daily demand

According to the above analysis, it is concluded that the designed system will perform well during the peak demand season, and it can be implemented on the trial product.

5.5 Kanban System Design

The Kanban board design is shown in Figure 5-19. The rectangular shapes represent different inventory areas. "R" represents the material release requirement, "W" represents the available material at the current stage, "P" represents production target for the current stage, and "I" represents finished goods inventory at the current stage. R area is the "Green" zone, the W area is the "Amber" zone, and the P area is the "Red" zone as described in section 4.7.

The operation procedures are listed below. Assume a demand D comes to stage 7 (the upstream stage is stage 6), which has already been converted into corresponding number of cards.

Step 1.Trigger material release. The demand is fulfilled with the finished goods inventory at stage 7. And the number of cards corresponding to the demand quantity are moved from I area to the R area to represent the material requirement for stage 6, as the first step in Figure 5-19. This step triggers material release in this production system.

Step 2.Release material. The material handler from stage 7 will release the required material from stage 6 to stage 7. After the material release, the cards in R area will be moved to W area as the second step in Figure 5-19. If there is not enough finished goods inventory at stage 6, corresponding number of cards will be left in R area to represents the stock out of stage 6. The material release is done in this step.

Step 3.Trigger production at the current stage. After the material release is done, production quantity P is calculated based on Eq.4-15. The "w" value used in the equation is the total quantity of material available for production at stage 7. For example, the status shown in Figure 5-19 is the start status at the beginning of a day, there are 2 cards in I, 1 card in R, 3 cards in W, and 1 card in P. So the number of cards of "w" used for P calculation should be the sum of all these cards, namely 7 cards. If the planned lead time for stage 7 is 4 days, the production target for the current day will be 2 cards. Because there is already one card in P, one more card will be moved from W are to P area. So after this step, there are 2 cards in W area, and 2 cards in P area. Production is carried out following cards in P area.

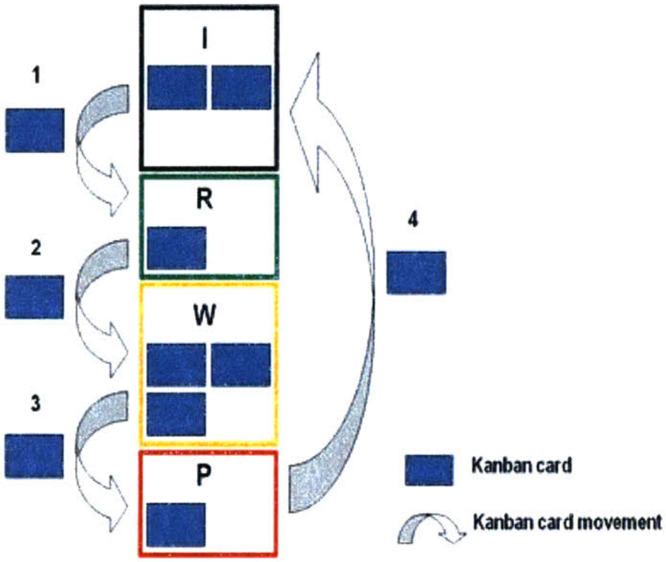


Figure 5-19.Kanban board design

Step 4.Replenish the finished goods inventory after production. After production, the corresponding cards are moved from P area to I area, which means the material has been moved into storage and are available to use. This is shown as the fourth step in Figure 5-19. Till here, the whole production and Kanban operation cycle is completed.

This Kanban system together with the inventory control policy will free the line supervisors from scheduling and planning production. They will have more time to focus on increasing yield and solving other quality issues..

Chapter 6. Conclusion and Recommendations

In this chapter, both project wide and individual conclusions and recommendations are presented. At the end, the current project is criticized, and possible future work is proposed and discussed.

6.1 Project Wide Conclusions and Recommendations

The M.Eng. project at PDAP Electronics Singapore aims to design a system for controlling inventory and directing daily production to facilitate the LEAN movement initiated in this factory. After a thorough study of the factory's operation, the M.Eng. project group identified problems in demand management, production planning, inventory control, and communication between different production stages.

In order to solve the problems identified above, the project group decided to propose a new base stock model combined with a Kanban visual management system for the factory. The group split into two teams to work on designing the system for different stages. Youqun Dong and Yuan Zhong focused on Stage 3. Xiaoyu Zhou and Zia Rizvi worked on Stage 4 to Stage 7, covering the end stages of various products. The systems designed by the two teams are expected to be implemented together on the production system to improve the overall operation efficiency. The Kanban system will link the different production stages together into an integrated operations management system.

