Design of a Demand Driven Multi-Item-Multi-Stage Manufacturing System: Production Scheduling, WIP Control and Kanban Implementation

by

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Abstract

The project is conducted in a multi-item-multi-stage manufacturing system with high volume products. The objectives are to optimize the inventory structure and improve production scheduling process. The stock building plan is studied carefully to understand the demand seasonality characteristics and the planning guidelines that the factory is currently following. A new base stock policy is introduced to the 5 focused production stages to establish a demand driven system with controlled inventory and new rules to guide the daily production. The line coupling concept is also added to further refine the inventory structure. After that, the production leveling method is employed to help reduce the variation of daily production targets. Finally, a Kanban system is designed to facilitate the demand driven manufacturing under the operation of the new base stock policy.

With the appropriate inventory control and production scheduling policy, the overall inventory level in the factory is reduced by 61% based on calculation, leading to a savings of 70% of the total inventory cost. Moreover, the establishment of Kanban system has simplified the daily manufacturing activity on the operation level and helped the factory become a lean manufacturer.

Key Words: New Base Stock, Production Leveling, Line Coupling, Kanban

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

Thesis Supervisor: Stanley B. Gershwin

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Chapter 1 Introduction

This chapter briefly introduces RP Electronics Singapore Pte Ltd and its subsidiary company PDAP Electronics Singapore, where the M.Eng project took place. It includes the company background, product classification and associated manufacturing process flow. The materials stated in this chapter are the basis for understanding the company and its current problem in inventory and production control.

1.1Company Background

Headquartered in Europe, RP Electronics is one of the leading electronic appliance companies in the world. RP Electronics Singapore (RP) was set up in 1951. With a history of more than 50 years, RP Singapore is one of the pioneers in Singapore industry. From here, over two hundred products are produced and sold to Asia, Europe and America. RP Singapore is always trying to maintain its leading position in the electronic appliance manufacturing industry.

The focus of this paper is one of its subsidiary company, PDAP Electronics Singapore, which is the global distribution center and R&D center for one of RP's main products. RP Electronics headquarter management has initiated the implementation of a system analogous to Toyota Production System (TPS) 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 reduction of wasteful activities and work in process (WIP) lying along the production lines that eventually decreases material flow lead times and blocks capital along the production lines. The management has therefore focused on controlling the inventory and lead times to establish a Lean production environment.

1.2 Products Classification

PDAP Singapore factory is dedicated to the production of a core component of one of the RP's main consumer products. In the following chapters, the core component is called SP for short. There are various kinds of SPs being manufactured in this factory, and they are classified into two major groups: Class-A and Class-B. Further, in class A there is one product family with 3 products. However, in class B there are 5 product families with a total of 11 products. Moreover, each product has further variants and thus the product portfolio has over 50 stock keeping units (SKU) in total at the finished goods level. To help demonstrate the product relationship, a tree diagram is shown in Figure 1.

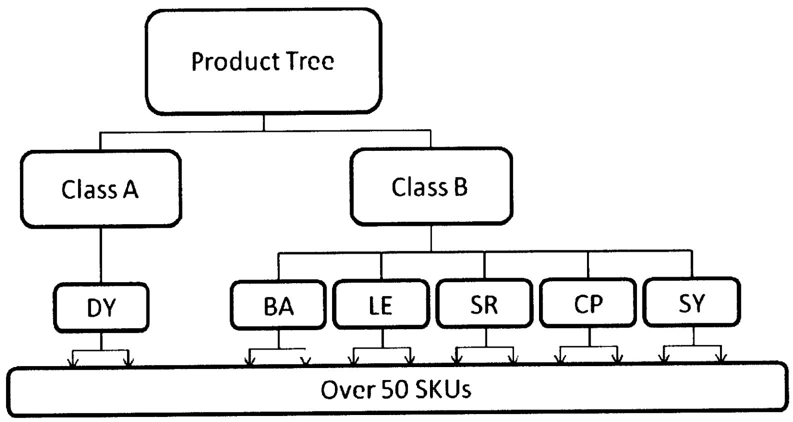

Figure 1 Product Tree for PDAP Factory

1.3 Production Process Flow

There are in total 7 production stages for processing SPs in this factory; 4 stages are equipped with multiple machine lines, each of them manufactures certain types of SPs under the same product family. The remaining 3 stages have only one machine each but those single machines are big and can handle all the SPs going through the production stage. Due to different process requirements, SPs are not send to all, but a subset of the 7 production stages to complete their own manufacturing process. See Figure 2.

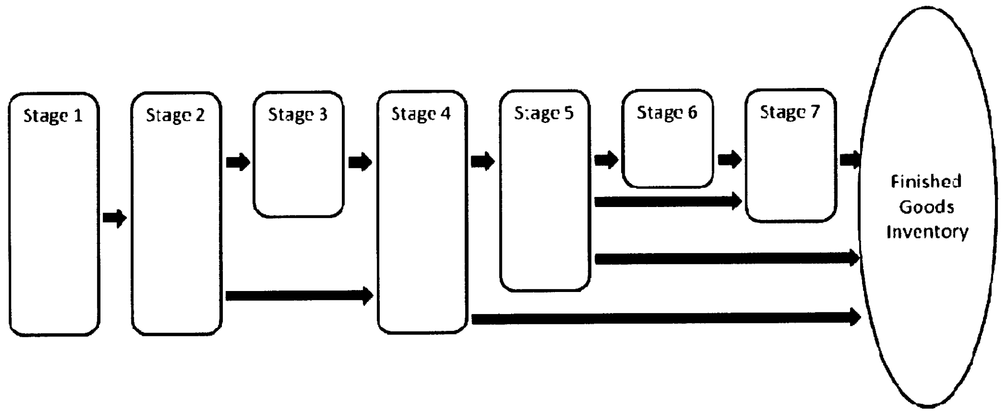

Figure 2 Production Process Flow

1.4 Demand Management

1.4.1 Production Planning Process

To begin the production planning process, the National Sales Organization (NSO) in RP Electronics Singapore uses the Advanced Planning Optimization (APO) tool and collaborates with Logistics Management Team (LMT), so as to generate the Monthly Demand Forecast for the coming year by the end of November of the current year. This monthly forecast is then updated each month with a timeframe from then till end of the year. They also provide a weekly rolling orientation values for next 52 weeks with rough estimates for weeks beyond current year. The demand management process can be disintegrated and described below:

1) Development of Monthly Production Schedule (MPS): The Production planner prepares the MPS by the end of third week (on Friday) of current month for the next month (up till end of year) at finished goods level (only) based on the monthly forecast from step 1. The production planner considers only the actual demand and final process capacity while preparing the MPS. The first version of the MPS serves as the basis for a manager who is responsible for developing stock plan as explained in subsequent section. The successive MPS revisions are finalized with assessment from production planner based on his analysis of the comparison between MPS and stock building plan.

2) Finalization of the monthly demand value: The commercial planner is informed of the capability for one product model, based on which he finalized the monthly demand value for that product model. Some products models have variants, and the commercial planner is allowed to change the demand of particular variant within the demand for the corresponding model, but he is not allowed to change the total demand for that particular product model given in MPS.

3) Weekly Constraint List development: Every Tuesday, the production planner provides a Weekly Constraint List based on his anticipated stock values for the coming week to bind the production planner Weekly Production Schedule (WPS) values.

4) Order placement: The constraints set in step 4 are sent to the commercial planner for planning order placement for next week. The Commercial planner updates order values every week (on Thursday) for next 18 weeks (1 firm while the rest 17 are tentative) at finished goods level considering the constraints provided by the production planner.

5) WPS finalization: Production planner converts the orders sent by the commercial planner in step 5 into firmed WPS for next week and tentative WPS of second next week. Hence the confirmed order for coming week serves as the basis for WPS and Shipment Plan (with 2 days leads to WPS) at finished goods level for production planner.

6) Daily production plan development: The production planner takes into account the first week firmed orders, the first two days order of the following week for assembly plant, and weekly satellite factories requirement from the WPS to develop the daily production plan for different production stages in the factory. He has to do a production leveling based on his own method to match demand with capacity while ensuring on time delivery of shipments. He consider the leveled finished goods requirements, quoted lead times of upstream stages, and individual stage inventory levels to develop a rough daily production plan for all the stages excluding ST. The 6 steps described above are shown in Figure 3.

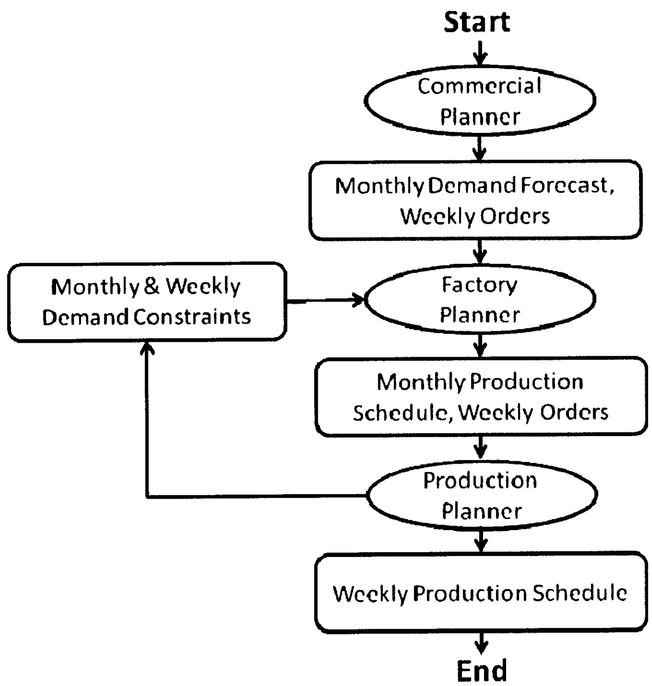

Figure 3 Production Planning Process

During the high demand season, the production requirements are decoupled from the shipment schedules because the factory builds up stock for the high runners in the low demand season. So the production planner usually tends to run bigger lots of every model to save on changeover times. However, the low runners are not stocked during the low demand season, so they have to be planned following the 6 steps described above.

1.4.2 Semi-Knocked Down (SKD) Parts Demand Management

SKD Manager receives forecast and confirmed orders directly from the satellite factories. The shipments to satellite factories are made on weekly basis and these planned requirements are given to the production planner so that he can plan accordingly. This factory also supplies Semi-Knocked Down (SKD) parts to satellite factories in Europe and China.

Chapter 2 Problem Statement and Project Objective

This chapter describes the main problems unveiled in the current PDAP manufacturing system, and the objectives of the team project. There are 3 main problems identified in the production system: the first is the demand seasonality, which causes problems in capacity planning; the second problem is their current production control policy that has generated more-than-required intra-stage inventory; the third problem is the desynchronized local production scheduling at each production stage that makes the system erratic. Based on these 3 problems, the project objective becomes to develop an improved production planning and inventory control system for the PDAP factory.

2.1 Problem Statement

2.1.1 Demand Seasonality and Stock Building

PDAP Singapore experiences peak demand starting from the third quarter of each year, i.e. during July to October, when advanced orders are placed by assembly plants and satellite factories in anticipation for the Christmas sale. This demand is higher than the existing capacity of the factory. The low season starts in November, and continues through January to June in the following year. Factory aims to satisfy all demand at the current operating level without extra investment to expand the capacity, as the added capacity can incur extra operating costs in addition to the initial investment. The company tackles the problem by employing a stock building policy that helps the company to utilize its capacity in the low demand season. The extra units produced in advance are kept at the factory and shipped to assembly plant and satellite factories when the factory capacity alone cannot meet the demand.

The stock building plan is of paramount importance as the production requirements are extracted from it rather than the daily shipment requirements. The capacity of the last production stage is examined to determine if the monthly demands, as projected in MPS, can be satisfied with monthly production. Any excess demand is shifted backwards to the earlier months. These adjusted demand values for the last stage become demand for the previous stage and the sequence follows till the first production stage. The production resources are exposed to requirements based on this plan.

Hence it serves as the input source for us to perform analysis and calculations.

However, this stock building practice only ensures the satisfaction of the demand, without taking account of the inventory costs incurred. The tradeoff between the extent of stocking and the associated inventory cost is not assessed. Furthermore, this scheme's heavy reliance on human intervention makes it vulnerable to mistakes and forecast errors. It should also be noted that this plan is only on aggregate demand level for SP product lines and it would be the job of the production planner to stock high runner variants based on these monthly targets. A more efficient and accurate way of making a stock building plan may need to be explored.

2.1.2 Production Control

The planning carried out by the production planner serves as the benchmark for production stages during the rest of the week. It is found that this plan was only given to 5 out of the 7 production stages in the factory, namely Stage 1, 2, 5, 6, and 7, the left 2 production stages have to trigger their own production based on the judgment of the supervisor to the upstream work-in-process level, its own stock level and the manufacturing capacity available. Production planner conducts a daily meeting with the production supervisors to follow up on production targets and shipments. This process is shown in Figure 4, where the block horizontal arrows represent the material flow direction, the straight dash line with arrow represents the planning signal sent from production planner to the individual production stages, and the curved dash line depicts the self-planning of other production stages.

The current production control mechanism results in problems such as unnecessarily high intra-stage WIP levels. Moreover, it does not give Production Stage 3 and 4 any plan to guide their production. Such a system leaves the whole production of this stage subjective to human judgments, and results in unreasonable inventory structure and varying inter-stage customer service level. The process involves a great deal of human factor that leads to arguments and confusion during the actual production.

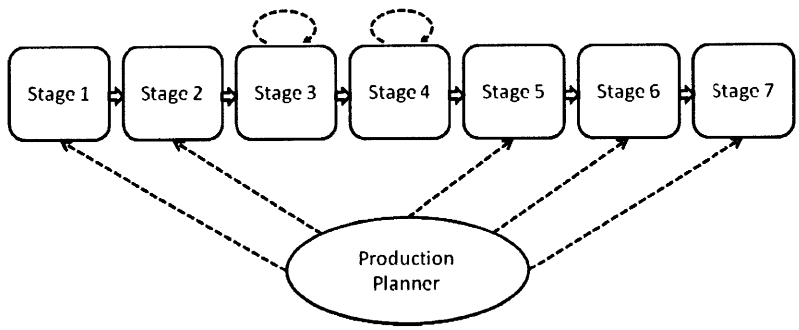

Figure 4 Current Production Planning

It is evident that current production control mechanism has issues that cannot support the management goal of establishing a Lean production environment. It was worthwhile to investigate what actually goes wrong and causes problems for the planner and supervisors, and eventually results in large inter-stage work-in-process.

2.1.3 Local Production Scheduling and Inventory Control

The machine lines installed in the factory are all shared resources. Each machine line is capable of processing multiple types of SP. The large SP variety with distinct process requirements adds to the complexity of the total manufacturing process flow. Although all machine lines can handle multiple types of SPs, they can be further classified into two groups: One group has machines that is the only machine within the production stage with huge capacity to process all types of SPs, the other group has machines that are equipped with smaller capacity and dedicate to certain types of SPs under a certain SP family.

In daily operation, the machine lines are usually subjected to simultaneous demand of multiple types of SPs needed by either downstream production stages or demand. The simultaneous demands create the puzzles as what to manufacture first and how many should be produced. Under the current manufacturing operation, both delays of production and overproduction are subject to line supervisor's performance.

In more detail, the line supervisors tend to follow the production plan finalized in the morning meeting and schedule their production relying on their experience. This results in different schedules of individual departments. If there is difficulty in executing the plan (e.g. shortage of raw materials or work-in-process from upstream), they tend to keep the lines running on any other available SP work-in-process (WIP) to maximize the machine utilization, even if the downstream lines do not require those SPs and this practice causes over production. Furthermore, uncertain WIP levels and unsynchronized schedules can cause either deviation of downstream stages from their plans and schedules or over production. As all the supervisors adopt this practice, it further causes abnormal day-to-day non-uniformity of the work-in-process levels and the production stage lead times for the released materials.

The careful investigation of all these leads us to the conclusion that this erratic system behavior is the result of desynchronized production planning and inventory control of involved production stages caused by supervisors' subjective judgment. Hence, a new production planning and inventory control system is needed to optimize the inventory levels along the line. This system will also help individual departments set correct production targets within their capacity constraints.

2.2 Project Motivation

The production system at PDAP factory is a complicated system. Although all the machines at each production stage can be considered as multi-part-type machine in some context, they are relatively different for several reasons. The difference stems from the SPs physical flow requirements along the machine lines, which actually merge and split at certain production stages according to the process requirements. In order to study the production system in a more efficient way, the internship team was divided into two groups, each with two students. The two groups focused on distinct production stages of the PDAP production system.

Among all 7 production stages, the project team focused area included the last 5 stages. Stage 5 and 6 are single-machine-line shared by all SPs that need to go through this process. Since it is a chemical coating process, different SPs can be processed together if they share the same coating. This allows Stage 5 supervisor to exploit the opportunity and schedule the production such that changeover time loss is minimum. As already described in the problem statement section, production planning and inventory control is based on supervisor's judgment and thus causes problems like over production and downstream line starvation.

Stage 4 and 7 are two similar processes and the flow between them can be characterized as direct flow, flow through Stage 5, flow through Stage 5 and 6 based on the SP process requirements. Since Stage 4 and 7 has close production rates, it provides an opportunity to couple their production.

2.3 Project Objectives

The main objective of the project is to develop an improved production planning and inventory control system for the PDAP factory. The specific objectives are:

1. Evaluate the whole production system and propose a suitable inventory control policy. The policy is to ensure smooth production and material flow through the whole production line and to improve customer service level.
2. Propose an approach to set up daily production targets at each production stage that is consistent with the chosen inventory control policy.
3. Design an appropriate visual management system at the factory for the solutions proposed above.
4. Implement 1, 2, and 3 to evaluate the performance of the system and make recommendations to the factory.

In this thesis, the four team members contributed together to the calculation of base stock for their responsible production stages, and developed a Kanban system under the designed guidelines. In addition to that, the author had an individual focus on short-term production leveling, his partner Zia Rizvi [1] worked on simulation and capacitated shipment planning. Youqun [2] and Zhongyuan [3] emphasized on demand seasonality analysis and long-term capacity planning.

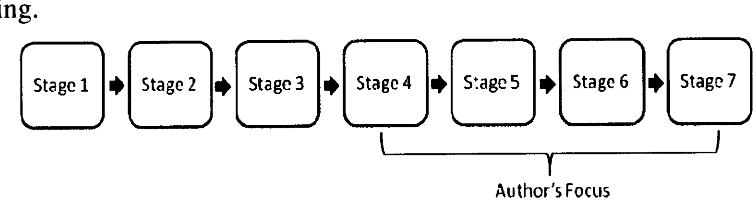

Figure 5 Author's Focused Area

Chapter 3 Literature Review

3.1Manufacturing Systems

3.1.1 Push Production System

A push production system builds up its inventory according to long-term forecasts [4]. This system is simple to set up and manage. It works well when the demand is steady and predictable, during ramp-up phase, or for predictable seasonal demand [5]. However, due to the innate forecast errors, such a system is prone to product shortages and overproduction 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.

3.1.2 Pull Production System

In essence, a pull production system only produces what the demand asks for, without relying on 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 three typical ways of realizing pull production in a factory: supermarket pull system; sequential pull system; mixed supermarket and sequential pull system [6].

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 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.

3.1.3 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.

3.1.4 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 [7]:

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

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

3.2 Inventory Control Policies

To initiate Lean manufacturing in this factory, one of the most important topics is the implementation of a right inventory control policy. There are lots of literatures talking about inventory control policies. MIT lecture material of course 15.763 discusses two inventory control policies for stochastic demand in general, one is Q-R policy and the other is Base Stock policy.

3.2.1 Q-R Policy

The main concept of Q-R policy is to set a reorder point and a reorder quantity. Once the inventory level hits the reorder point, a fixed reorder quantity will be released to the factory floor, and the inventory level is under continuous review. This policy is suitable for dedicated high volume production line. Basic equations and parameters for this policy are shown below.

1) Reorder Point R:

R = Expected lead-time demand + safety stock

$$R = \mu L + z\sigma\sqrt{L} \tag{3-1}$$

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

E[I]= cycle stock + safety stock

$$E[I] = \frac{E[I^-]+E[I^+]}{2} = \frac{Q}{2} + z\sigma\sqrt{L} \tag{3-2}$$

- Q: re-order quantity
- μ: demand rate
- r: review period in days
- z: safety factor
- б: standard deviation of demand
- L: lead time for replenishment

3.2.2 Base Stock Policy

The main concept of this policy is to set a base stock level and a review period. Inventory level will be reviewed every fixed review period. If it is lower than the predetermined base stock level, production order will be released to the factory floor to replenish the inventory level to the base stock level. This policy is suitable for shared resource line with multiple products. Basic equations and parameters are shown below.

Base stock B,

$$B = \mu(r+L) + z\sigma\sqrt{r+L} \tag{3-3}$$

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

E[I]= cycle stock + safety stock

$$E[I] = \frac{E[I(r+L^-)]+E[I(r+L^+)]}{2} = \frac{\mu r}{2} + z\sigma\sqrt{r+L} \tag{3-4}$$

r: fixed review period

The parameters used here are the same as in Q-R policy

3.2.3 Limitations of the Previous Inventory Control Policies

The Q-R policy is suitable for dedicated resources whereas the production system studied in this thesis has production resources with heavy sharing by multiple resources in downstream. This can cause simultaneous replenishment signals and eventually prioritization will affect the performance of the policy. Base stock policy may be a better choice for this case where replenishment of individual model inventories can be carried out in different review periods but there are also some limitations of the same.

Conventional base stock policy assumes that a production stage can be operated under a fixed and deterministic lead-time. This can be a good approximation for single product processed on such a resource. Since the production lead times are predetermined and fixed, there are no interactions between the production decisions and inventory levels of different products processed on the shared resource. It implies that the base stock planning is carried out in isolation for each product but setting up individual review periods would still be subjective as there is no systematic approach that considers the resource capacity constraints.

Moreover, fixing a lead-time of a production resource implies that it is completely flexible in context of its ability to change production rate but it doesn't explicitly take into account the trade-off between flexibility and base stock levels.

3.3 A New Base Stock Policy for Multi-Part-Type Line

Base stock model proposed by Prof. Stephen Graves in "Safety stock in manufacturing systems", 1988, dealt the limitations of conventional base stocky policy for shared resource. This model takes the capacity constraint of the production line into account, and works well in smoothing daily production of a multi-item machine using a linear production rule and determines each model's individual inventory level (B_i). Some of the key calculations and parameters of the model are listed as follows:

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

$$n = \frac{(k^2\sigma^2 + \chi^2)}{2\chi^2} \tag{3-5}$$

k = parameter that is associated with customer service level

б = standard deviation of weekly demand

χ = excess capacity

b) Daily leveled production

$$P_t = \frac{W_t}{n} = \frac{D_t}{n} + \frac{(n-1)P_{t-1}}{n} \quad (3\text{-}6)$$

t: time period index

P: daily production quantity

D: daily demand quantity

W: WIP at the production stage

c) Individual model (s) 'i' raw material released exactly equal to demand on day 't'

$$R_{i,t} = D_{i,t} \quad (3\text{-}7)$$

R: material release quantity

d) Base stock for individual model(s)

$$B_i = E[W_{i,t}] + E[I_{i,t}] = n\mu_i + k[n\sigma_i\sqrt{2n-1}] \quad (3\text{-}8)$$

μ_i : average demand for item i

3.4 Visual Management

Visual management uses visually stimulating signals, objects and easy-to-understand symbols to creat and information-rich environment. In simple terms, visual management uses signs, lights, notice board, bright or contrasting painted equipment to display information and catch people's attention, so as to enhance the communication of important information or messages in the working environment [8].

In Lean manufacturing, the goal of visual management is simply generating meaningful signals, and facilitate people in factory to access information about what their tasks quickly and accurately, especially for those who do not hold any knowledge of the logic behind the High Tech solutions are not necessary to bring about visual management, the rule is "the simpler the better", simple tools such as photos, painted symbols, bold print and informative colors are usually more robust.

As Lean manufacturing system is to be easily understood and continuously monitored, an appropriate associated visual management system is really critical to the successes of all Lean operations. Nowadays the most developed and widely used visual management tool in factories is called the Kanban system, which has all the features noticed above.

Chapter 4 Methodology

4.1Project Flow

As shown in Figure 6, a project roadmap shows the sequence of major project stages and specific activities involved. Rectangles represent project stages and ovals represent detailed activities of the corresponding project stages. The arrows represent the sequence.

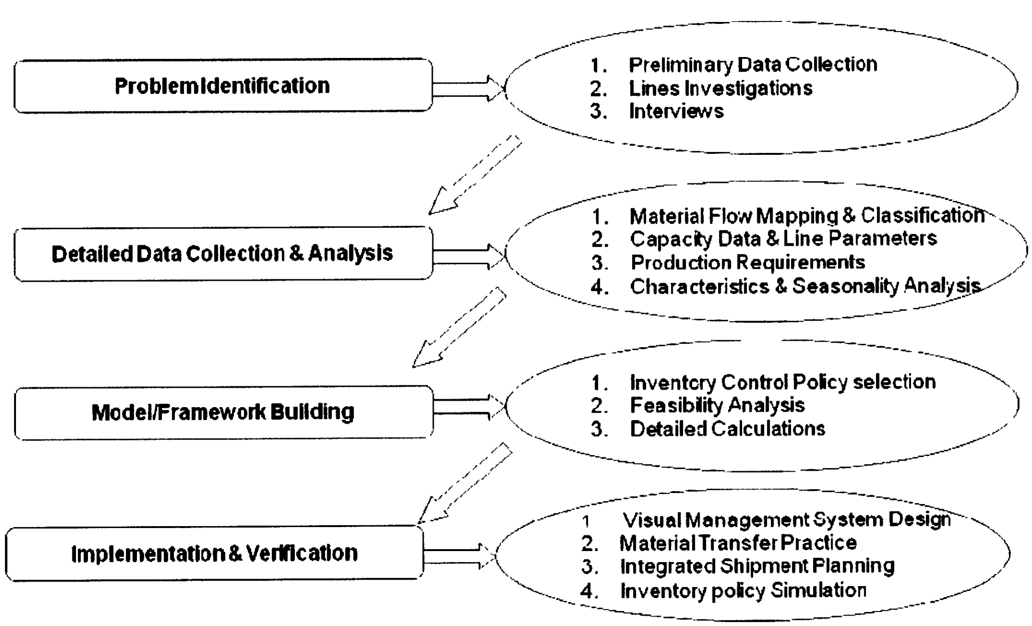

Figure 6 Project Roadmap

4.2 Problem Identification

The project started with the problem identification stage. The author was initially given briefing on what the management was aiming to achieve in the future; then the project team focused in depth on the production floor issues that were the biggest potential obstacles. Interviews were conducted with the production planner and supervisors to understand the production process of the SP assemblies at PDAP, and to identify the issues that these people were facing. The inventory profiles from history were shown; real data was collected for later comparison. The major issues had already been discussed in Chapter 2.

4.3 Data Collection and Analysis

As part of the preliminary research, the data relevant to the project was collected and sorted into two categories: structural data and quantitative data. Structural data included the material flow mapping, product categories, factory layout, and the value stream map of the factory. Quantitative data included line performance data, historical demand data, demand forecast data and inventory data.

4.3.1 Source of Data

In order to understand the general demand characteristics throughout the year, daily shipment data for 2008 were obtained from the production planner for analysis. The daily shipment data detailed the shipment volumes of all SKUs to the customer. Hence, these data were treated as the best source of the historical demand.

The demand forecast and stock building plan files for 2009 were also obtained from the production planner. The forecast provided the predicted monthly demand from customers, and the stock building plan was used to shift some demand to be fulfilled earlier with consideration of capacity constraints. The stock building plan file was used as the input for the inventory control policy calculation, which was the most accurate data currently used to plan production.

4.3.2 Planned Production Seasonality Analysis

Demand driven production is one important feature of Lean Production to eliminate waste and increase profit. In PDAP factory, the planned production targets specified in the stock building planned is used as the actual demand from the manufacturing perspective of view. Hence, to properly select the inventory control policy and calculate the respective inventory levels, the seasonality analysis to the stock building planned was needed.

As mentioned in Section 1.2, there are two product categories in this factory: Class A and Class B products. Class A is about 30% of the total demand, and Class B is about 70% of the total demand. Because Class B products were mostly sold in America and Europe, holidays in these regions such as Christmas had heavy impacts on the demand of Class B product. This formed the seasonality demand pattern for Class B product. However, for Class A product, since they were sold mostly to where the holiday effect was not so influential, the demand for Class A products is more consistent throughout the year. In the end, for simplicity, the seasonality analysis considers Class A and Class B demand together.

The task here is to determine the seasonality of total demand volume throughout a year, verify and improve the current pattern that the factory is now following in production. To achieve this goal, the planned production values are retrieved from the 2009 stock building plan, monthly production targets are obtained. Then, several potential groupings of seasons are proposed and analyzed by ANOVA, the distinct seasons are therefore chosen based on the F-value and P-value from ANOVA for the grouping that provides the highest F-value and lowest P-value. See Figure 7.

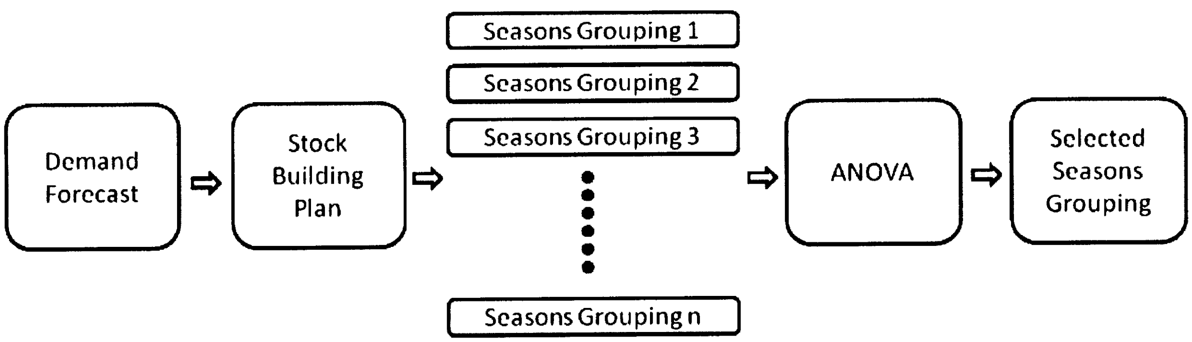

Figure 7 Procedures of Seasonality Analysis

4.3.3 Selection of High Runners & Obtain Daily Demand Pattern

The total demand is formed by gathering individual demand from over 50 SKUs produced in this factory. However, not every SKU receives constant level of orders. The majority of the total demand comes from a group of popular SKUs, which are called the high runners. To optimize the inventory structure, the new base stock policy will only be applied to the high runners. Constant inventory will be kept only for them at each of the production stages involved to facilitate the pull manufacturing. The production for the non-popular SKUs will follow the push-based planning, and this aspect is not the focus in the thesis.

The selection of high runners was primarily based on the historical demand records. Both the shipment frequency and quantity were considered. The production planner also made suggestions for selecting several new SKUs as high runners, which were recently released to the market, and no long-term shipment record was available.

Because of the need to obtain the daily demand and standard deviation from the 2009 stock building plan, some data processing is required. In the stock building plan, the demand volume is specified only on a weekly basis. Moreover, instead of individual SKU, only the aggregated demand for each product family or a group of similar SKUs was available. So first of all, the aggregated daily demand and its standard deviation can be obtained as follow:

$$\mu_d = \frac{\mu_w}{7}, \quad \sigma_d = \frac{\sigma_w}{\sqrt{7}} \tag{4-1}$$

Further data processing was needed to dig out the demand pattern for each individual SKU considered as high runner. A reasonable assumption is made here, that the demand for all SKUs within the same product family will share identical coefficient of variance (C.V.). Also, it is assumed that their contribution to the total demand volume is assumed to be the same as the 2008 demand records with approval from the production planner. Once the weekly demand is obtained for individual SKU, the daily demand pattern is calculated by the following formula:

1) Let n be the number of SKUs within a certain family, i is the index of different SKU under the same product family.

$$\mu_d = \sum_{1}^{n} \mu_{i,d} \tag{4-2}$$

2) Assume all SKUs share the same individual C.V., then the C.V. can be calculated as follows:

$$\sigma_d^2 = (CV \times \mu_{1,d})^2 + (CV \times \mu_{2,d})^2 + \ldots + (CV \times \mu_{3,d})^2 \tag{4-3}$$

$$CV = \frac{\sigma_d^2}{\sum_{1}^{n} \mu_{i,d}^2} \tag{4-4}$$

3) With C.V. obtained for individual SKU and the mean, the demand standard deviation of individual SKU can be determined as:

$$\sigma_{i,d} = \mu_{i,d} \times CV \tag{4-5}$$

Figure 8 shows the procedures:

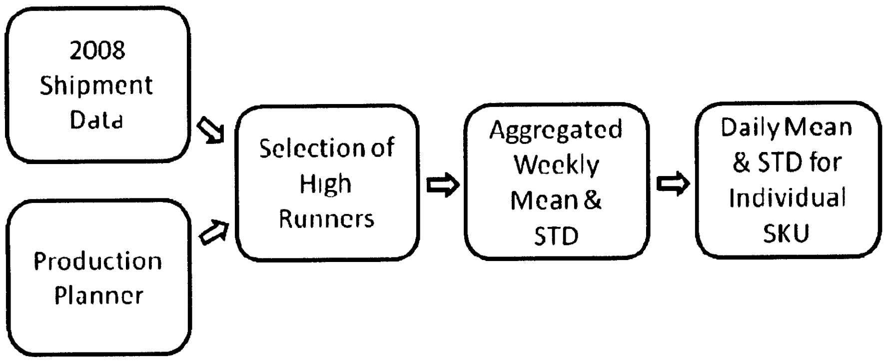

Figure 8 High Runner Selection & Daily Demand Pattern for Individual SKU

4.3.4 Line Data & Performance Measures

Various important process parameters for each production stage were obtained from the factory. Among them, the most important one was the effective capacity from each machine line. With the capacity file given by the production planner, weekly effective capacity were shown, thus the daily capacity were obtained with simply calculation.

In addition, process lead times and cycle time were collected for several SKUs. Other critical production line performance measures, such as the inventory levels at each production stage (WIP and FGS) were obtained. The inventory levels at each production stage were tracked using data maintained in SAP system. Data were extracted from the system and compiled for specific production stages. Inventory holding costs and unit costs of components at all the stages were provided by the factory.

4.4 Production Leveling

As stated in Section 1.4.1, the daily production plan was finalized by the production planner based on the locked demand of next week plus the following two days' orientation. The weekly satellite factory requirement (SKD) was also considered. With the consolidated demand file on hand, the production planner then leveled the production from his own experience so that he could match demand with available capacity while ensuring on time delivery of shipments. As the production plan will be issued to 4 production stages. The quoted lead times of upstream stage, and individual stage inventory levels are also considered and therefore add complexity into the planning.