Methods were proposed to assist the production planning process. Youqun Dong developed a capacity planning optimization framework to handle excess demand during peak demand season. Yuan Zhong proposed to apply ANOVA analysis to facilitate demand characterization during the planning process. Xiaoyu Zhou proposed a production leveling method functioning as a demand filter, which was shown to improve customer service level during simulation. Zia Rizvi developed an interface tool for production planner that enables integration of shipment planning and proposed inventory policy with capacity considerations.

The performance of the proposed base stock model was studied using computer simulation that modeled multiple production stages in the chain. It was found that the model was able to conserve the overall inventory levels of the multiple production stages in the chain. Furthermore, the base stock model delivered a satisfactory customer service level and improved the overall inventory structure via demand-driven production. As a result, an appreciable reduction of total inventory cost was achieved. Youqun Dong and Yuan Zhong's simulation at stage 3 also indicated that small batch sizes could be more cost-efficient in actual operation. Xiaoyu Zhou and Zia Rizvi proposed to incorporate the line-coupling concept into the system to further reduce the inventory at certain production lines with close production rates.

Based on the above results, the group recommends that PDAP Electronics Singapore implement the proposed system on its production system. Further study of the system could be carried out in the future to understand the performance of the system in different scenarios. After further fine-tuning, the system could be extended to the rest of stages in the factory. As PDAP Electronics Singapore is not the only factory of its type, the proposed models and methods can be applied to other factories with similar characteristics.

6.2 Individual Conclusions and Recommendations

6.2.1. Individual Conclusions

Besides the project wide conclusions presented in section 6.1, there are also some individual conclusions based on the author's individual work.

1. The long-term capacity planning method proposed in this thesis can satisfy the capacity planning requirement and achieve the lowest extra cost during the stock building process. It reduces more cost than Hua Xia's method when the stock building products have value differences.

2. To implement the new base stock method successfully, the material release rule described by Eq.4-9 needs to be followed strictly; the temporary buffer (TB) described in section 4.3 can solve the batch size mismatch between stage 3 and stage 4 effectively.

3. Batch size has an impact on the performance of this inventory policy. First, the cost saving achieved by the new base stock policy decreases from 17% to 9.5%.as batch size changes from 1pc to 840pcs; second, batch size also affects the customer service level. A batch size over 200pcs will provide a smaller stock out probability than a batch size under 200pcs.

6.2.2. Individual Recommendations

(1) From the discussion in Chapter 5, the operational change made in section 4.3, such as batch size coordination and temporary buffer concept between stages with batch size mismatch, are recommended to be followed. These operational changes can eliminate unnecessary work in process inventory along the line. And a batch size of 224pcs/batch is recommended.

(2) The author recommends that the factory establish a cross training mechanism to enable regular knowledge sharing as well as personnel flow within the company. This will create and maintain a company culture of criticizing, discovering and creating. The factory should also increase the communication between departments to achieve overall development in the whole company instead of in one single department.

(3) From the discussion in Chapter 4 and 5, a general procedure containing 5 steps in order to implement the new base stock policy and the Kanban system is recommended to the company. They are:

Step 1.Identify the bottleneck stage by systematic capacity evaluation. After that, the capacity planning method proposed in this thesis should be applied at the bottleneck stage if necessary.

Step 2.Analyze demand seasonality and choose inventory mix. After the capacity planning, apply ANOVA to each production stage to identify demand seasonality for that particular stage. And apply Pareto Chart to identify the high runners for that particular stage.

Step 3.Apply the base stock policy to set up inventory. After step 2, the new base stock policy should be applied to individual production stages to setup inventory if necessary.

Step 4. Set up the Kanban system.

Step 5.Monitor data updates. Because the demand forecast is updated monthly, so the capacity planning will be updated monthly. This updated demand data should be monitored to see if it changes the demand seasonality and whether the inventory calculation needs to be revised.

(4) It was discovered from the research that the inventory setup depends heavily on the available capacity of the target production stage. As the demand for this factory is expected to increase for the next few years, it is strongly recommended that the company increase the capacity of stage 6.

(5) Stage 3 is a single line stage, so it is also recommended to install a new line at stage 3 to guarantee smooth production for the downstream stages.

6.3 Future Work

This section first criticizes current work done by the M.Eng. group, and then discusses potential future work for the company.

6.3.1. Critique of the Current Work

1. This project set up the inventory for individual production stages in the factory, but whether the inventory set up is optimal or not has not been evaluated. To evaluate the system more precisely, a more complex simulation model is needed.
2. The implementation data has not been collected and analyzed. So the effects of the changes made in this project have not been verified by real factory data.

6.3.2. Future Work

1. Implementing and analyzing the designed system

The designed system has already been run on two trial products, and the company should keep it running for another 3 months. After the trial running, the company could involve more products in the designed system and run it for another 6 months. After all these preparations, the company could involve the whole factory into the designed system and run it for 1 year to test the effect of the research results from this project thoroughly.