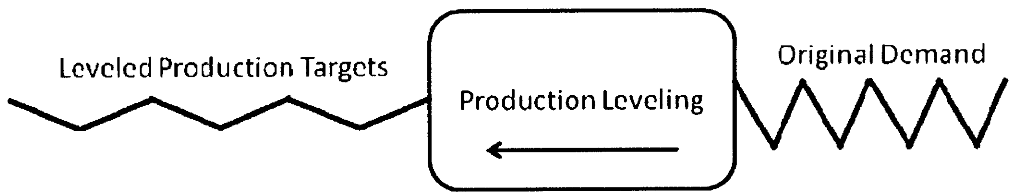

Figure 9 Objectives of Production Leveling

With the goal of improving the production planning process within this factory, the above stated operations can be simplified into setting the production targets only at the end production stage for each SKU. With the requirement of fulfilling demand from the customer side and the goal of smoothing daily production, an optimization tool for production leveling is developed. In the following context, three different methods are proposed and compared, the first two methods are generic, and the last one is an improved one based on the first two methods.

4.4.1 Heuristic Method

The Heuristic Method is a manual method developed to leveling the daily production targets. The leveling period is chosen to be 7 days to reflect the real scenario, the operation procedures are shown in sequence below

1) Leveling input & output:

$$\text{Input Demand: } D_i \quad i=1, 2, 3, ..., 7$$

$$\text{Production Target: } P_i \quad i=1, 2, 3, ..., 7$$

2) Production constraints:

(i) The accumulated production must always be equal to or higher than the demand

$$\sum P_i \geq \sum D_i \quad i= 1, 2, 3, ..., 6 \tag{4-6}$$

(ii) The total production quantity at the end of the leveling period must be equal to the total demand to avoid overproduction.

$$\sum P_i = \sum D_i \quad i=7 \tag{4-7}$$

3) Objective:

The leveling effect will be evaluated by the coefficient of variance of P_i i=1, 2, 3, ..., 7

Minimize: C.V.(P_i) i=1, 2, 3, ..., 7

4) Calculation:

(i) To determine P_i, a decision variable S_{ij} (i,j=0, 1, 2, ..., 7 i<j) is introduced. S_{ij} is a calculated value. It is obtained by the formula shown below:

$$S_{ij} = \frac{\sum_i^j D_i}{j-i} \tag{4-8}$$

With S_{ij}, the daily production target P_i can be determined in sequence, starting from P_i

(ii) To get P_1, S_{0j} (j=0, 1, 2, ..., 7) is calculated to look for its maximum value and the respective j. Once j_{max} is obtained, let n_1=j-0=j. Then P_1 is calculated by the following formula. If n_1>1, then $P_1 = P_2 ... = P_{n_1}$, and the calculation can jump to day n_1+1.

$$P_1 = ... = P_{n_1} = \frac{\sum_0^j D_i - \sum_0^0 D_i}{j-0} = \frac{\sum_0^{n_1} D_{n_1}}{n_1} \tag{4-9}$$

(iii) Starting from day n_1, again we need to calculate and compare the S_{ij} for another round, the maximum $S_{n_1 j}$ shall be obtained.

$$S_{n_1 j} = \frac{\sum_{n_1}^j D_i}{j-n_1} \tag{4-10}$$

$$j = n_1 + 1, ..., 8$$

With maximum $S_{n_1 j}$, denote the current j by n_2, then a new set of production target will be obtained:

$$P_{n_1+1} = ... = P_{n_2} = \frac{\sum_0^{n_2} D_i - \sum_0^{n_1} D_i}{n_2 - n_1} = \frac{\sum_{n_1}^{n_2} D_i}{n_2 - n_1} \tag{4-11}$$

(iv) Repeat the calculation until P_7 is obtained

4.4.2 Excel Solver Method

Excel Solver is a build-in optimization tool in Microsoft Excel. With the same objective and constraints specified in the Heuristic Method, the leveling process and requires less effort to operate in the Excel Solver. By properly setting the objective function, design variable and constraints, the optimized result can be obtained quickly. To explain the details, the leveling procedure is decomposed into the following 6 steps, also shown in Figure 10:

1) Input the daily original demand data
2) Calculate the accumulative demand for each day
3) Set the initial values of production quantity for each day and appoint them as variable cell. The initial value can be the same as the original daily demand.
4) Set production constraints
5) Run Excel Solver
6) Obtained the result and verify it by plotting the demand and the leveled production for each day within the leveling period.

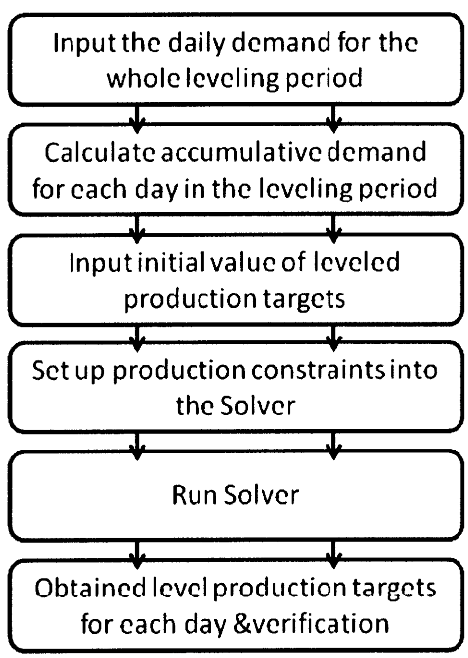

Figure 10 Leveling Procedure in Excel Solver

4.4.3 Improved Excel Solver Method

On each Thursday, the production planner receives locked (confirmed) demand for the next Monday to Sunday. By considering the two days' shipment lead time, the previous leveled production targets are able to be modified, so as to prepare for the possible demand surge at the beginning of the next week. In addition, the two days' demand orientation followed by the locked demand is included into the leveling period. The leveling process will still be done by Excel Solver, and it is called the Improved Excel Solver Method

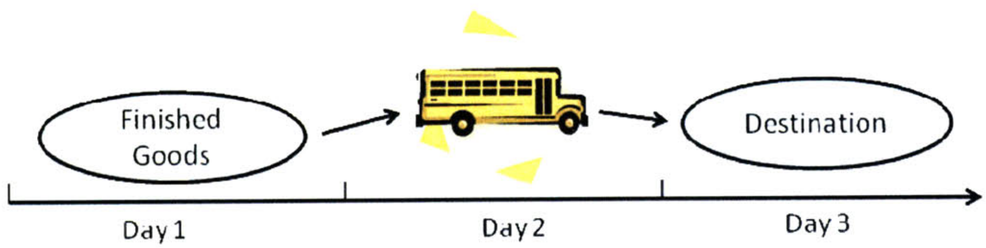

Figure 11 Shipment Lead Time

The main operation procedures for the optimized Excel Solver Method will still remain the same as the previously introduced Excel Solver Method. However, since the leveling periods are now overlapped by 3 days, and the shipment lead time takes only two days, one modification must be made to the demand input, so that overproduction can be avoided. The new leveling periods is demonstrated in Figure 12.

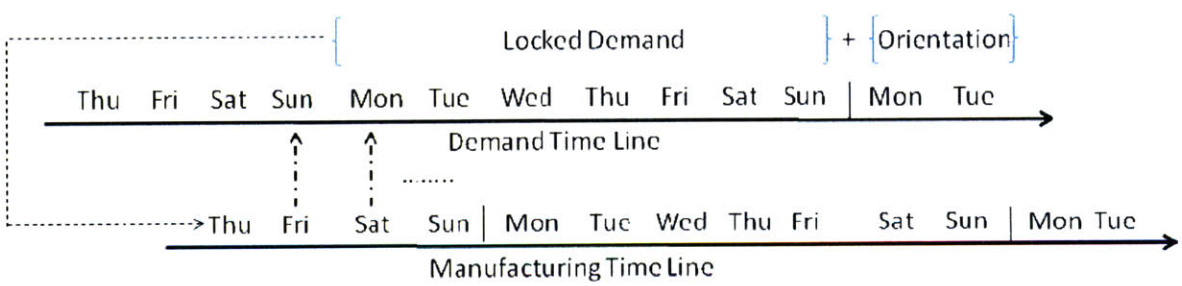

Figure 12 Optimized Excel Solver Method

As now the leveling periods are overlapped by three days, the remaining 7 days production targets in the previous leveled period will not change. But in most cases, the first 7 days total production volume is higher than the demand volume. If the excess is not subtracted from the demand in the new leveling periods, which is overlapped with the previous one, over production will happen. The subtraction will first be done from the first day of the new leveling periods, until all the overproduced quantities are consumed by the demand in the new leveling period. Details will be shown in the result section.

4.5 New Base Stock Policy

4.5.1 Model Building

The new base stock policy was developed in 1987 at MIT by Professor Stephen C. Graves. This policy specifies new production control rules and calculation of inventory levels for each product manufactured on the same machine line. This policy is able to model multiple machine lines and can be extended to a multi-stage manufacturing system. However, for demonstration purpose, one production stage that processes multiple SKUs is chosen here to explain how the new policy works. Below is a list of important parameters used for the calculation:

- D: Demand
- R: Release of raw material
- P: Manufacturing quantity
- B: Base stock level
- C: Line capacity
- W: Intra-stage inventory
- I: Inter-stage inventory
- t: Time period index
- i: Individual SKU index
- n: Planned lead-time
- χ: Excess capacity that is normally available at the production stage
- μ: average demand
- б: standard deviation of demand
- k: Safety Factor

I_t and W_t are aggregate inter-stage and aggregate intra-stage inventories at time period t, they can also be interpreted as finished goods inventory and raw material inventory at a certain production stage. P_t and R_t are manufacturing target and quantity of raw material release at time t. 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 model. For example: $I_t=\Sigma I_{it}$, where I_{it} is the inter-stage inventory for product I at the start of time period t

The balance equations for aggregated entities are:

$$W_t = W_{t-1} + R_t - P_{t-1} \tag{4-12}$$

$$I_t = I_{t-1} + P_{t-1} - D_t \tag{4-13}$$

The release rule is: $$R_t = D_t \quad (4\text{-}14)$$

These equations can be easily extended to individual entities, namely:

$$W_{i,t} = W_{i,t-1} + R_{i,t} - P_{i,t-1} \quad (4\text{-}15)$$

$$I_{i,t} = I_{i,t-1} + P_{i,t-1} - D_{i,t} \quad (4\text{-}16)$$

The release rule becomes: $$R_{i,t} = D_{i,t} \quad (4\text{-}17)$$

The other two important parameters are χ and n, both of them obtained by calculation:

χ= Line Capacity - Aggregated Average Demand

$$n = \frac{(k^2\sigma^2 + \chi^2)}{2\chi^2} \quad (4\text{-}18)$$

With the mathematics behind the theory, χ should be less than or equal to k*б, otherwise n is equal to1.

With χ and n determined at each production line, the control rules for individual model i are given by:

$$R_{i,t} = D_{i,t} \quad (4\text{-}19)$$

$$P_{i,t} = \frac{W_{i,t}}{n} \quad (4\text{-}20)$$

And the expected inventory values for individual SKU i are given by:

$$B_i = E[W_{i,t}] + E[I_{i,t}] = n\mu_i + k[n\sigma_i\sqrt{2n-1}] \quad (4\text{-}21)$$

Hence, for the later calculation, the $E[W_{it}]$ and $E[I_{it}]$ will be obtained for every selected SKUs at each production stage with consideration of reasonable grouping. And the floor production will execute according to:

$$P_{i,t} = \frac{W_{i,t}}{n} \quad (4\text{-}22)$$

With Equation 4-22, the daily manufacturing quantity is determined, which usually differs from the daily production target. Moreover, since the n and W_{it} at each production stages are usually different, for the same SKU, the daily manufacturing quantity will be different.

4.5.2 Preliminary Calculation & Modified Results

Based on the demand information for high runners and the calculation specified in Section 4.5.1, the base stock level for each high runner at every involved production stage can be determined accordingly. However, this result only contains the theoretical value and ignores all implementation constraints. Modifications are made to comply with these constraints, the details are discusses later.

4.5.3 Kanban Implementation & Other Implementation Issues

The most important part of the project work verification lies in the implementation and modification stage. From the management requirement, a Kanban system will be set up throughout the factory to operate under the new base stock policy, many implementation issues are raised by the constraints not considered is the new base stock policy but in the factory.

Kanban card design

To set up a Kanban system in PDAP factory, the design of the Kanban card is important. Since this factory has previous experience on designing and using Kanban cards for some special operation, the author choose to adopt their current design and made necessary modifications. The contents on the card are listed below:

1) Card ID number
2) Name of the model
3) Part transit number (12NC)
4) Represented quantity
5) Production Stage

Kanban quantity

Being part of the information shown on the card, the represented quantity of each Kanban card (Kanban Quantity) is critical to the designed pull system and must be carefully determined. To choose the right Kanban Quantity, investigations have been done on the containers used for material transfer among different production stages. Suggestions are made to modify the size of various containers, so as to synchronize the sizes. As a universal quantity represented by a card would greatly simplify the operation of the system, the size of containers is modified to either an factor or multiples of standard pallet size for shipment. The shipment size is 600 or 480 according to different SKUs, thus 600 and 480 will be the quantity represented by each Kanban card in all production stages involved (Stage 4, 5, 6 and 7).

Determine number of cards required

With the quantity represented by each card determined and the calculated base stock level, the total quantity of cards can be determined. The results were stated in Section 5.6.2.

Kanban operation procedure

The new base stock policy specified strict control rules and operation procedures in withdrawing raw material, setting daily manufacturing quantity, and finished goods shipment. In the Kanban system designed to operate according to the new base stock policy, all material transfer will be guided purely by the movement of cards. The number of cards shown on the Kanban board will be used to monitor the real time inventory levels and the manufacturing activities. The details are stated in Section 0.

Modifications to Production Leveling

After leveling by Excel Solver, the output values will not be multiples of 480 or 600. Thus to assign daily production targets correctly by moving the Kanban cards, the numbers need to be modified. An extra step is needed after leveling to round up the daily production targets to multiples of 480 or 600. The details are shown below:

1) Modify every day production targets to multiples of 480 or 600
2) Add constraint so that the accumulative value after modification is more than or equal to the accumulative production targets provided by Excel Solver

It is found out that after this modification, the accumulative production targets will be slightly more than the demand quantity. However, after consulting the production planner, this concern is not necessary, as the customer will be able to adjust their order slightly in the next week if they receive more finished goods in the current week.

4.6 Line Coupling

SKUs belong to the CP and SR families pass through production stage 4 and 7 as a direct flow. From the original base stock calculation, W and I inventory will be set up separately for each SKU at both stage 4 and 7, so are the CP and SR SPs. However, with an interesting finding that the capacity of machine lines at these two stages are very close or even equal to each other, they can be virtually linked together by a specially designed coupling stock. By doing so, the I inventory for stage 4 and the W inventory in Stage 7 can be saved for CP and SR SPs, instead a line coupling stock will be placed in between to connect the production between two machine lines. This treatment is expected to further reduce the inventory.

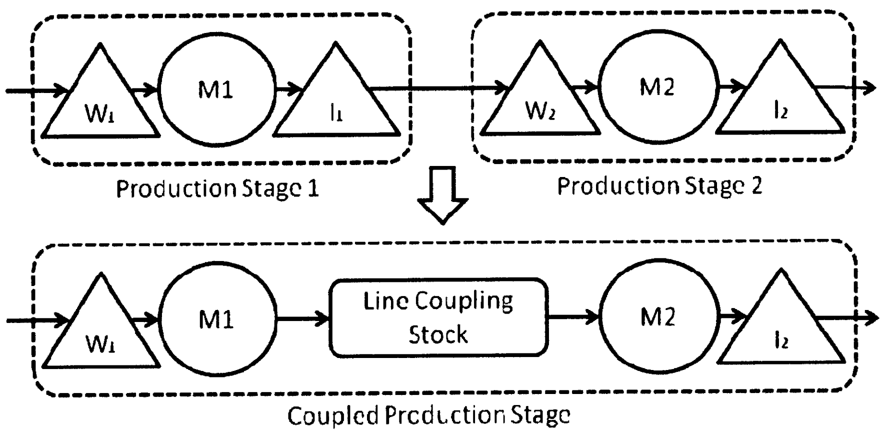

Figure 13 Objective of Line Coupling

See Figure 13. As specified by the line coupling method, both of the machine lines should start processing the same SPs at the same time. Since the M2 line is generally slightly faster than the M1 line and their process lead-time are different, the coupling stock is used to cover the potential shortage of SP supply from M1 to M2. Several parameters directly used in the coupling stock calculation are listed below:

<u>Parameters needed for each SKU to set up base stock:</u>

UT_i: Unit time of machine line i

CT_i: Process lead-time of machine line i

T: Container size

K: Service level factor

P_{max}: Maximum manufacturing batch size

CS: Coupling stock

σ : Pooled standard deviation of all products sharing the same machine line

μ : Aggregated demand mean of all products sharing the same machine line

Calculation:

The process cycle time is calculated from the effective capacity stated in Table 17.

$$UT = \frac{24 \times 60 \times 60}{Daily\ Effective\ Capacity} \tag{4-23}$$

The process lead-time is obtained by collecting real data from the machine line.

Base on the new base stock policy, the daily manufacturing quantity P_t would have the following characteristics:

$$\mathrm{E}[P_t] = \mu \tag{4-24}$$

$$Var[P_t] = \frac{\sigma^2}{2n-1} \tag{4-25}$$

Thus, the daily maximum batch size P_{max} can be determined as:

$$P_{\max} = \mu + k \times \frac{\sigma}{\sqrt{2n-1}} \tag{4-26}$$

Here the k in Equation 4-26 is a manually chosen service factor, for example, k=1.65 is related to a 95% service level.

With P_{max} determined for each SKU, the coupling stock CS can be determined, so as to cover the potential raw material shortage for M2 line. The calculation formula is shown below:

$$CS = \frac{[CT_1 + (T-1) \times UT_1] \times UT_2 + [P_{\max} \times UT_2 - CT_1 - (T-1) \times UT_1] \times (UT_1 - UT_2)}{(UT)^2} \tag{4-27}$$

4.7 Results Verification

4.7.1 Simulation & Factory Implementation Trial

Two approaches are used to test the validity and significance of the above proposed methodologies. One is simulation, followed by actual implementation in the factory. For production leveling, simulation is used to obtain the significance of the leveling effect. The input data is from random number generator for standardization purpose.

Simulation of two selected SKUs is also conducted to evaluate the designed inventory structure and production control rules under the new base stock policy. For the generality purpose, Production Stage 3 is also added to the simulation. See the work of Yuan Zhong [3] and Dong Youqun [2]. Figure 14 shows the process flow. The objective of simulation is to obtain the overall manufacturing performance of the designed manufacturing system. The system service level and WIP inventory at different production stages are monitored. As the simulation is of discrete type and the logic behind is able to be built in Excel, a spread-sheet simulation tool named Cristal Ball is used to conduct the simulation. Reasonable assumptions are made when stock out happens. For the Cristal Ball simulation details, please refer to the work of Zia Rizvi [1].

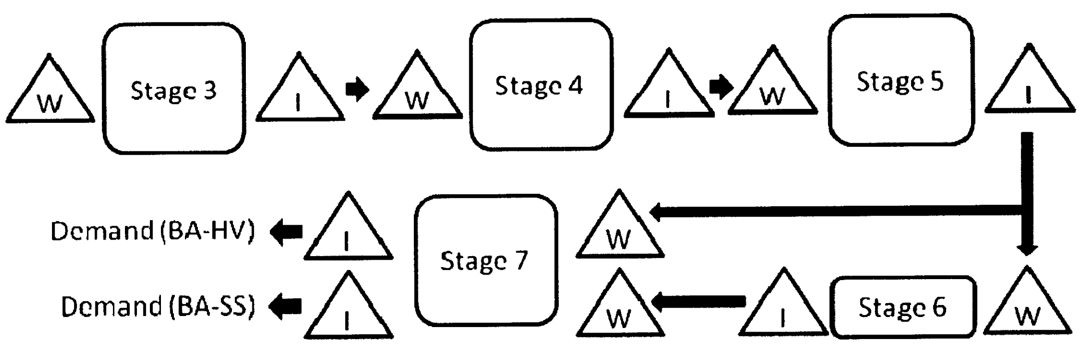

Figure 14 Process Flow for SKUs: BA-HV and BA-SS

In addition to simulation, actual implementation in the factory started in July with permission of the factory. The same selected SKUs from Class-B are chosen for the trial.

4.7.2 Financial Impact Analysis

To goal of the M.Eng project in PDAP factory is to optimize the inventory and daily production while maintaining satisfactory service level, but the actual stimulus behind them is to save cost. To calculate the reduction in inventory and savings on inventory cost, the base stock calculations are compared to the current inventory kept in the factory. The unit price for SPs at each production stage is also obtained from the factory to compute the positive effects from the improved inventory structure.

4.8 Summary

Chapter 4 enclosed several methodologies that will work together to control production and optimize inventory in the focused manufacturing system, and finally, to verify the significance and financial impact. The methods started with demand analysis, which provided the segmentation of demand seasons and the daily demand pattern. Then, the new base stock policy specified production and inventory control rules and used the demand information obtained from the demand analysis to calculate the base stock levels for each high runner SKU that should be kept within this manufacturing system. In addition to that, two other methodologies: Production Leveling and Line Coupling are proposed to further reduce the inventory and increase customer service level. A Kanban system is set up to facilitate the operation, and a financial impact analysis is conducted to examine the overall improvement of the designed system.

Chapter 5 Results and Discussion

5.1 Overview

This chapter first presents how the preliminary analysis is done on the raw data processing for later calculation. Then, the calculation results are obtained based on three major methodologies: Production Leveling, New Base Stock Policy and Line Coupling. A Kanban visualization system is developed following the control rules specified in the new base stock policy. Implementation issues are also discussed. Computer simulation is used to help verify the validity and significance of the proposed methodologies. Finally, the calculated base stock levels and simulation results are compared with the current factory data, a financial impact analysis is carried out to estimate the savings in inventory cost.

5.2 Preliminary Analysis

This section introduces how the Stock Building Plan in 2009 is processed for future calculation. First, a seasonality analysis is done by ANOVA with the best seasons grouping chosen. Then, 19 SKUs are selected as high runners based on historical data. Daily demand pattern is extracted for each of the high runner SKU from the 2009 Stock Building Plan. All the results obtained in this section will be used for production leveling and the base stock calculation.

5.2.1 Seasonality Analysis

See Figure 15, the demand for PDAP factory shows a strong seasonality throughout the year. In order to set up proper and need based base stock inventory, a whole year should be divided into different periods. ANOVA is used for hypothesis test of 4 proposed groupings, test results are compared with the best grouping chosen.

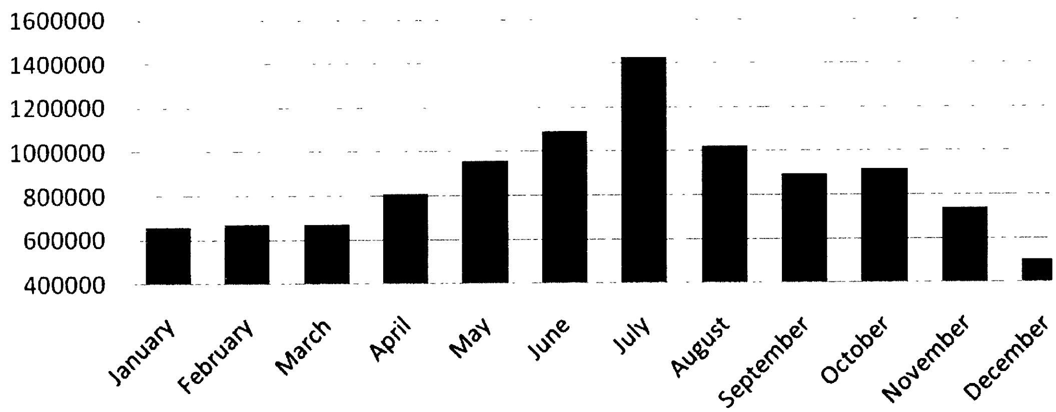

Figure 15 2009 PDAP Stock Building Plan

Hypothesis Test:

Premises:

1) One year can be divided into either two or three seasons.

2) Seasons must be groups of complete months.

Input Data:

The data source used in the ANOVA test is 2009 Stock Building Plan. It is the most appropriate data that can be used to determine distinct seasons.

Proposed Groupings:

As can be observed from Figure 15, the monthly total demand for PDAP products is high from June to October. The demand for the rest of the year is generally lower. Based on the preliminary observation, 4 seasons groupings are proposed to be tested under ANOVA. Table 1 shows the groupings.

Table 1 Proposed Groupings

Combination	Season 1	Season 2	Season 3
1	Jan-Apr	May-Oct	Nov-Dec
2	Jan-May	Jun-Oct	Nov-Dec
3	Nov-Apr	May-Oct	-
4	Nov-May	Jun-Oct	-

Run ANOVA:

The ANOVA tool is Excel is used to analyze the proposed groupings with 95% confidence. The result is shown in Table 2.

Table 2 ANOVA Result

Grouping	Season 1	Season 2	Season 3	F-Critical Value	F-Value	P-Value
1	Jan-Apr	May-Oct	Nov-Dec	4.256494729	8.2956484	0.009071435
2	Jan-May	Jun-Oct	Nov-Dec		6.329040435	0.019222126
3	Nov-Apr	May-Oct	-		17.40059168	0.001913695
4	Nov-May	Jun-Oct	-		12.05851274	0.005995595

As can be seen in Figure 16 and 17, the third grouping provides the highest F value and the lowest P value. Therefore, two seasons will be set up for planned production in 2009. The high season starts from May and ends in October, and all of the rest months will be considered as the low season.

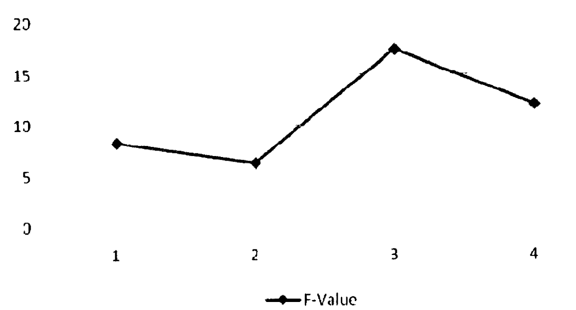

Figure 16 F-Values from Grouping 1, 2, 3 and 4

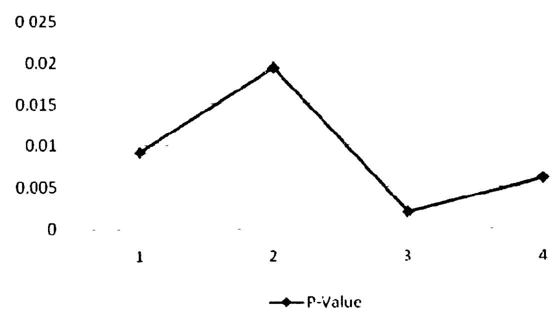

Figure 17 P-Values from Grouping 1, 2, 3 and 4

5.2.2 Average Daily Demand & Standard Deviation for High Runners

With the seasons for the planned production in 2009 determined, the demand information for different seasons can be extracted and processed based on the 2009 Stock Building Plan. First, high runners are selected from all SKUs; then, the average daily demand and standard deviation are determined for each of the high runners. As the calculation results will be implemented from July 2009, for better accuracy, the calculation of base stock level will exclude the past planned production value in May and June, which are already past. The input data is from July to October.

The selection of high runner SKUs is a process based on both historical data and the input from the production planner. Finally, 19 SKUs are selected as high runners because they contribute over 97.5% of the total demand volume. In future, the proposed methodologies will only be applied on these 19 SKUs. The selected SKUs and their relative contributions to the total demand are listed in Table 3:

Table 3 High Runners and Contribution in Demand

Family	SKU	% in 2008 total output
DY	DY-MRGL	5.75%
DY	DY-MRGC	3.30%
DY	DY-DL	6.10%
DY	DY-DC	3.66%
DY	DY-ND	4.19%
LE	LE-ESL	2.67%
LE	LE-ESC	2.11%
LE	LE-ESGC	3.42%
CP	CP-ST	2.69%
CP	CP-PT	10.66%
BA	BA-HV	10.16%
BA	BA-SS	20.73%
SR	SR-44I	0.65%
SR	SR-44NI	6.36%
SR	SR-46I	3.24%
SR	SR-46NI	7.38%
SY	SY-BNS	2.20%
SY	SY-BS	1.20%
SY	SY-SS	1.14%
	Total	97.61%

The Stock Building Plan only specifies the total production target on a weekly basis. The quantities are not detailed to each SKU but are aggregated values for each product family. To obtain the average daily demand and standard deviation, the data from Stock Building Plan must be assigned to individual SKU on a daily basis.

Premises:

1) Assume the demand for all product models within the same family share the same coefficient of variance (C.V.)

2) Assume the contribution for individual model to the total production output remains the same as 2008 demand record.

Result:

Follow the procedures specified in Section 4.3.3, the result is consolidated into the Table 4.

Table 4 Mean & Standard Deviation

Family	Model	Mean	Standard Deviation
DY	DY-MRGL	2246	1289
DY	DY-MRGC	1290	740
DY	DY-DL	3206	2719
DY	DY-DC	1527	736
DY	DY-ND	1745	841
LE	LE-ESL	1463	2693
LE	LE-ESC	1039	1912
LE	LE-ESGC	429	790
CP	CP-ST	953	606
CP	CP-PT	3779	2402
BA	BA-HV	2241	1968
BA	BA-SS	4572	2226
SR	SR-44I	1358	1358
SR	SR-44NI	139	139
SR	SR-46I	691	691
SR	SR-46NI	1574	1574
SY	SY-BNS	836	296
SY	SY-BS	450	159
SY	SY-SS	429	152

From Table 4, it can be noticed that the average daily demand among different SKUs differs significantly; however, the reason for still keeping these low demand SKUs is that they are important products; failing to fulfill their orders would generate cost that the factory is not willing to accept. Hence, the factory wants to fulfill its order on a daily basis even if the production batch size will become smaller. It is also found that the demand standard deviation is high for most of the SKUs, which provides the stimulus for production leveling and the new production control policy introduced by the new base stock policy. They will be discussed later.

5.2.3 Discussion

The seasonality analysis is based on each year's stock building plan, which serves as a compromise of the demand forecast and capacity constraints in high season. The method provided in this section can be used as a model to differentiate distinct seasons at the beginning of each year with appropriate mathematical basis, so that the inventory setup can be planned accordingly and avoid waste. The selection of high runners needs to be updated each year with previously popular products fade out and new products introduced. Although the majority of the calculation is using forecasted values, they are the most accurate and trustworthy data source available. The calculations can be adjusted continuously when the updated forecast arrives with higher accuracy.

5.3 Production Leveling

As explained in Section 4.4, on each Thursday, the factory will receive confirmed order for the coming week with demand orientation followed. This order is considered as locked shipment requirement from Monday to Sunday in high season. By knowing the shipment quantity ahead of time, the production planner has opportunity to level the daily production targets. To realize the concept, two preliminary approaches are first investigated. As there is no analytical formula to calculate the reduction in the variance of the production targets, spreadsheet simulation is used to test the leveling effect. Based on the simulation results and some extra findings, an improved leveling approach is proposed.

5.3.1 Heuristic Method

Premises:

1) The yield for production is counted at the production planning process, so it is not considered in the daily production leveling.

2) The raw data used in the test cases are generated in Excel using random number generator with specified mean and standard deviation stated in Table 4. To show the real situation, all negative values are rounded up to zero, which means no demand for that day.

3) This simulation only covers the high season from July to October. The factory is running on a 7 day per week basis and there are 120 days in total. The treatment in low season will be the same, which will not be discussed.

4) Due to container size restriction and operation requirement, demand for each model will be rounded up to multiples of 480 or 600 in real situation. However, for the purpose of simulation, the data used here neglect this treatment because the round up effect is trivial.

5) The real manufacturing quantity for a certain machine line will be slightly different than the assigned production quantity after the leveling. This is due to the math behind the new based stock policy stated in Section 4.5.1.

6) Because of shipment lead-time constraint, the manufacturing plan will be two days prior to the demand date.

Parameters:

i,j : time index

D_i : Confirmed demand on day i

P_i : Planned manufacturing quantity for day i after leveling

S_{ij} : Decision variable used in the calculation

n : Temporary parameter used to help the calculation

Simulation:

SKU: DY-MRGL

Step 1:

Obtain the confirmed demand and calculate the accumulative demand, see Figure 18.

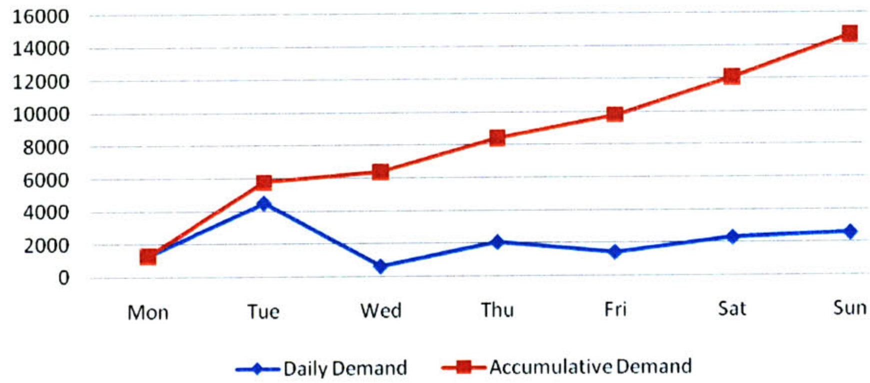

Figure 18 Confirmed Demand Pattern for SKU: DY-MRGL

Table 5 contains the details for the confirmed demand for the first week

Table 5 Confirmed Demand Pattern for DY-MRGL

DY-MRGL	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Daily Demand	1272	4473	614	2030	1403	2271	2540
Accumulative Demand	1272	5745	6359	8389	9792	12063	14603

Step 2:

Let 1 to 7 represent Monday to Sunday, S_{ij} (i=0, j=1,2,3,….,7) is calculated by the formula specified in section 4.4. The maximum S_{ij} is picked out as Max (S_{ij}) = S_{02} = 2873. Appropriate P_i can be calculated as: $P_1 = P_2 = 2873$. They represent the leveled production targets for the next Monday and Tuesday. See Figure 19 and Table 6, the accumulative production constraint is meet.