Important line performance measures should be collected during implementation. The inventory levels at each station and production outputs should be monitored every day. The customer service level and average production lead time should be recorded. The cost saving effect should be evaluated after implementation.

Other information such as the feedbacks from the work force should be surveyed for continuous improvement of the designed system.

2. System wide simulation

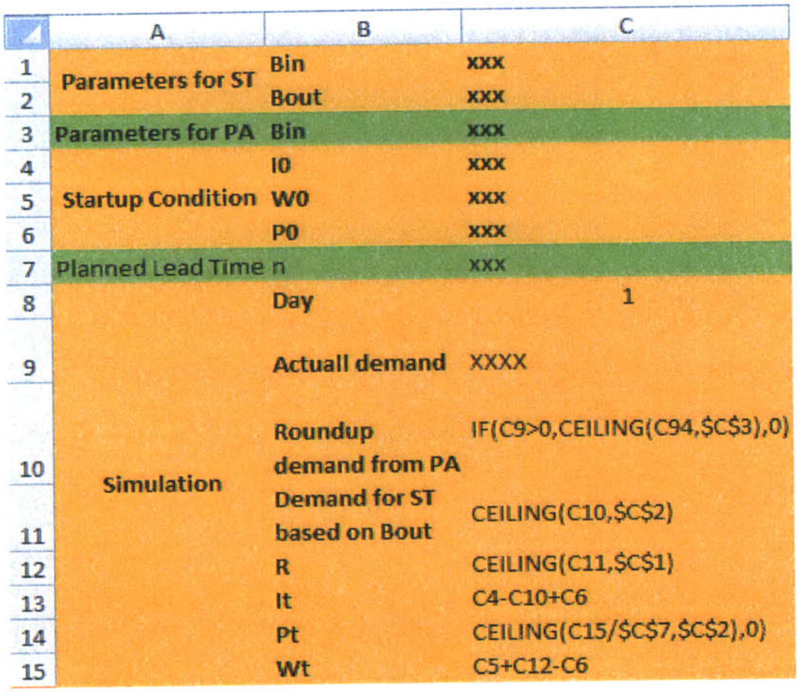
A more detailed, more complex system wide simulation model could be built with professional software to identify the optimum inventory and batch size settings for the current production system.

3. External electronic Kanban system

To eliminate the waste further, the company could expand the current internal Kanban system to external customer and supplier electronic Kanban system to take a further step in LEAN transformation of this factory.

Appendix

Appendix I. Basic simulation model

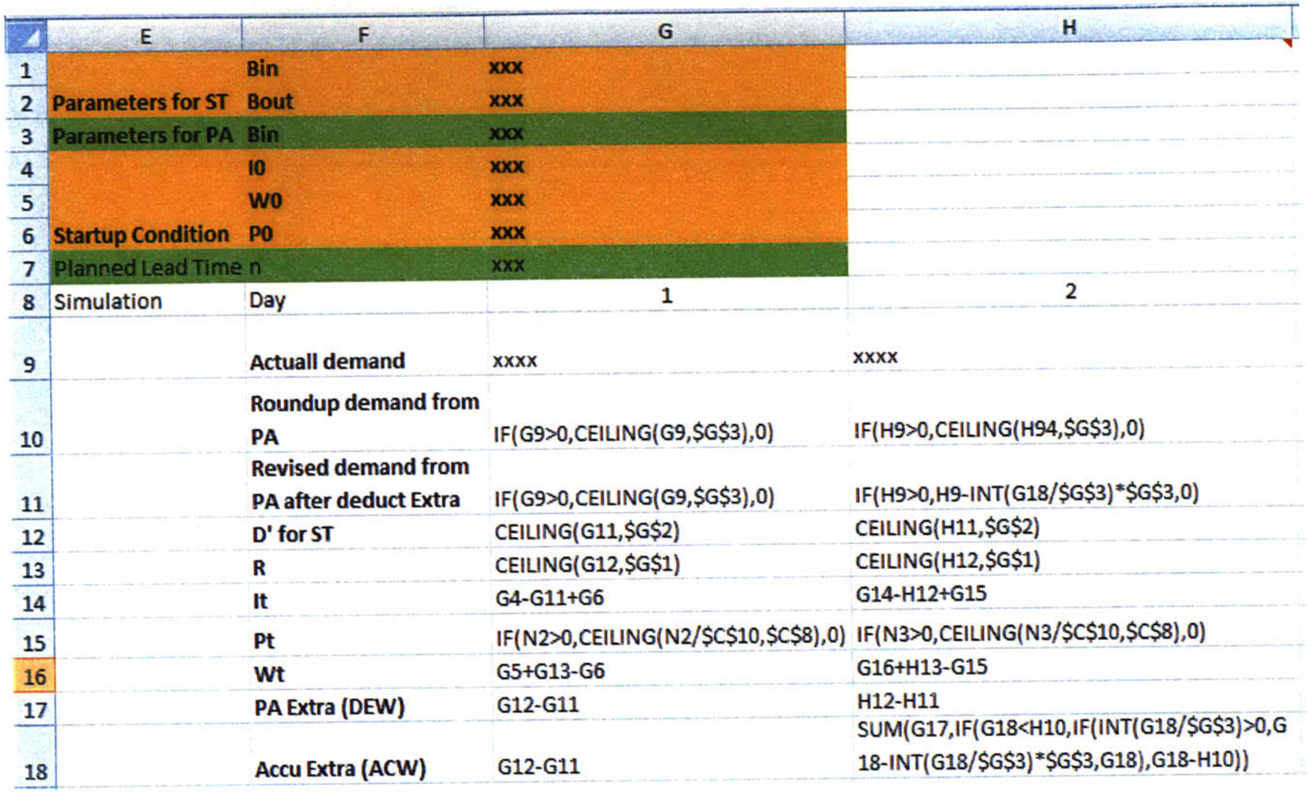


	A	B	C
1	Parameters for ST	Bin	xxx
2		Bout	xxx
3	Parameters for PA	Bin	xxx
4	Startup Condition	I0	xxx
5		W0	xxx
6		P0	xxx
7	Planned Lead Time	n	xxx
8	Simulation	Day	1
9		Actuall demand	XXXX
10		Roundup demand from PA	IF(C9>0,CEILING(C94,$C$3),0)
11		Demand for ST based on Bout	CEILING(C10,$C$2)
12		R	CEILING(C11,$C$1)
13		It	C4-C10+C6
14		Pt	CEILING(C15/$C$7,$C$2),0)
15		Wt	C5+C12-C6

Appendix II. Demand data (All data has been revised for confidentiality)

Day	1	2	3	4	5	6	7
Actuall demand	5280	5473	5500	5193	5088	1910	5234
Day	8	9	10	11	12	13	14
Actuall demand	5400	4916	4538	3433	1664	0	3635
Day	15	16	17	18	19	20	21
Actuall demand	1363	3495	3612	1374	5523	5560	5449
Day	22	23	24	25	26	27	28
Actuall demand	4466	576	1757	5019	5397	5413	5344
Day	29	30	31	32	33	34	35
Actuall demand	5336	1392	5099	5450	5422	5213	5271
Day	36	37	38	39	40	41	42
Actuall demand	1816	5234	5371	4135	4839	5241	1614
Day	43	44	45	46	47	48	49
Actuall demand	5090	5472	5421	5406	4740	10529	0
Day	50	51	52	53	54	55	56
Actuall demand	5477	5421	5546	5321	7323	5136	5532
Day	57	58	59	60	61	62	63
Actuall demand	5597	6545	5419	4426	2916	1790	1664
Day	64	65	66	67	68	69	70
Actuall demand	0	4942	4263	5231	5503	5371	5405
Day	71	72	73	74	75	76	77
Actuall demand	2548	3827	5165	4870	4312	0	0
Day	78	79	80	81	82	83	84
Actuall demand	7818	4776	4896	4848	4452	1160	3605

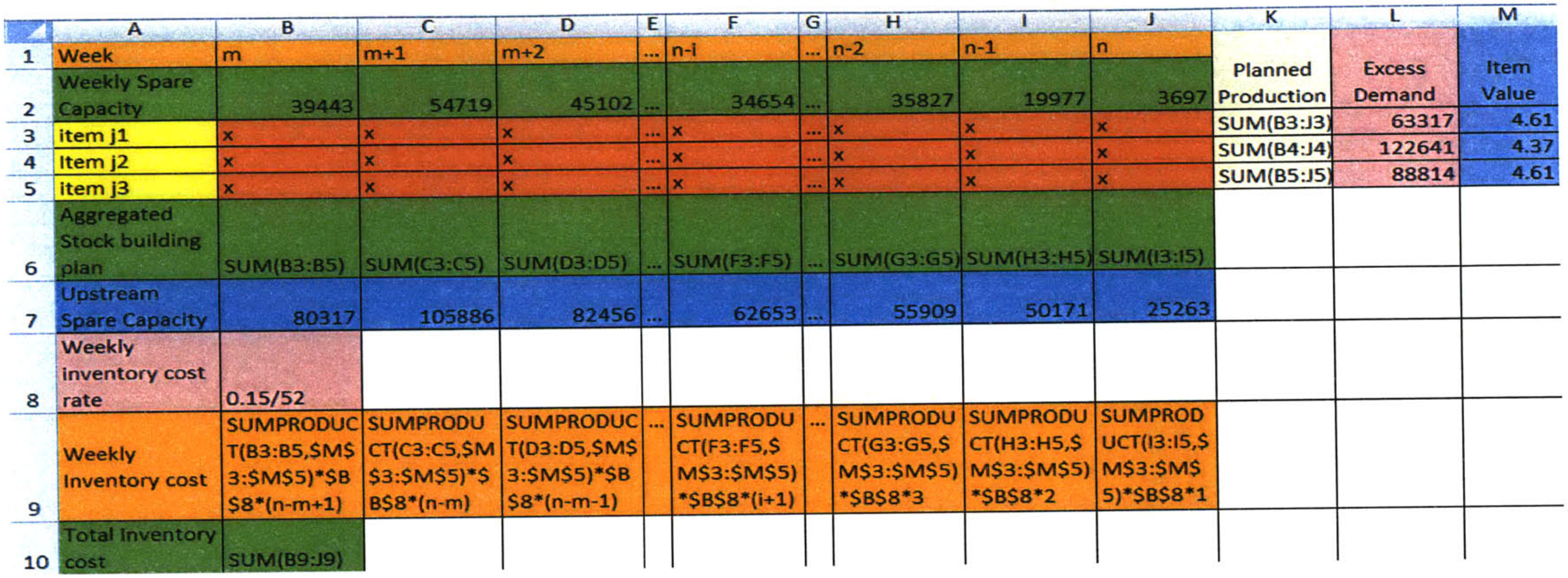
Appendix III. New simulation model incorporating the TB concept