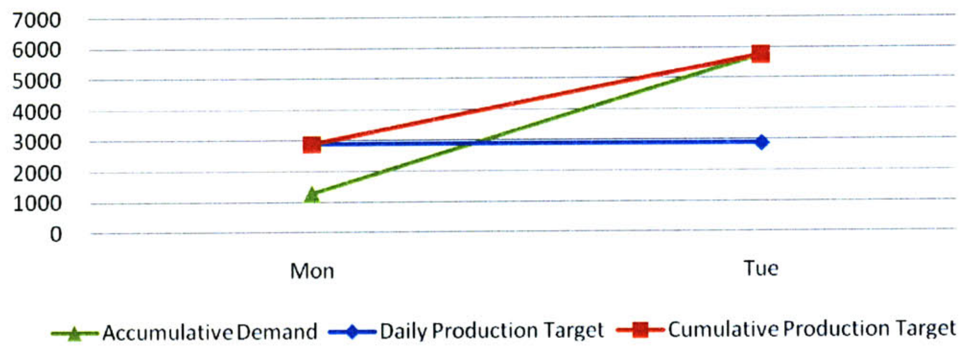

Figure 19 Leveled Production Targets from Monday to Tuesday

Table 6 contains the details of the currently planned production targets.

Table 6 Leveled Production Targets from Monday to Tuesday

DY-MRGL	Mon	Tue	Wed	Thu	Fri	Sat	Sun
I	1	2	3	4	5	6	7
Decision Variable (S_{ij})	1272	2873	2120	2097	1958	2011	2086
Daily Production Target	2873	2873	-	-	-	-	-
Cumulative Production Target	2873	5746	-	-	-	-	-

Step 3:

Start from Wednesday and repeat the previous calculation to determine the production targets for the next a few days covered by the new maximum S_{ij}.

Now, Max (S_{ij}) = 1772, then $P_3 = P_4 = P_5 = P_6 = P_7 = 1772$

Since Sunday's production target is determined from the above calculation, all calculations are done for this particular leveling period.

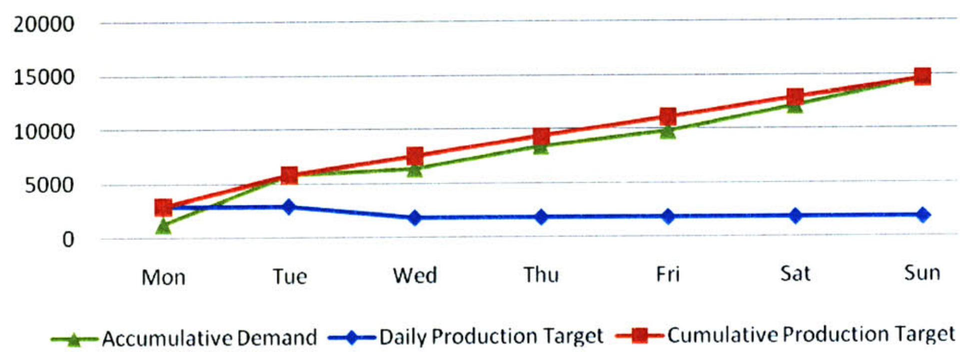

Figure 20 Leveled Production Targets from Monday to Sunday

The complete set of leveled production targets are consolidated in Table 7.

Table 7 Leveled Production Target from Monday to Sunday

DY-MRGL	Mon	Tue	Wed	Thu	Fri	Sat	Sun
I	1	2	3	4	5	6	7
Decision Variable	1272	2873	2120	2097	1958	2011	2086
Daily Production Target	2873	2873	1772	1772	1772	1772	1772
Cumulative Production Target	2873	5746	7518	9289	11061	12832	14604

Figure 20 proves that the cumulative production is constantly higher or equal to the accumulative demand at any day of the leveling period, and the total production volume equals the total demand volume at the end of the production leveling period. All the leveling constraints are met. Hence, the demand fulfillment is guaranteed.

Figure 21 compares the daily production targets and the original demand. Clearly, the leveled production targets now have a smaller variation compared to the original demand.

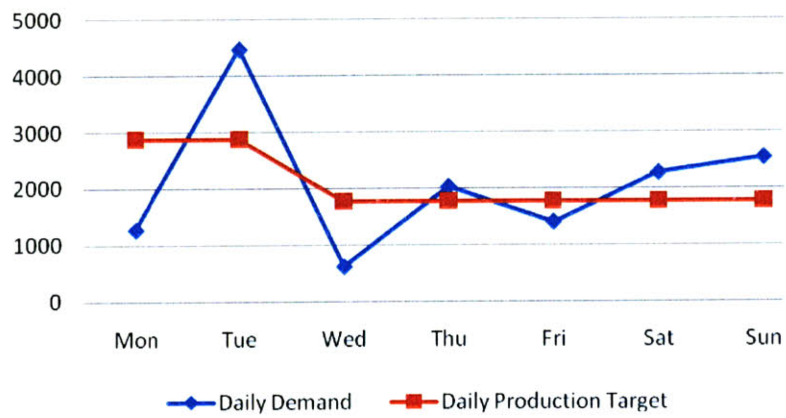

Figure 21 Daily Demand and Planned Production

Step 4:

Verify the calculation and repeat the leveling process for the entire 120 days to obtain a more general leveling effect.

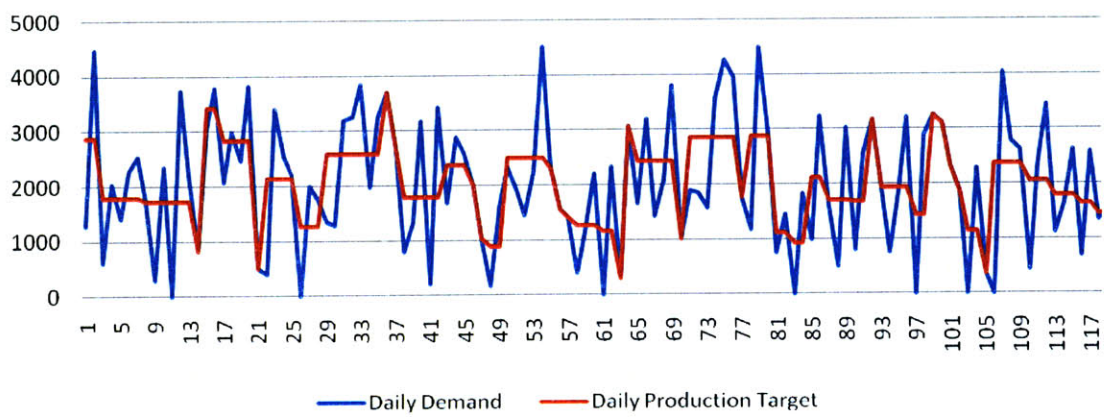

Figure 22 Demand and Planned Production Targets in 120 days

With the leveling process repeated for each week within a 120 days' period, the leveling effect becomes obvious. See Figure 22.

Table 8 shows the reduction in variance through production leveling, the coefficient of variance (C.V.) is used to describe and compare the significance of the leveling effect:

Table 8 Leveling Effect from the Heuristic Method

	Max	Min	C.V.
Original Demand	4511	0	0.58
Leveled Production	3696	282	0.35

Compare the coefficient of variance, the C.V. for this particular model has dropped by 40%. The maximum daily production is reduced by 18%.

5.3.2 Excel Solver Method

The previous simulation is conducted in Excel spreadsheet manually, thus is called the Heuristic Method. Although the benefit is satisfactory, the calculation itself involves multiple steps that must be carried out by the production planner. To simplify the operation, the Excel optimization tool named Excel Solver is tried out and has achieved the same leveling effect as the Heuristic Method. Since by Excel Solver the leveling can be done very quickly, simulations are carried out for multiple models to obtain a more general result.

The premises remain the same as the Heuristic Method.

<u>Simulation:</u>

SKU: DY-MRGL

Step 1:

Obtain the confirmed demand and calculate the accumulative demand, see Table 9.

Table 9 Demand Pattern for DY-MRGL

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
I	1	2	3	4	5	6	7
Demand	1272	4473	614	2030	1403	2271	2540
Accumulative demand	1272	5745	6359	8389	9792	12063	14603

Step 2:

Excel Solver set up

1) Set the variable cells for P_i

2) Set up the constrains for leveling:

   - Accumulative production >= Accumulative Demand on the same day

   - Daily production targets should be integers

   - Total production volume equals total demand volume at the end of the leveling period

3) Set up the optimization target:

   Minimize: coefficient of variance (C.V.) of leveled production targets

Step 3:

Run Excel Solver, obtain the optimized production targets.

As can be seen from Figure 23, the leveling constraint is met because the accumulative production target is constantly more than or equal to the accumulative demand. The optimized production targets for the leveling period are shown in Figure 24.

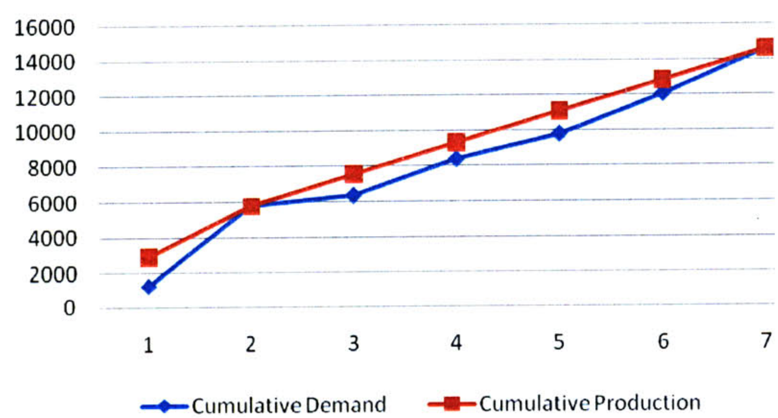

Figure 23 Cumulative Demand vs. Cumulative Production for DY-MRGL

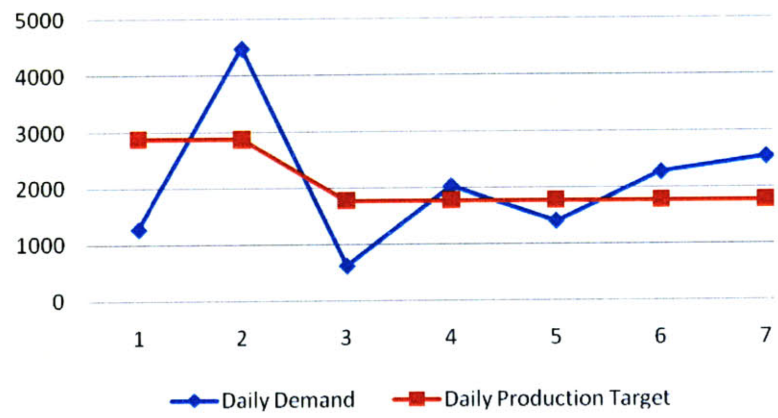

Figure 24 Daily Demand vs. Daily Production for DY-MRGL

Table 10 contains the detailed data of the planned production targets and the leveled production targets.

Table 10 Demand vs. Leveled Production for DY-MRGL

DY-MRGL	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Daily Demand	1272	4473	614	2030	1403	2271	2540
Cumulative Demand	1272	5745	6359	8389	9792	12063	14603
Daily Production Target	2873	2872	1772	1772	1772	1771	1771
Cumulative Production	2873	5745	7517	9289	11061	12832	14603

Step 4: Extend the calculation to the entire 120 days.

Similar to the Heuristic Method, the optimization process is repeated for 120 days at a seven days' interval to obtain a more general leveling effect. The results are summarized into Table 11.

Table 11 Leveling Effect from the Excel Solver Method

DY-MRGL	Max	Min	C.V.
Before Leveling	4511	0	0.58
After Leveling	3696	282	0.35

5.3.3 Comparison between the Heuristic Method and the Excel Solver Method

It is interesting that both Heuristic Method and Excel Solver Method are providing the same results under the same data input. Table 12 compares the C.V.s of demand and planned production targets under the two different approaches. The C.V.s are equal to each other up to the accuracy of 0.01. Since Excel Solver is much simpler to operate and is providing satisfactory results, it would be a preferable tool for the calculation of production leveling.

Table 12 Comparison of Leveling Effect from the Two Preliminary Approaches

DY-MRGL	Before Leveling	After Leveling
Heuristic Method	0.58	0.35
Excel Solver	0.58	0.35

In order to obtain a more general conclusion based on the Excel Solver leveling mechanism, another 3 high runners are chosen for simulation. The final results are shown in Figure 25, the reduction in C.V. for different models ranges from 39% to 50%. Thus a conclusion can be made that the C.V. of leveled production targets has a 40% reduction compared to the original demand C.V..

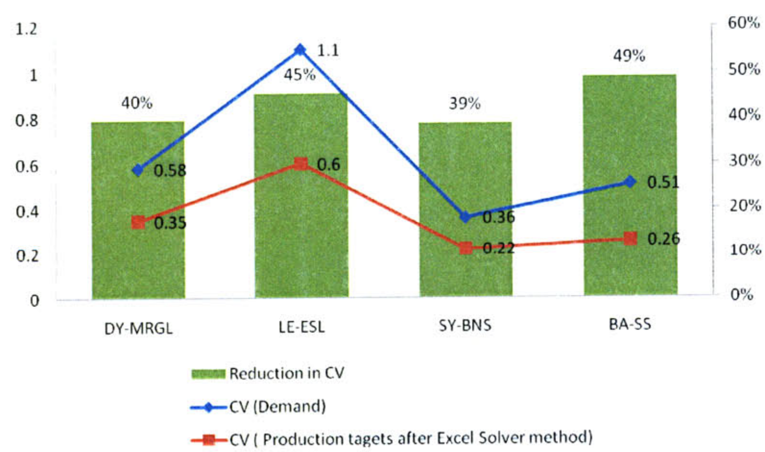

Figure 25 Reduction in C.V. after Excel Solver Method

5.3.4 Improved Excel Solver Method

Section 4.4.3 explained the opportunity to extend the leveling period by considering the two days' transportation lead time as well as to include the two days' orientation data. The demand for the coming week (Monday to Sunday) is received on Thursday of the current week. Because of the transportation lead-time, the products are required to be produced and shipped two days prior to the demand date, so that the goods will arrive at the destination on time.

Simulation is done to examine the benefits obtained from the Excel Solver Method. For comparison purpose, the SKU used was still DY-MRGL. The computer generated demand in week 2 and 3 are included into the time window for simulation. The Monday's demand from week 2 and 3 are chosen to be large value on purpose for demonstration.

Simulation:

SKU: DY-MRGL

Step 1:

With leveled production targets for the first week, Friday's production plan is updated by considering the new locked demand from week 2 and first two days' demand orientation from week 3.

Considerations:

In contrast to the previous leveling procedure, the new method requires modification of the input data, which is the original demand, before inputting the numbers into the Solver. This is due to the previous constraint that the total demand volume equals the total production volume. With each run of the leveling, the first 7 day's production quantity is permanently fixed; however, the rest 3 day's production volume are subject to change in the next leveling period. Under the new circumstances that the leveling period has been extended to 10 days, the demand and production equality will hold at the 10^{th} day but not for the 7^{th} day. It is possible that the first seven days will overproduce a certain quantity of products to prepare for the rest of the 3 days, as what is behind the leveling concept. As the new method has overlapping leveling periods, the over produced quantity at the 7th day of each period should be deducted from the original demand from next leveling period to guarantee the equivalence. Figure 26 shows the relationship:

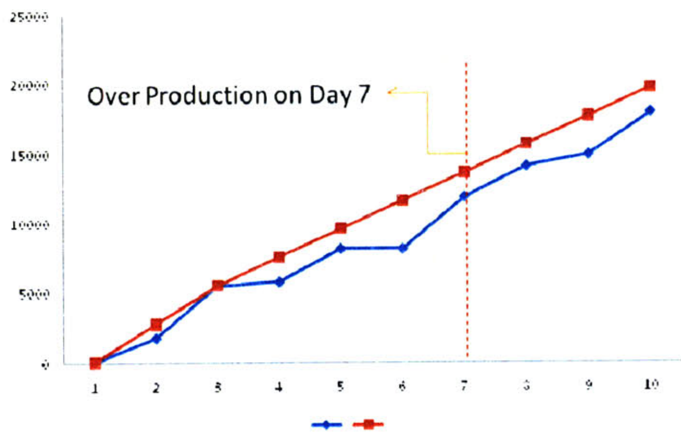

Figure 26 Over Production on Day 7

An example is presented in Figure 27 to show the leveling effect gained by using the Extended Solver Method.

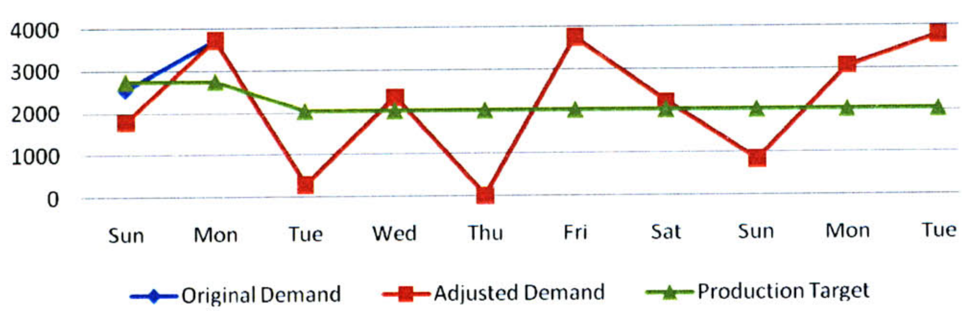

Figure 27 Leveling Effect under Different Leveling Methods

The original planned production data and the leveled production targets are recorded in Table 13. The over produced quantity in week 1 can be calculated as 768, this 768 SPs are deducted from the input data used for the new leveling period, as explained above.

Table 13 Leveling Effect under Different Leveling Methods

DY-MRGL	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue
Original Demand	2540	3723	286	2344	0	3739	2208	822	3046	3771
Adjusted Demand	1772	3723	286	2344	0	3739	2208	822	3046	3771
Production Target	2747	2748	2027	2027	2027	2027	2027	2027	2027	2027

As can be seen from Figure 28, the original leveled production targets are modified after counting the over produced quantity. The Monday's surge in planned production is handled by adding previous Sunday into the leveling period, because a portion of it is shifted and will be manufactured on previous Sunday.