	E	F	G	H
1		Bin	xxx	
2	Parameters for ST	Bout	xxx	
3	Parameters for PA	Bin	xxx	
4		I0	xxx	
5		W0	xxx	
6	Startup Condition	P0	xxx	
7	Planned Lead Time	n	xxx	
8	Simulation	Day	1	2
9		Actuall demand	xxxx	xxxx
10		Roundup demand from PA	IF(G9>0,CEILING(G9,$G$3),0)	IF(H9>0,CEILING(H94,$G$3),0)
11		Revised demand from PA after deduct Extra	IF(G9>0,CEILING(G9,$G$3),0)	IF(H9>0,H9-INT(G18/$G$3)*$G$3,0)
12		D' for ST	CEILING(G11,$G$2)	CEILING(H11,$G$2)
13		R	CEILING(G12,$G$1)	CEILING(H12,$G$1)
14		It	G4-G11+G6	G14-H12+G15
15		Pt	IF(N2>0,CEILING(N2/$C$10,$C$8),0)	IF(N3>0,CEILING(N3/$C$10,$C$8),0)
16		Wt	G5+G13-G6	G16+H13-G15
17		PA Extra (DEW)	G12-G11	H12-H11
18		Accu Extra (ACW)	G12-G11	SUM(G17,IF(G18<H10,IF(INT(G18/$G$3)>0,G18-INT(G18/$G$3)*$G$3,G18),G18-H10))

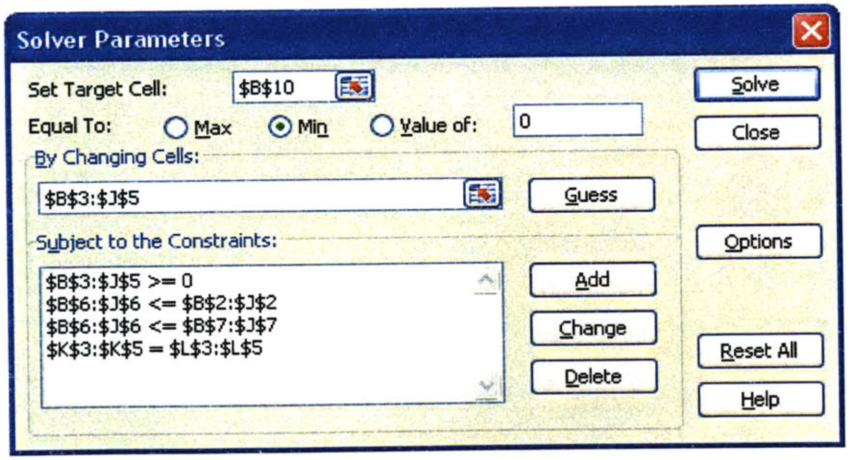
Appendix IV. Long term capacity planning framework