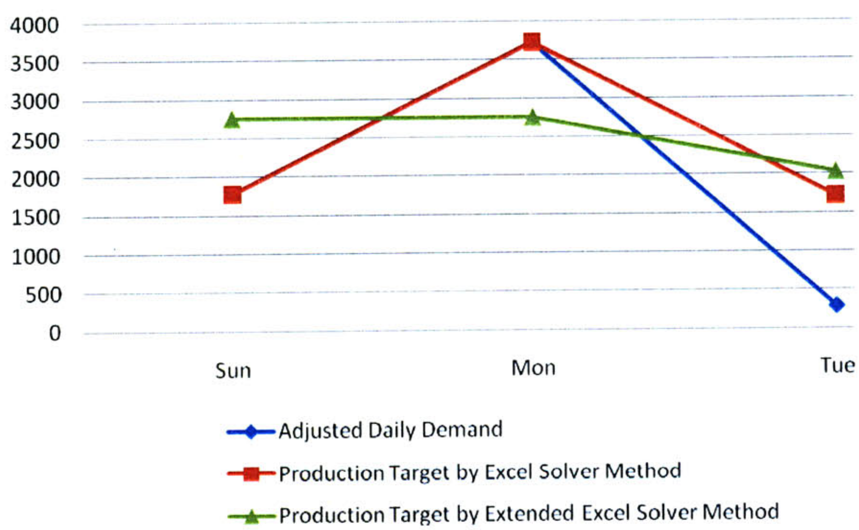

Figure 28 Comparison of Different Methods

Table 14 shows the details of the leveling by the Improved Excel Solver Method.

Table 14 Comparison of Excel Solver Method and Extended Excel Solver Method

DY-MRGL	Sun	Mon	Tue
Adjusted Daily Demand	1772	3723	286
Production Target set by Excel Solver Method	1772	3723	1715
Production Target set by Extended Excel Solver Method	2747	2748	2027

Step 2:

Again, in order to obtain a more general result, the simulation is extended to 120 days by repeating the calculation in Step 1.The new leveling effect are summarized in Table 15.

Table 15 Leveling Effect of DY-MRGL

	Max	Min	C.V.
Planned Production	4511	0	0.58
Leveled Production with Excel Solver Method	3696	282	0.35
Leveled Production with Extended Excel Solver Method	2873	1273	0.2

Step 3:

Three other models are put into simulation to obtain a more general leveling effect. The simulation results are recorded and compared in Table 16.

Table 16 Leveling Effect Summary for 4 Selected SKUs

Model	Demand C.V.	Excel Solver Method	Extended Excel Solver Method	Reduction
DY-MRGL	0.58	0.35	0.20	65%
LE-ESL	1.1	0.6	0.37	66%
SY-BNS	0.36	0.22	0.13	64%
BA-SS	0.51	0.26	0.16	69%

Figure 29 shows the further improvement from the second round leveling to the first round leveling.

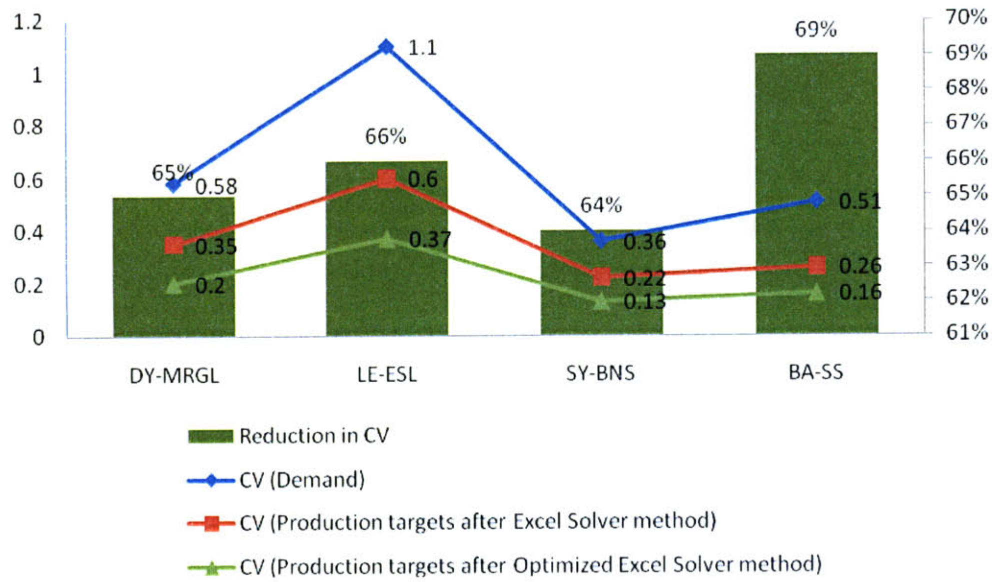

Figure 29 Summary of Reduction in C.V. (modify the picture)

As can be seen in Figure 29, the C.V. from second round leveling to the original demand is reduced by 64% ~ 69%, the leveling effect is significant.

5.3.5 Discussion

The objective of production leveling is to find an easy and robust method to help the production planner smooth the daily production without harming the customer service level. With the help of Excel Solver, the planning process can be automated with the confirmed demand each week. After three approaches proposed to level the daily production, the best one is chosen and proved to have the most significant reduction on the variation of daily production targets. As the leveled production targets will later be used as the signal to trigger the daily production, the reduced variation of daily production targets can lower the chance of stock out for all production stages involved.

5.4 The New Base Stock Policy

Based on the methodology stated in Section 4.5.1 and the processed demand data in from the preliminary analysis in Section 4.5.2, the base stock levels at each production stage for each of the higher runners are calculated. A spreadsheet simulation is conducted for selected SKUs to test the validity of the inventory control policy.

5.4.4 Base Stock Calculation

To calculate the base stock level at each production stage, the line effective capacity must be obtained first. With the help of PDAP staff, the data is collected and summarized in the Table 17.

Table 17 Line Effective Capacity

Production Stage	Machine Line	Daily Line Capacity (Pcs)
Stage 4	4-SR	8571
	4-CP	11140
	4-BA+SY	16290
	4-LE	10970
	4-DY	14571
Stage 5	5- ALL	19575
Stage 6	6-All	21400
Stage 7	7-SR	9428
	7-CP	11140
	7-BA	8914
	7-SY	3600
	7-LE	10970

<u>Calculation of expected lead-time parameter "n":</u>

Knowing the machine line capacities, the critical value of "n" can be calculated accordingly based on the methodology specified in Section 4.5.1. The "n" value represents the average lead-time for a SP to pass a particular machine line for processing, and serves as an important parameter used to calculate the base stock levels. Since each machine line at the same stage may not have the same capacity due to process requirement of different SKUs, the "n" value is calculated separately for each of lines. The input of line capacity is modified by subtracting the total demand volume of low runners. This part of the capacity will be left for producing low runners when demand comes. By reserving the capacity, the low runner SKUs' manufacturing will not disturb the base stock operation of the selected 19 high runner SKUs.

Table 18 Expected Lead Time

Stage	Machine Line	Daily Capacity	Reserved Capacity	Machine Line Lead Time "n"
Stage 4	4-SR	8571	172	1
	4-CP	11140	2819	1.15
	4-BA+SY	16290	927	1
	4-LE	10970	1042	1.46
	4-DY	14571	1205	1.81
Stage 5	5- ALL	19575	2082	2.88
Stage 6	6-All	21400	12964	2
Stage 7	7-SR	9428	172	1
	7-CP	11140	2819	1.15
	7-BA	8914	571	5.63
	7-SY	3600	356	1
	7-LE	10970	1076	1

From Table 18, it can be seen that several machine lines have a "n" value of 1, which means the machine lines have large free capacity. Once being withdrawn into this machine line, the raw material will be processed and consumed completely by the downstream production stage. Another extreme is the machine line named 7-BA. The lead time for the line is 5.63 days , which means once an SP comes into the raw material inventory of this machine line, it will stay for around 6 days until it is processed and consumed by the downstream production stage. The bigger the "n" value, the more base stock the machine line is going to keep.

<u>Base stock calculation:</u>

With the demand information and "n" values determined for each machine line within the 4 focused production stages, the base stock level can be calculated following the formulas introduced in Section 4.5.1. The base stock levels at different production stages are stated in the following four tables.

Table 19 Base Stock Levels at Production Stage 7

SKU	I	W	B
LE-ESL	4443	1463	5906
LE-ESC	3155	1039	4194
LE-ESGC	1304	429	1733
CP-ST	1008	1095	2103
CP-PT	3997	4340	8337
BA-HV	5709	12625	18334
BA-SS	6458	24757	31215
SR-44I	229	139	368
SR-44NI	2241	1358	3599
SR-46I	1140	691	1831
SR-46NI	2597	1574	4171
SY-BNS	836	488	1324
SY-BS	262	450	712
SY-SS	403	429	832

From Figure 30, it can be seen that the calculated base stock levels for SKUs BA-HV and BA-SS are much higher than the rest of the SKUs. This finding is partly due to its high demand, but also because of the large "n" values of the 7-BA machine line. This line processes both the BA-HV and BA-SS SPs with little spare capacity.

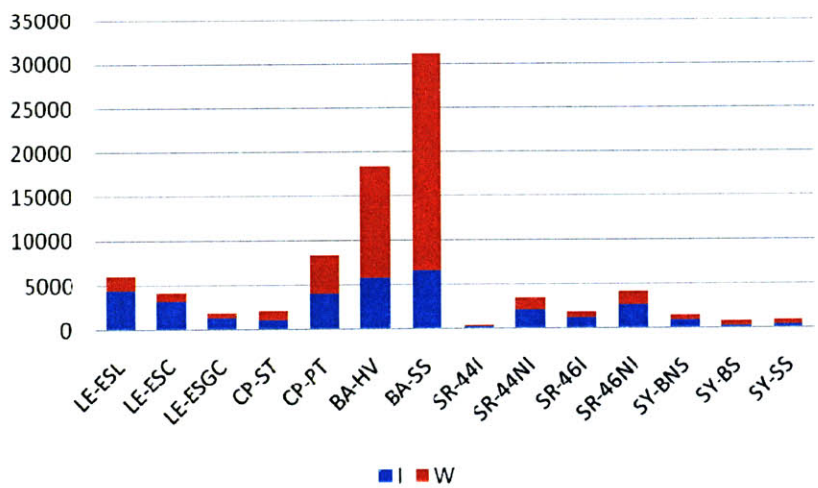

Figure 30 Base Stock Levels in Production Stage 7

The calculation went on to obtain the base stock levels for SKUs that pass through Production Stage 6. This production stage has only one machine line but is equipped with huge capacity.

Table 20 Base Stock Levels at Production Stage 6

SKU	I	W	B
BA-SS	4242	9147	13389
SY-BNS, SY-BS, SY-SS	703	3431	4134

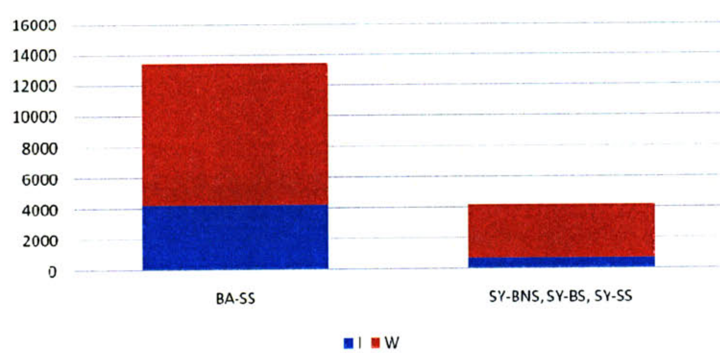

Figure 31 Base Stock Levels in Production Stage 6

As can be seen from Table 20, because the SPs for SKU SY-BNS, SY-BS and SY-SS are in nature the same raw material and end product at Production Stage 6, they share the same raw material and finished goods inventories. Once the downstream production stage has separate demands for the three mentioned different SKUs, the machine line will withdraw raw material from the same inventory in Production Stage 6.

Table 21 Base Stock Levels at Production Stage 5

SKU	I	W	B
LE-ESC	4162	2988	7150
LE-ESGC	1720	1234	2954
DY-MRGC	1611	3710	5321
DY-DC	1602	4392	5994
DY-ND	1831	5019	6850
BA-HV	4284	6446	10730
BA-SS	4846	13150	17996
SY-BNS,SY-BS,SY-SS	803	4933	5736

Same as Production Stage 6, Production Stage 5 is a single machine stage. However, different than Production Stage 6, Production Stage 5 processes more types of high runner SKUs with larger volume. Again, the "n" values is comparably high for the only machine line in this production stage, thus it caused high inventory for all SKUs involved in this stage, see Figure 32.

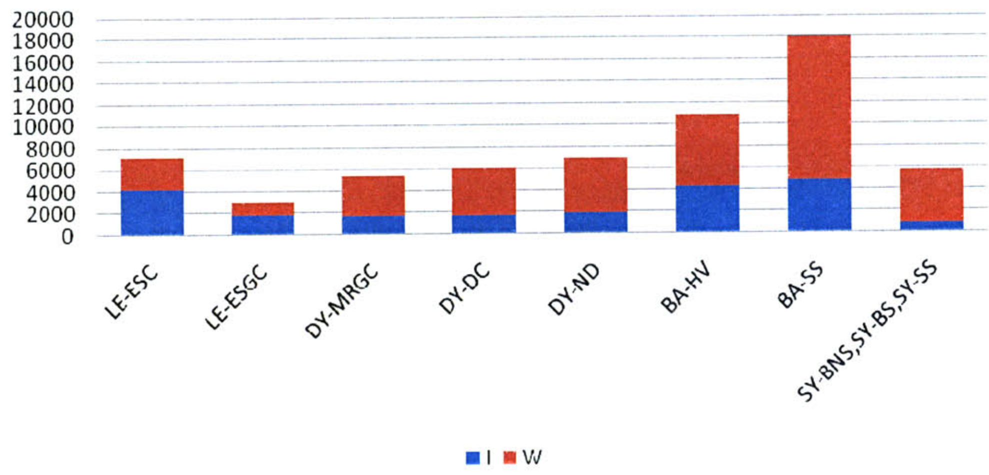

Figure 32 Base Stock Levels in Production Stage 5

The base stock calculation ended in Production Stage 4, the base stock levels are summarized into Table 22.

Table 22 Base Stock Levels at Production Stage 4

SKU	I	W	B
LE-ESL,LE-ESC	5740	3647	9387
LE-ESGC	4972	3230	8202
SR-44NI	2241	1358	3599
SR-44I	229	139	368
SR-46NI, SR-46I	2836	2265	5101
CP-ST, CP-PT	4122	5435	9557
DY-MRGL, DY-MRGC	2744	6415	9159
DY-DL	5020	5817	10837
DY-DC	1359	2770	4129
DY-ND	1553	3166	4719
BA-HV, BA-SS	4902	6813	11715
SY-BNS, SY-BS, SY-SS	608	1715	2323

Different than the above mentioned 3 production stages, Production Stage 4 operates as a basic process for all Class-A and Class-B SKUs. See Figure 33.

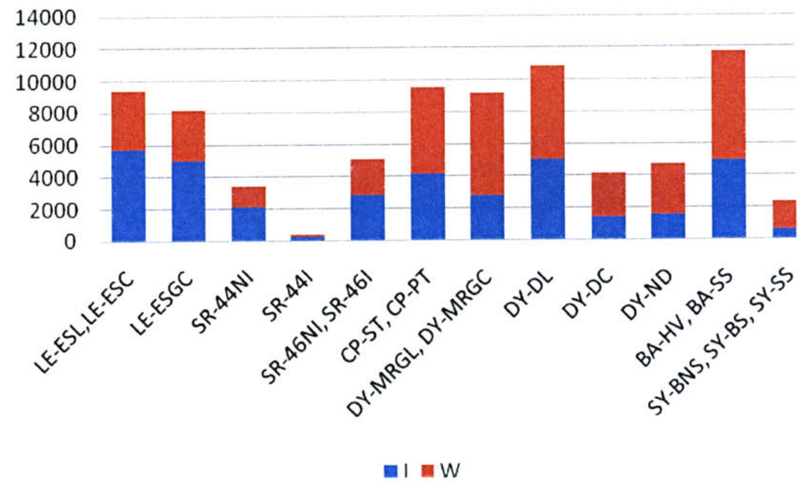

Figure 33 Base Stock Levels in Production Stage 4

Table 23 is a summary of the base stock levels calculated for BA-HV and BA-SS, and the "n" values for machine lines processing them at the 4 distinct production stages.

Table 23 Base Stock Levels for BA-HV and BA-SS

Production Stage	Stage 7	Stage 6	Stage 5	Stage 4
n	5.63	2	2.88	1
Base Stock (BA-HV)	18334	-	10730	11715
Base Stock (BA-SS)	31215	13389	17996	
Base Stock (Both)	49549	13389	28726	11715

As stated in the new base stock policy, at each production stage, every SKU has its own raw material inventory and finished goods inventory, preparing to be pulled from the demand. However, as can be seen in Figure 34, the base stock levels for the same SKU at Production Stage 1, 2, 3 and 4 can differ significantly. The explanation is that the base stock calculation is closely correlated to the "n" values at each production stage. A large "n" means the machine is less flexible thus the base stock should be kept higher to maintain the specified service level. While the "n" value is small, the machine is more capable of fulfilling demand in real time, and the base stock level can be kept lower.

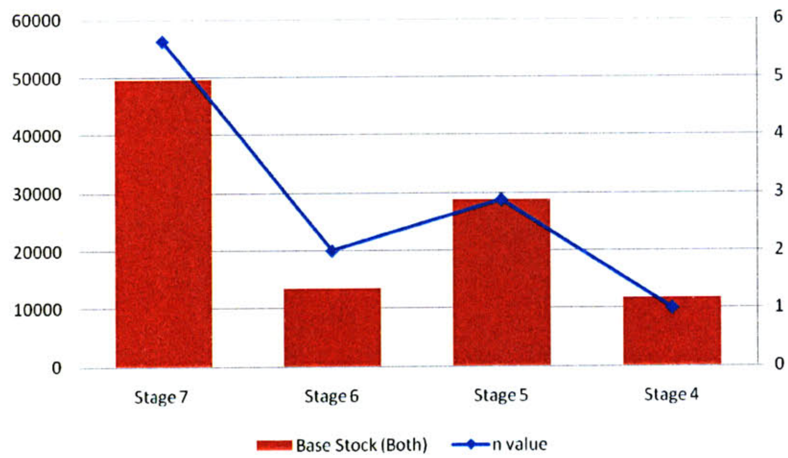

Figure 34 Base Stock Level vs. "n" values

5.4.2 Simulation

As stated in Section 4.7.1, a 5-stage-wide simulation is conducted for two selected SKUs: BA-HV and BA-SS. The simulation is conducted by Oracle Cristal Ball in an Excel spreadsheet. The objective is to evaluate the system performance (customer service level) under the new base stock policy. Table 24 states the input parameters, which are all obtained from the previous calculation.

Table 24 Cristal Ball Simulation Input Parameters

Prod. Stage	3		4		5		6		7	
Model	BA-HV	BA-SS	BA-HV	BA-SS	BA-HV	BA-SS	BA-HV	BA-SS	BA-HV	BA-SS
n	3.46		1		2.88	2.88	-	2	5.63	5.63
E[W]	24989		6813		6446	13150	-	9147	12625	25757
E[I]	6970		4902		4284	4846	-	4242	5709	6458
Mean	6813		6813		2241	4572	-	4572	2241	4572
Standard Deviation	2971		2971		1968	2226	-	2226	1968	2226

10,000 trials are conducted in the simulation. The length for each trial is 120 days, representing the 4 months referred to as high season. The overall customer service level is obtained as the order fulfillment rate at Production Stage 7, which is pulled by the demand directly. See Figure 35.

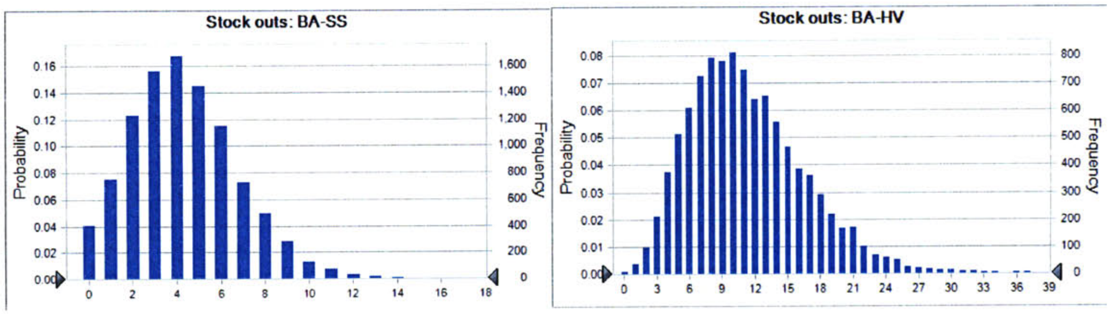

Figure 35 Histogram of Stock out at Production Stage 7

Table 25 shows the statistics of stock outs for the two selected SKUs at Production Stage 7. The overall service level for BA-HV and BA-SS are 91.7% and 96.7% respectively. However, after simulation, it is found that the system performance is largely depended on the policy specified to deal with stock outs. See Zia Rizvi [1] for detailed explanation.

Table 25 The Mean of Stock Outs

SKU	BA-HV	BA-SS
Trials	10000	10000
Mean	11	4

It is also worth investigating the customer service level when production leveling is added. Based on the results from Section 5.3.4, we can safely assume a 60% reduction in standard deviation for the tested SKUs. Table 26 shows the new pattern of leveled production targets for BA-HV and BA-SS as the simulation input.

Table 26 Pattern of Leveled Production Targets

SKU	BA-HV	BA-SS
Mean	2241	4572
Original Standard Deviation	1968	2226
New Standard Deviation	787	890

With a new data input under smaller standard deviation, the simulation results have shown great improvement. For both of the SKUs, the customer service level is raised to 100% during the simulation. See Figure 34.

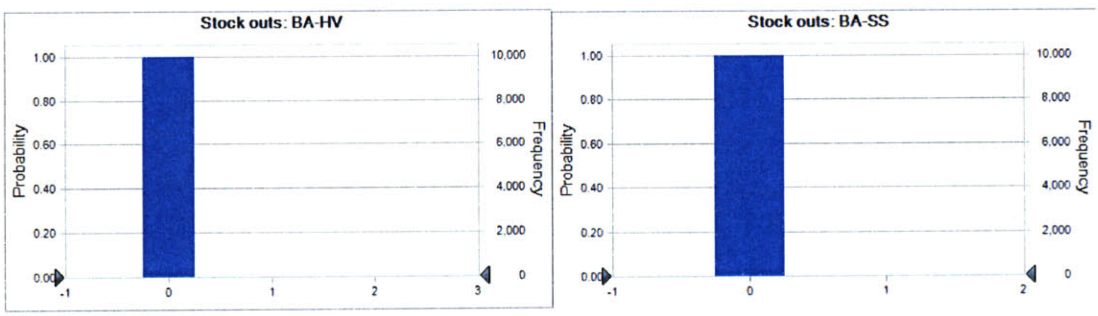

Figure 36 Histogram of Stock Outs at Production Stage 7 with Production Leveling

5.4.3 Discussion

For the selected 19 high runner SKUs, base stock will be kept at all of the production stages they go through in the focused manufacturing system. With the daily manufacturing quantity set by the control rules and the real time base stock level, each machine line has formed its own territory. By constantly monitoring its own inventory level, the machine lines are now self-directed for its daily manufacturing activity. More importantly, as all machine lines are now connected together as a network, a pull manufacturing system is built under the same inventory control policy. The overall customer service level is obtained by simulation, and the result is within expectation. It has also being proved that the production leveling method can successfully smooth the daily production targets, hence a further improvement on customer service level can be achieved.

5.5 Line Coupling Calculation

5.5.1 Considerations

The principle of line coupling is to link two capacity-close production lines, so that the related base stock can be replaced by a coupling stock which is much smaller. By linking the lines, the previously separated production processes are connected together with the help of a coupling stock. To calculate the size of the coupling stock, rules are made that the coupled machine lines should operate at the same time. The coupling stock is set up to cover the potential material shortage during the processing of each batch of SPs.

5.5.2 Parameters

To determine the size of the coupling stock, there are two critical parameters: process cycle time (CT) and process unit time (UT). The process lead time for the 6 involved SKUs are collected from the line, the process unit time is obtained from the effective daily capacity. All parameters are consolidated into Table 27.

Table 27 Parameters

Parameters		SR-44NI	SR-44I	SR-46NI	SR-46I	CP-ST	CP-PT
Process Cycle Time	UT4	10.08	10.08	10.08	10.08	7.76	7.76
	UT7	9.16	9.16	9.16	9.16	7.76	7.76
Process Unit Time	CT4	335	335	335	335	1200	1200
	CT7	1200	1200	1200	1200	1200	1200
Container Size	Z	150	150	150	150	150	150

5.5.3 Calculation

First the maximum production batch size P_{max} is determined by the method stated in Section 4.6.

Table 28 Maximum Batch Size Calculation

SKU	SR-44NI	SR-44I	SR-46NI	SR-46I	CP-ST	CP-PT
k	1.65	1.65	1.65	1.65	1.65	1.65
n	1	1	1	1	1.15	1.15
P_{max}	3599	368	4171	1831	2093	8298
Coupling Stock	542	218	600	365	304	304

With P_{max} determined, the coupling stock for each involved SKU is determined according to Formula 4-27. The values are summarized in Table 28.

5.5.4 Significance Verification

To simplify the line operation, the coupling stock will be rounded up to multiples of 150, which is the size of containers that will hold the coupling stock. Inventory savings are calculated for the 6 SKUs to see the significance of replacing the base stock between Production Stage 4 and 7 by the coupling stock. The numbers are compared with their original base stock level. The total saving is 16210 SPs. See Table 29.

Table 29 Summary of Saved Inventory

SKU	calculated value	round up value	Stage 4 I	Stage 7 W	Saved Inventory
SR-44NI	542	600	2241	1358	2999
SR-44I	218	300	229	139	68
SR-46NI	600	750	2836	1574	4351
SR-46I	365			691	
CP-ST	304	450	4122	1095	9107
CP-PT	304			4340	
				Total Saving	16525

5.5.5 Discussion

Line coupling is a special treatment can work together with the new base stock policy. By virtually combining two machine lines with very close capacity, the inventory levels for the involved SKUs can be reduced significantly.

5.6 Implementation of Kanban system & Other Implementation Issues

5.6.1 Considerations

To implement the new base stock policy by means of Kanban, the calculated base stock levels in previous sections cannot be directly applied. In the Kanban operation, inventory levels will be monitored and represented by cards shown on the Kanban board. To avoid an overwhelming number of cards, each card will represent a specific quantity of products, which is referred to as Kanban quantity. During operation, the material transfer must be done by transferring the cards, thus modifications are made to comply with the Kanban quantity constraints. The Production Leveling methodology is also slightly modified to comply with.

5.6.2 Kanban System Design

To simplify the operation of the Kanban system, the size of the Kanban card (Kanban quantity) must be carefully determined. With the collected information of container sizes for WIP transfer and shipment of finished goods, the standard container size for shipment is either 600 or 480 except for the SKD shipment. However, the containers used within the factory differ drastically. Some production stages use trolleys that can hold 160 or 192 SPs, while the other stages use plastic boxes with a size of 56 or 50 each. A summary of container sizes currently used within the focused manufacturing system are shown in Table 30.

Table 30 Summary of Container Sizes

SKU	Stage 4	Stage 5	Stage 6	Stage 7	Shipment
DY-MRGL	600	-	-	-	600B/4224SKD
DY-MRGC	200	600B/4224SKD	-	-	600B/4224SKD
DY-DL	600/200	600	-	-	600
DY-DC	200	4224SKD	-	-	4224SKD
DY-ND	200	4224SKD	-	-	4224SKD
LE-ESL	200	-	-	160	600

LE-ESC	200	200	-	160	600
LE-ESGC	200	200	-	160	600
CP-ST	150	-	-	160	480
CP-PT	150	-	-	160	480
BA-HV	200	200	192	160	600
BA-SS	200	200	192	160	600
SR-44I	150	-	-	160	480
SR-44NI	150	-	-	160	480
SR-46I	150	-	-	160	480
SR-46NI	150	-	-	160	480
SY-BNS	200	200	192	72/144	480B/720SKD
SY-BS	200	200	192	72/144	480B/720SKD
SY-SS	200	200	192	72/144	480B/720SKD

The shipment size currently used for SKD is following another system, and they will be enforced to adopt the Kanban quantity decided later for the regular products shipment. As the Kanban system is designed to be pulled directly from the shipment, the Kanban quantity can be chosen as either 600 or 480, based on different SKUs. However, not all of the containers used within the manufacturing system have sizes which are factors of 600 or 480. In order to solve this problem, modification of the container sizes for material transfer within the factory must be made to guarantee the correct movement of Kanban cards. The modifications are shown in Table 31.

Table 31 Modifications to the Container Sizes

Shipment Size	Original Size	Modified Size
600	160	150
	192	200
480	144	160
	72	80
	192	160
	200	160

As mentioned in Section 4.5.3, the Kanban card itself will contain the following information

1) Card ID number
2) Name of the model (SKU)
3) Model transit number (12NC)
4) Represented quantity
5) Production stage

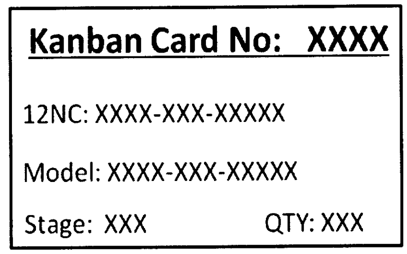

Figure 37 Kanban Card Design

With the quantity represented by each card determined, the total number of cards required can be obtained based on the base stock levels previously calculated. See Table 32.

Table 32 Kanban Card Sizes

Kanban Card Size	Family
600	DY,LE,BA
480	CP,SR,SY

All calculated base stock levels are rounded up to meet their specifications in Kanban quantity. Table 33 shows the modified base stock level for all involved SKUs.

Table 33 Inventory Summary after Round-up

SKU	Stage 7	Stage 6	Stage 5	Stage 4	Line Coupling Stock
DY-MRGL	-	-	-	9600	-
DY-MRGC	-	-	5400		-
DY-DL	-	-	-	11400	-
DY-DC	-	-	6000	4200	-
DY-ND	-	-	7200	4800	-
LE-ESL	6000	-	-	9600	-
LE-ESC	4200	-	7200		-
LE-ESGC	1800	-	3000	8400	-
CP-ST	1440	-	-	5760	450
CP-PT	4320	-	-		
BA-HV	18600	-	10800	12000	-

BA-SS	31800	13800	18000		-
SR-44I	480	-	-	480	300
SR-44NI	2400	-	-	1440	600
SR-46I	1440	-	-	2400	750
SR-46NI	2880	-	-		
SY-BNS	1440	4320	5760	2400	-
SY-BS	960				-
SY-SS	960				-
Total	234780				

With the base stock level rounded up, the number of cards is determined accordingly.

Table 34 Summary of Kanban Cards

SKU	Stage 7	Stage 6	Stage 5	Stage 4
DY-MRGL				16
DY-MRGC			9	
DY-DL				19
DY-DC			10	7
DY-ND			12	8
LE-ESL	10			16
LE-ESC	7		12	
LE-ESGC	3		5	14
CP-ST	3			12
CP-PT	9			
BA-HV	31		18	20
BA-SS	53	23	30	
SR-44I	1			1
SR-44NI	5			3
SR-46I	3			5
SR-46NI	6			
SY-BNS	3	9	12	5

SY-BS	2			
SY-SS	2			
Total	404			

5.6.3 Kanban Operation

Following the control rules specified in the new base stock policy, two procedures were developed to facilitate the Kanban operation.

Standard Kanban Operation

Based on the new base stock policy, there are three parameters that must be shown on the Kanban board to control and monitor the daily manufacturing activity at each machine line:

1) Raw material inventory (W)
2) Finished goods inventory (I)
3) Daily manufacturing quantity (P)

As a Kanban system will be set up and run under the new base stock policy, it is reasonable to place 3 kinds of cards, namely the W card, I card and P card onto the Kanban board. The cards on the board are used to display the real time inventory level and the daily manufacturing quantity for a specific SKU or a group of SKUs that share the same SP at certain intermediate production stages. The operation is decided to have the following 5 steps:

1) At the beginning of the daily production cycle, the number of I cards will be updated to reflect the previous shipment quantity or material movement quantity to the downstream production stage.

2) Based on the number of I cards missing, pull raw material from the upstream production stage at the amount represented by the missing I cards. Update the number of I cards in the up stream's Kanban board to inform them your withdrawal. Then, with the refill of raw material, add W cards onto the Kanban board to reflect your new level of raw material inventory.

3) Calculate the manufacturing quantity for this production cycle (one day) specified by the new base stock policy. Round up the result to multiples of Kanban cards and put the cards on to the Kanban board to trigger the production for the current production cycle.

4) Whenever the quantity of products specified by a P card is manufactured, put away one P card and one W card from the board. Add one I card onto the board to reflect the material movement and the new inventory level.

5) Repeat Step 4 until all P cards are put away from the board, the manufacturing is finished.

Simplified Kanban Operation

With the Standard Kanban Operation, the inventory levels and production target are known by counting the number of different cards shown on the board. However, since there are three different cards displayed on the board, the operator must frequently put away and add cards of certain type to update the real time inventory level. For example, each fulfillment of one P card would require simultaneous movements of all 3 types of cards on the board. In order to simply the Kanban operation, a new procedure is developed.

The new operation reduces the types of cards from three to one. The function of the card is represented by the different locations they are shown on the board, which are areas named I, R, W and P. The R region is a newly introduced part that shows the material release requirement. During the operation, the material transfer will be updated simply by moving the cards from one location to another. And the total number of cards for one specific SKU or SP will remain constant throughout the whole production cycle, which fully demonstrates the principle of the new base stock policy.

1) At the beginning each production cycle, the number of cards in I region will be updated to reflect the previous shipment quantity or material movement quantity to the downstream production stage. However, instead of putting I cards away from the board, now the cards are only shifted from I area to the material release area, which is represented by R.

2) With the material release requirement shown by the number of cards stayed within the R region, the line worker will go and pull raw material from the upstream production stage, and then shift the correct number of I cards in the upstream to their own R region to inform them

the withdrawal. With the replenishment of raw material, the line worker will shift the respective number of cards from the R region to the W region to reflect the new raw material inventory at this particular production stage.

3) Calculate the manufacturing target for this production cycle by counting the total number of cards stayed in the W region, round up to multiples of Kanban cards and shift the respective number of cards from the W region to P region as the triggering signal for production in the current production cycle.

4) Once production is done for the quantity represented by one Kanban card, shift one card from the P area into I area to reflect the new finished goods inventory.