1. Excel Cells



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Week	m	m+1	m+2	...	n-i	...	n-2	n-1	n	Planned Production	Excess Demand	Item Value
2	Weekly Spare Capacity	39443	54719	45102	...	34654	...	35827	19977	3697			
3	item j1	x	x	x	...	x	...	x	x	x	SUM(B3:J3)	63317	4.61
4	Item j2	x	x	x	...	x	...	x	x	x	SUM(B4:J4)	122641	4.37
5	item j3	x	x	x	...	x	...	x	x	x	SUM(B5:J5)	88814	4.61
6	Aggregated Stock building plan	SUM(B3:B5)	SUM(C3:C5)	SUM(D3:D5)	...	SUM(F3:F5)	...	SUM(G3:G5)	SUM(H3:H5)	SUM(I3:I5)			
7	Upstream Spare Capacity	80317	105886	82456	...	62653	...	55909	50171	25263			
8	Weekly inventory cost rate	0.15/52											
9	Weekly Inventory cost	SUMPRODUCT(B3:B5,$M$3:$M$5)*$B$8*(n-m+1)	SUMPRODUCT(C3:C5,$M$3:$M$5)*$B$8*(n-m)	SUMPRODUCT(D3:D5,$M$3:$M$5)*$B$8*(n-m-1)	...	SUMPRODUCT(F3:F5,$M$3:$M$5)*$B$8*(i+1)	...	SUMPRODUCT(G3:G5,$M$3:$M$5)*$B$8*3	SUMPRODUCT(H3:H5,$M$3:$M$5)*$B$8*2	SUMPRODUCT(I3:I5,$M$3:$M$5)*$B$8*1			
10	Total Inventory cost	SUM(B9:J9)											

2. Solver Interface for optimization the stock building plan based on the spreadsheet shown above



Solver Parameters

Set Target Cell: $B$10

Equal To: ○ Max ● Min ○ Value of: 0

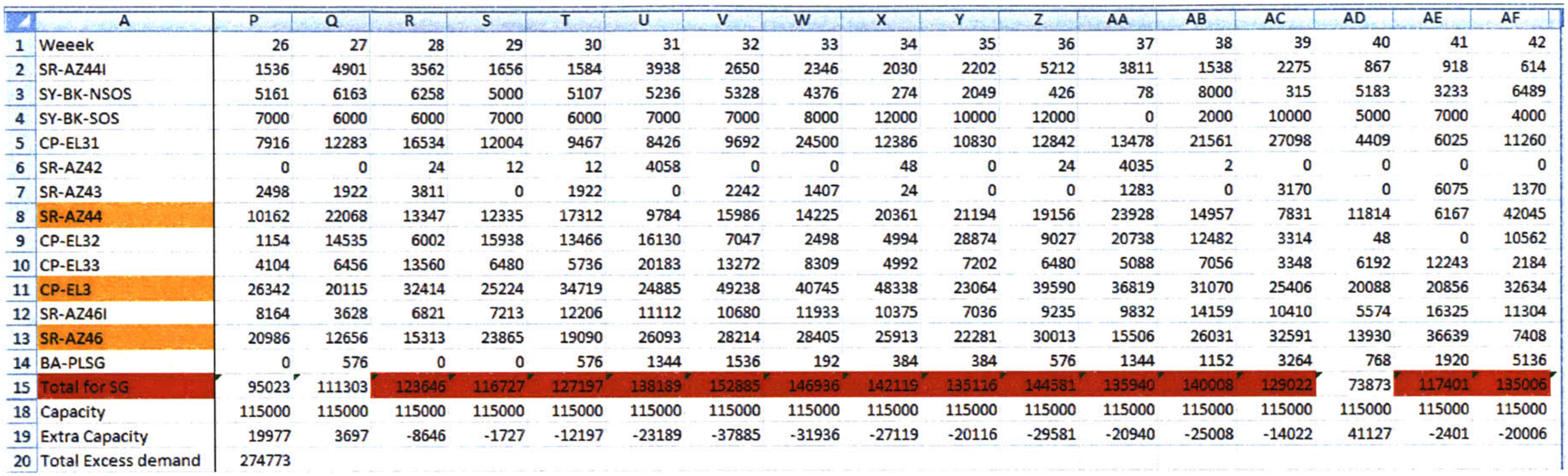
By Changing Cells:

$B$3:$J$5

Subject to the Constraints:

$B$3:$J$5 >= 0
$B$6:$J$6 <= $B$2:$J$2
$B$6:$J$6 <= $B$7:$J$7
$K$3:$K$5 = $L$3:$L$5

Appendix V. Peak season identification during long term capacity planning (The data has been revised)

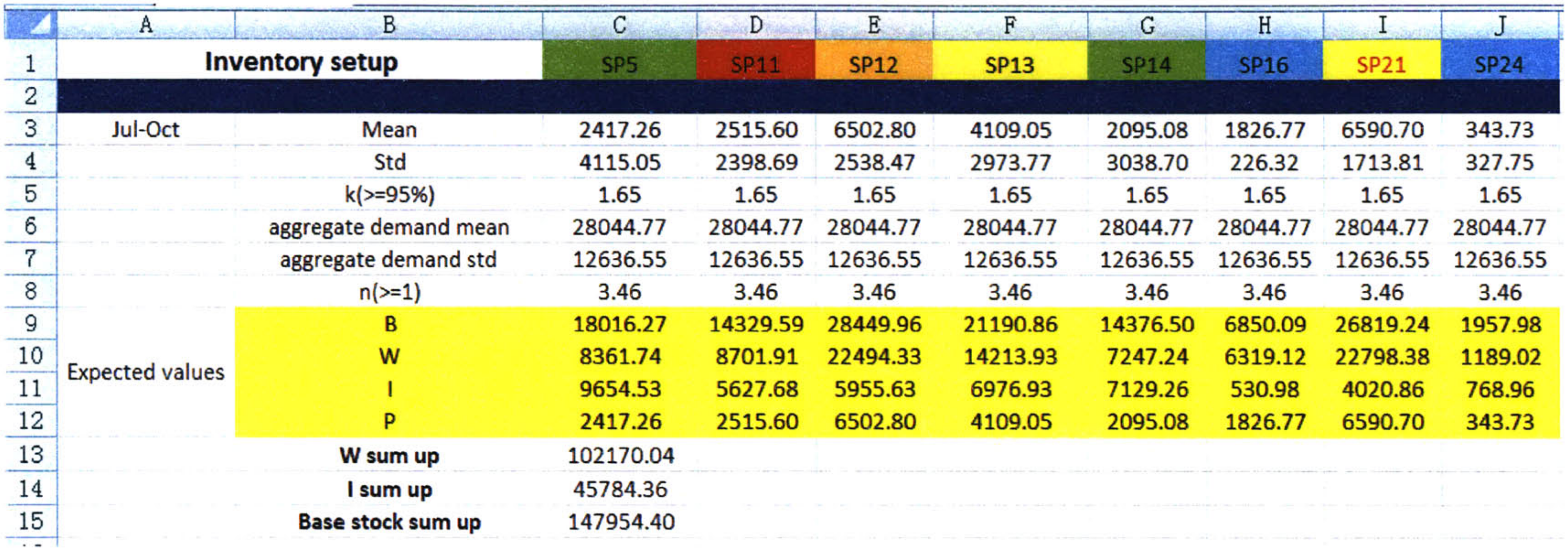


	A	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF
1	Weeek	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
2	SR-AZ44I	1536	4901	3562	1656	1584	3938	2650	2346	2030	2202	5212	3811	1538	2275	867	918	614
3	SY-BK-NSOS	5161	6163	6258	5000	5107	5236	5328	4376	274	2049	426	78	8000	315	5183	3233	6489
4	SY-BK-SOS	7000	6000	6000	7000	6000	7000	7000	8000	12000	10000	12000	0	2000	10000	5000	7000	4000
5	CP-EL31	7916	12283	16534	12004	9467	8426	9692	24500	12386	10830	12842	13478	21561	27098	4409	6025	11260
6	SR-AZ42	0	0	24	12	12	4058	0	0	48	0	24	4035	2	0	0	0	0
7	SR-AZ43	2498	1922	3811	0	1922	0	2242	1407	24	0	0	1283	0	3170	0	6075	1370
8	SR-AZ44	10162	22068	13347	12335	17312	9784	15986	14225	20361	21194	19156	23928	14957	7831	11814	6167	42045
9	CP-EL32	1154	14535	6002	15938	13466	16130	7047	2498	4994	28874	9027	20738	12482	3314	48	0	10562
10	CP-EL33	4104	6456	13560	6480	5736	20183	13272	8309	4992	7202	6480	5088	7056	3348	6192	12243	2184
11	CP-EL3	26342	20115	32414	25224	34719	24885	49238	40745	48338	23064	39590	36819	31070	25406	20088	20856	32634
12	SR-AZ46I	8164	3628	6821	7213	12206	11112	10680	11933	10375	7036	9235	9832	14159	10410	5574	16325	11304
13	SR-AZ46	20986	12656	15313	23865	19090	26093	28214	28405	25913	22281	30013	15506	26031	32591	13930	36639	7408
14	BA-PLSG	0	576	0	0	576	1344	1536	192	384	384	576	1344	1152	3264	768	1920	5136
15	Total for SG	95023	111303	123646	116727	127197	138189	152885	146936	142119	135116	144581	135940	140008	129022	73873	117401	135006
18	Capacity	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000	115000
19	Extra Capacity	19977	3697	-8646	-1727	-12197	-23189	-37885	-31936	-27119	-20116	-29581	-20940	-25008	-14022	41127	-2401	-20006
20	Total Excess demand	274773																