5) Repeat step 4 until there are no cards left in the P region, production is finished.

For graphical demonstration, please refer to Appendix A.

5.6.4 Modification to Leveled Production Targets

As for the Kanban system, the daily production targets should be assigned as multiples of 480 or 600, depending on different models. To achieve that, the original leveled targets are changed with the method specified in section 4.5.3. One example is used for a 10-day-long leveling to demonstrate the results of modification, the Kanban quantity is 600 in this case.

Table 35 Original vs. Modified Production Targets

Day	1	2	3	4	5	6	7	8	9	10
Original Production Targets	2873	2872	1772	1771	1771	1772	1971	1971	1971	1971
Modified Production Targets	3000	3000	1800	1800	1800	1800	1800	1800	2400	1800

Figure 38 shows the production surplus by subtracting the accumulative leveled production targets by the accumulative original demand. It can be seen that the surplus always exist, thus the customer requirement is constantly met. It is noticeable that there is surplus at the end of the leveling period, which violates the equivalence constraint that was specified in the production leveling method. However, this surplus will be automatically adjusted with the new demand from the customer, as explained in Section 5.6.4.

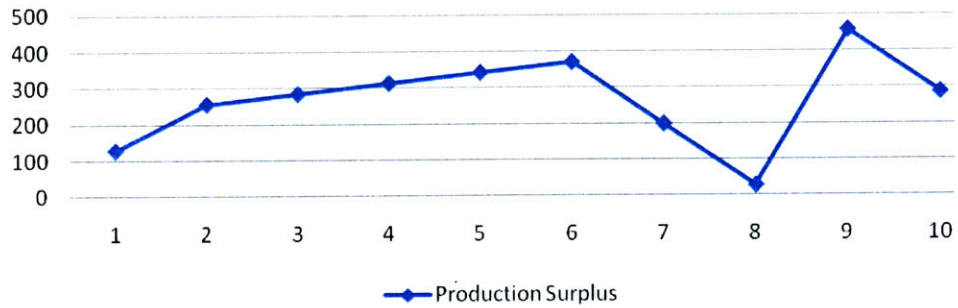

Figure 38 Production Surplus

5.6.5 Simulation of Round-up Effect on Daily Manufacturing Quantity

As the daily manufacturing quantity is calculated by Equation 4-22, it should be rounded up to meet the Kanban quantity as either multiples of 480 or 600. To test if the production is still under control after round up, a simulation is done on SKU BA-SS at Production Stage 7. The result shows the that the daily manufacturing targets are still under control, and the finished goods inventory at Stage 7 has a mean shift to a slightly higher level. The mean shift is reasonable because the manufacturing quantity is increased each day to meet the Kanban quantity constraint, thus more raw materials are transferred into finished goods, see Figure 39, 40.

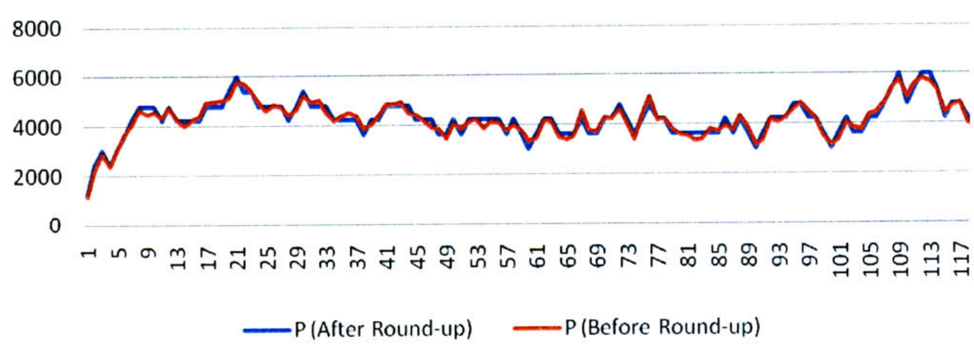

Figure 39 Comparison of Manufacturing Quantities

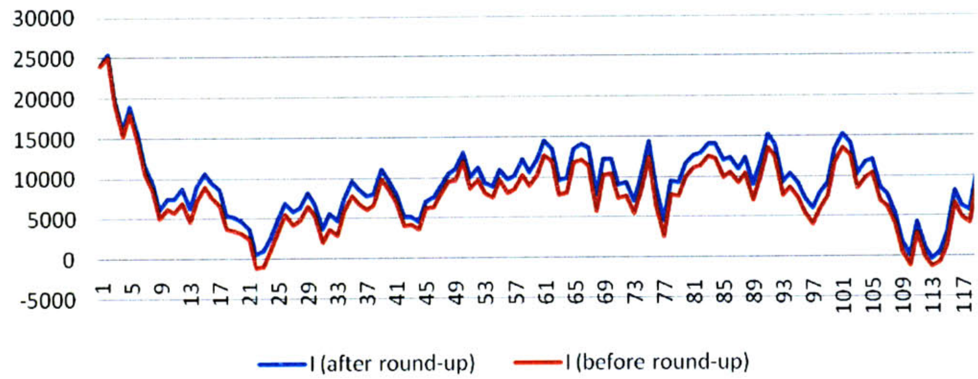

Figure 40 Comparison of Finished Goods Inventory

5.6.6 Discussion

A successful implementation is the ultimate goal of the team project in PDAP factory. With the developed inventory structure and operation procedures, modifications must be made to transfer theoretical solution into practical solution. Optimization of the operation is done with active involvement from the factory staff. Finally, simulation results provided evidence for robustness of the designed Kanban system.

5.7 Financial Impact Analysis

Table 36 compares the calculated inventory levels and the current stock levels the factory, which the factory is keeping right now. The current inventory levels are obtained by averaging 3 weekly summaries in June, which is the best source to calculate the stock levels. The table also contains the average unit value for SPs at each production stage within focus to calculate the cash blocked by the inventory kept within the factory.

Table 36 Comparison of Stock Level & Dollar Savings

Production Stage	Stage 3	Stage 4		Stage 5		Stage 6		Stage 7		
Base Stock Type	I	W	I	W	I	W	I	w	I (BTM)	I (SKD)
Base Stock Level	45784	42770	26898	41872	20859	12578	4945	41680	33520	262
Line Coupling Stock			2100							
Expected Stock Building Level									32750	
Calculated Inventory Summary	88554		70870		33437		46625		66270	262
Current Inventory Level	118435		59006		32328		11534		533438	30906
Unit Price (S$)	3.80		4.00		4.40		6.70		8.00	6.00
Cash Blocked (Calculated)	336505		283480		147123		312388		530160	1572
Cash Blocked (Current)	450055		236026		142242		77280		4267501	185437
Dollar Savings (S$)	9084		-3796		-390		-18809		313696	
Total Saving	299785									

From the table, the inventory level in the new manufacturing system was reduced significantly when compared to the current level. In terms of cash blocking, the saving is around 4 million. Assume an 8% annual interest cost, the net saving is S$ 300K.

Another finding from Table 36 is that the inventory distribution is changed. The current inventory level keeps a huge amount of inventory in the final stages. However, under the new manufacturing system, the intermediate production stages are storing more while the inventory level at the last production stage is reduced significantly. See Figure 41.

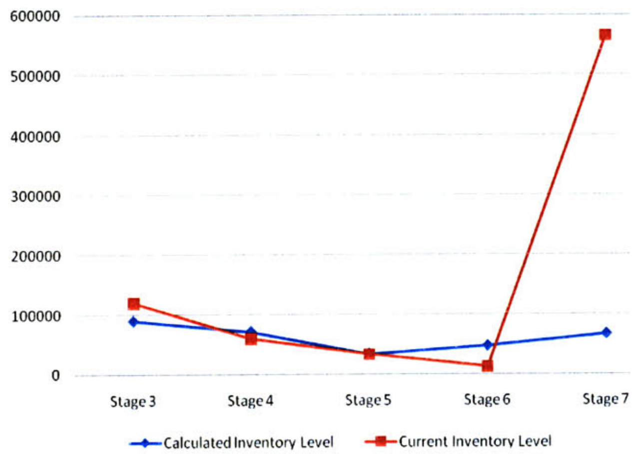

Figure 41 Comparison of Stock Levels

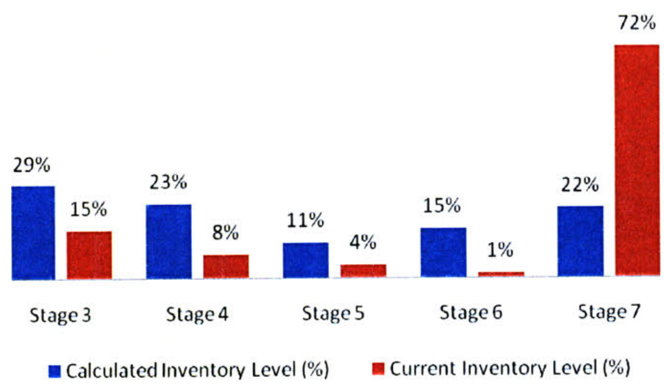

Figure 42 Distribution of Stock Levels

This redistributed inventory is also preferable from the financial perspective of view, because the average unit value for each SP is reduced by stocking more in the early production stages. See Table 37.

Table 37 Reduction in Average Unit Value

	Stock Level	Cash Blocked S$	Average Unit Value
Calculation	306018	1611228	5.27
Current	785648	5358541	6.82
Reduction (%)	61%	70%	23%

Chapter 6 Recommendations and Conclusion

6.1 Recommendations

There are three main methodologies proposed to the focused manufacturing system: New Base Stock Policy, Production Leveling and Line Coupling on selected high runners.

The New Base Stock Policy provides an innovative method to schedule the daily manufacturing activity under a pull manufacturing environment for multiple types of SPs that share the same manufacturing resource. The policy is also used to controlled inventory and to maintain certain customer service level. In order to successfully implement this method, several recommendations are made:

1) The base stock calculation is able to be continuously updated if more accurate demand forecast becomes available.
2) As part of the base stock at each machine line, the finished goods inventory should be monitored with more attention. If the number of stock outs started to increase and falls below the designed service level, it is very likely that the demand pattern has been changed. Thus the base stock levels should be increased manually, vice versa.
3) Feedback from the line workers is very important on the operations of the Kanban system, same important is constant improving with any problems come out through the operation of the designed system. The improvements may include choosing the best location of Kanban board, information sharing and synchronization with staff from different production stages, etc.

Production Leveling serves as an optimization tool for processing preliminarily demand. It transfers confirmed demand into leveled production targets and uses it to work collaboratively with the base stock policy by pulling from the end stage of the manufacturing system. The leveling process can be done in Excel with an all-in-one spreadsheet. However, if any variables or requirements involved in the calculation are changed, the spreadsheet shall be updated accordingly.

For Line Coupling, it is important that manufacturing activity is strictly following the rules specified in the method. To successfully implement the coupling mechanism and reduce inventory, the manufacturing at both of the machine lines shall start together. Moreover, as there might be unconsidered constraints in the real factory floor scenario, modification of the coupling stock should be made when appropriate.

6.2 Conclusion

The M.Eng project at PDAP Electronics Singapore aims to design a system for controlling inventory and directing daily manufacturing activity. After a thorough study of the factory's operation, the M.Eng project group identified problems in 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 the bottleneck of the production system, the 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.

ANOVA analysis was proposed by Yuan Zhong as a method to facilitate demand characterization during the planning process. It effectively identified the seasonality of demand in the year and guided the setting of appropriate inventory targets for respective seasons.

The performance of the proposed base stock model was studied using computer simulation that modeled the chain of production stages. It was found that the model was able to conserve the overall inventory levels of the production stages in chain. Furthermore, the base stock model delivered satisfactory customer service level and improved the overall inventory structure, via demand-driven production. As a result, 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.

Methods were also proposed to assist the production planning process. Youqun Dong developed a capacity planning optimization framework to handle excess demand during peak demand season. 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.

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.

6.3 Future Work

To further improve the manufacturing performance of the PDAP factory, several works are worth doing by the factory itself, the supplier, or the customers. They are listed below:

Container size standardization

The size of the containers used for material transfer within the factory shall be standardized for all 7 production stages to smooth the Kanban operation. In the last 4 production stages, small modification has been made without much cost. However, for the upper 3 stages, small modification is not physically feasible, thus further investigation on the container sizes is required.

Optimization of machine line capacity

It has been identified that several machines are facing capacity shortage, thus high level inventory is kept to buffer its manufacturing. On the other hand, some other machine lines have a lot extra capacity that remains idle for most of the time. Hence, the capacity of machines can be modified to comply with the demand for different SKUs that they are processing. Thus all of them would have similar stage lead-time under the new base stock model, and the system will become more balanced.

Improved order receiving and production planning

The new inventory control policy and production planning allow the factory to be pulled on a daily basis. Thus it is no longer necessary for the customer to give one week's confirmed demand but just to send their demand each day with higher accuracy. By doing this, the customer will feel more convenient, which would finally bring rewards to the factory itself.

Optimization of the manufacturing at Production Stage 5

Due to process requirement and the long changeover time, different SKUs in Production Stage 5 can be grouped and manufactured together. With that interesting characteristic, there is an opportunity to optimize its production scheduling process as well as the time for changeovers.

Others

1) Improve floor layout to make material transfer easier under the designed Kanban system.
2) Encourage suppliers to adopt Kanban system and share information.

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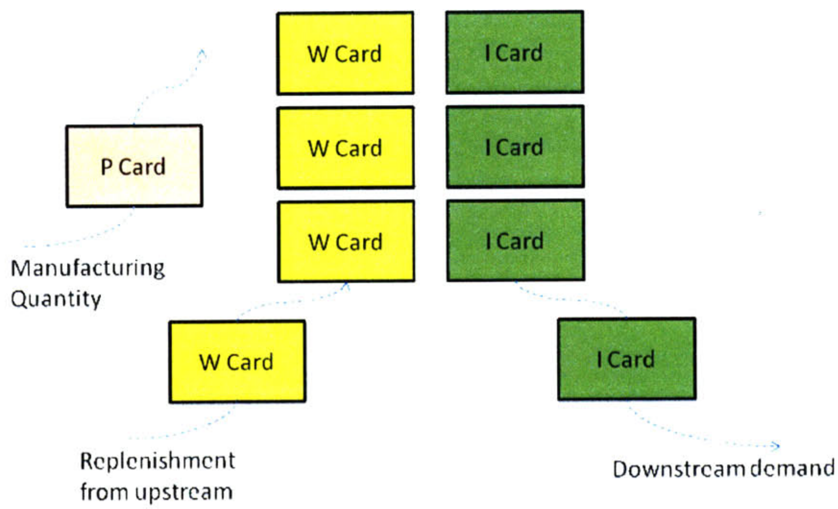
[7] Graves, S.C., Lecture notes, 15.762, Massachusetts Institute of Technology, February 9, 2009, unpublished material.

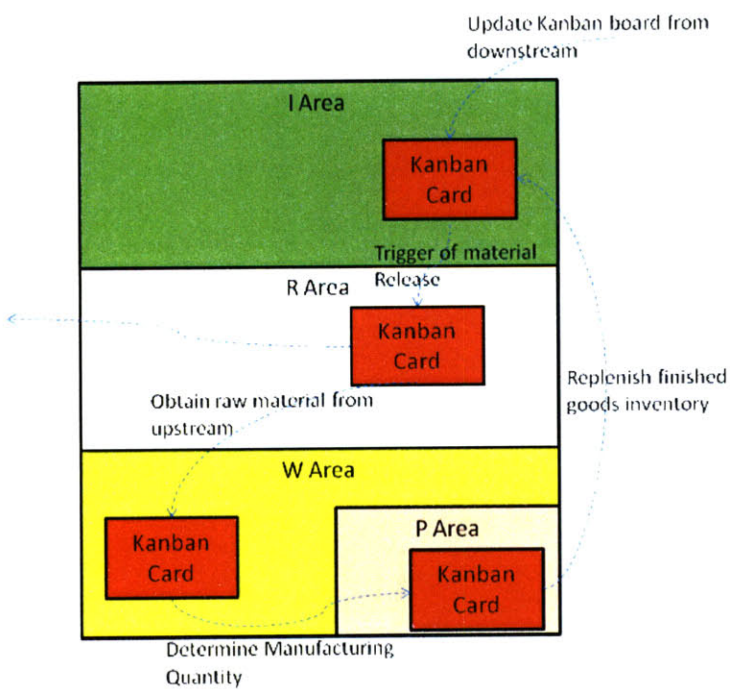
[8] Swain, B., 2007, "Visual Management", Lean Construction Institute UK Summit 2007, accessed June 18, www.lci-uk.org/Visual Management note.pdf.

Appendix A

Standard Kanban Operation



Simplified Kanban Operation



Appendix B

Excel Solver Operation Manual

Defining an optimization model

Model	Maximize or minimize	Target
Production Leveling	Minimize	C.V. Production Targets

Target cell

The target cell represents the objective or goal. In Production Leveling, the target cell is the C.V. of leveled production targets.

Changing cells

Changing cells are the spreadsheet cells that we can change or adjust to optimize the target cell. In production leveling, the changing cells are the daily production targets within the leveling period.

Constraints

Constraints are restrictions you place on the changing cells. The first is that all leveled production targets must be integers; second, daily accumulative targets should be more than or equal to the accumulative demand; third, the total production targets and total original demand volume shall equal to each other at the end of each leveling period.

Installing and running Solver

To install Solver, click Add-Ins on the Tools menu, and then select the Solver Add-in check box. Click OK, and Excel will install the Solver. Once the add-in is installed, you can run Solver by clicking Solver on the Tools menu. After inputting the target cell, changing cells, and constraints, we can run the solver to get the optimized solution. The left figure is the Solver Interface.