Appendix VI. Stock building plan

Week		20	21	22	23	24	25	26	27	Planned Qty	Calculated Qty	Value
Excess Capacity		39443	54719	45102	55750	34654	35827	19977	3697			
Product	SR-AZ44	0	0	0	34007	12541	13714	3053	0	63317	63317	5
	CP-EL3	25047	54719	42875	0	0	0	0	0	122641	122641	4
	SR-AZ46	0	0	2226	21742	22112	22112	16923	3696	88814	88814	5
Weekly planned qty		25047	54719	45101	55749	34653	35826	19976	3696			
Upstream Spare Capacity		80317	105886	82456	89569	62653	55909	50171	25263			
Weekly inventory rate		0.003										
Weekly total Inventory cost		2312.031	4419.612	3160.904	4020.361	1999.212	1550.163	576.2308	53.30769			
Total Inventory cost		18091.82										

Appendix VII. Inventory setup for the coming peak season (The data has been revised)



	A	B	C	D	E	F	G	H	I	J
1	**Inventory setup**		SP5	SP11	SP12	SP13	SP14	SP16	SP21	SP24
2										
3	Jul-Oct	Mean	2417.26	2515.60	6502.80	4109.05	2095.08	1826.77	6590.70	343.73
4		Std	4115.05	2398.69	2538.47	2973.77	3038.70	226.32	1713.81	327.75
5		k(>=95%)	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
6		aggregate demand mean	28044.77	28044.77	28044.77	28044.77	28044.77	28044.77	28044.77	28044.77
7		aggregate demand std	12636.55	12636.55	12636.55	12636.55	12636.55	12636.55	12636.55	12636.55
8		n(>=1)	3.46	3.46	3.46	3.46	3.46	3.46	3.46	3.46
9	Expected values	B	18016.27	14329.59	28449.96	21190.86	14376.50	6850.09	26819.24	1957.98
10		W	8361.74	8701.91	22494.33	14213.93	7247.24	6319.12	22798.38	1189.02
11		I	9654.53	5627.68	5955.63	6976.93	7129.26	530.98	4020.86	768.96
12		P	2417.26	2515.60	6502.80	4109.05	2095.08	1826.77	6590.70	343.73
13		**W sum up**	102170.04							
14		**I sum up**	45784.36							
15		**Base stock sum up**	147954.40							

Reference

1 Zhong, Y., 2009,"Improved Inventory and Production control on a Multi-Product Production Line: Seasonality Analysis, Inventory Supermarket, and Kanban Design," M.Eng. thesis, Massachusetts Institute of Technology, Cambridge, MA

2. Zhou, X.Y., 2009, "Design of a Demand Driven Multi-Item-Multi-Stage Manufacturing System: Production Scheduling, WIP Control and Kanban Implementation," M.Eng. thesis, Massachusetts Institute of Technology, Cambridge, MA

3. Rizvi, S.Z.A., 2009, "Production and Inventory Control of a Multi-Item Multi-stage manufacturing System: Simulation Modeling, Capacitated Shipment Planning and Kanban Design," M.Eng. thesis, Massachusetts Institute of Technology, Cambridge, MA

4. Xia, H., 2008, "Multiple-Part-Type Systems in High Volume Manufacturing: Long-Term Capacity Planning & Time-Based Production Control," M.Eng. thesis, Massachusetts Institute of Technology, Cambridge, MA

5. Womack, Janmes P., Daniel T. Jones, and Daniel Roos, 1991,*The Machine That Changed the World: The Story of Lean Production*, New York: Harper Perennial.

6. Amber J. Chesborough, 2004, "Inventory reduction: Applying a pull ordering system to a distribution business," S.M. and M.B.A. thesis, Massachusetts Institute of Technology, Cambridge, MA

7. Smalley, A., 2005, "Pull systems must fit your production needs," Lean Directions, http://www.sme.org/cgi-bin/get-newsletter.pl?LEAN&20051011&1, accessed June 16, 2009

8. Graves, S., Lecture notes, 15.762, Massachusetts Institute of Technology, February 9, 2009, unpublished material

9. Gershwin, S., Lecture notes, 2.854, Massachusetts Institute of Technology, July 1, 2004, unpublished material.

10. Graves, S., 1988,"Safety Stocks in Manufacturing Systems," Journal of Manufacturing and Operations Management 2 (1988): 67-11

11. Swain, B., 2007,"Visual Management," LCI summit, Lean Construction Institute UK, www.lci-uk.org/Visual Management note.pdf , accessed June 18, 2009

12. "Traffic Light Systems Make Problems Visible," Lean Directions, http://www.sme.org/cgi-bin/get-newsletter.pl?LEAN&20040408&2&, accessed July 10, 2009

13. "Introduction to optimization with the Excel Solver tool," Microsoft Corporation, http://office.microsoft.com/en-us/excel/HA011245951033.aspx, accessed May 22, 2009

14. "Oracle and Crystal Ball," Oracle Corporation, http://www.oracle.com/crystalball/index.html, accessed May 23, 2009