Production and Inventory Control of a Multi-item Multi-stage Manufacturing System: Simulation Modeling, Capacitated Shipment Planning and Kanban Design

by

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Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

The project work presented in this thesis has proposed solutions related to the control of production and work-in-process inventory in a multi-item multi-stage manufacturing system. A suitable base-stock inventory control policy is recommended to ensure that the desired service levels are maintained between production stages and for the final customers. Concept of coupling the production lines though coupling-stock under suitable assumptions is then introduced to reduce the stock levels at certain consecutive production stages. A framework for demand seasonality and characteristic analysis is also established to enable the inventory control policy to respond to seasonal variations.

Monte Carlo simulation was performed on a model of chain of production stages controlled under base-stock policy for the verification of results and to study the effects of stock-outs on base-stock levels. The results of simulation study showed that overall system performance is satisfactory and desired service levels were achieved. Simulation work was also carried out to validate the line coupling concept and its performance under certain conditions.

A novel Kanban based visual management system design, which is aligned with the requirements of inventory control policy, along with the material transfer batch sizes between production stages is proposed to facilitate the implementation of inventory control policy. Furthermore, capacitated shipment planning approach is proposed and implemented in form of a spreadsheet-based interface to aid planning personnel in shipment planning under the constraints provided by the inventory control policy.

Key words: Multi-item multi-stage manufacturing system, Base-stock inventory control policy, Monte Carlo simulation, Kanban system design, Capacitated shipment planning

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

Thesis Advisor: Stanley B. Gershwin
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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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CHAPTER ONE: INTRODUCTION

Increasing industrialization and fierce competition in the markets requires manufacturing business firms to maintain an edge and competitiveness that depends not only on the technological advancements acquisition but also on how they conduct their business. Great products can bring great opportunities but sustainable growth is significantly dependent on how these products are manufactured and how the operations are managed. Manufacturing companies are actively looking at improving their operations efficiency by getting 'Lean', which primarily focus on optimizing the inventory levels and improving the production control system. This thesis is a result of internship work by four MIT MEng-Manufacturing students at the PDA Singapore, as part of their lean production initiative. This chapter briefly introduces RP Electronics Singapore Pte Ltd and its subsidiary company PDA Singapore, including company background, products classification, manufacturing process flow and demand management process.

1.1 Company background

Headquartered in Europe, RP Electronics is one of the leading consumer electronics appliance companies in the world and sells over two hundred products in Asian, European and American markets. RP Electronics Singapore started operations in 1951 and is considered one of the pioneers in Singapore industry.

This work took place at one of the RP Electronics Singapore subsidiary companies, PDA Singapore, which is the global distribution and R&D center for RP Electronics irons. RP Electronics global management has initiated the implementation of an operations management system analogous to Toyota Production System and encourages the facilities to operate in a Lean environment. PDA Singapore is among the few chosen factories around the globe that are included in the pilot implementation project. Factory management is committed to lean production and has set goals for reduction of wasteful activities and work-in-process inventory blocked along the production lines that causes increased material flow lead-times and increased operations budget. The management has therefore focused on controlling the inventory and lead times to establish a lean production environment.

1.2 Products classification

PDA Singapore factory is dedicated to production of a component named Sole Plate (SP) assembly that is used in irons. All the SPs manufactured in this facility can be classified on the basis of their product target market and technical specifications, broadly as Dry Iron Sole Plate or Steam Iron Sole Plate. There are three product lines in dry irons SP class and six product families with a total of eleven product lines in steam irons SP class. Each product line has further variants and thus PDA product portfolio has over fifty stock keeping units (SKU) at finished goods level. The product classification tree is shown in Figure 1-1.

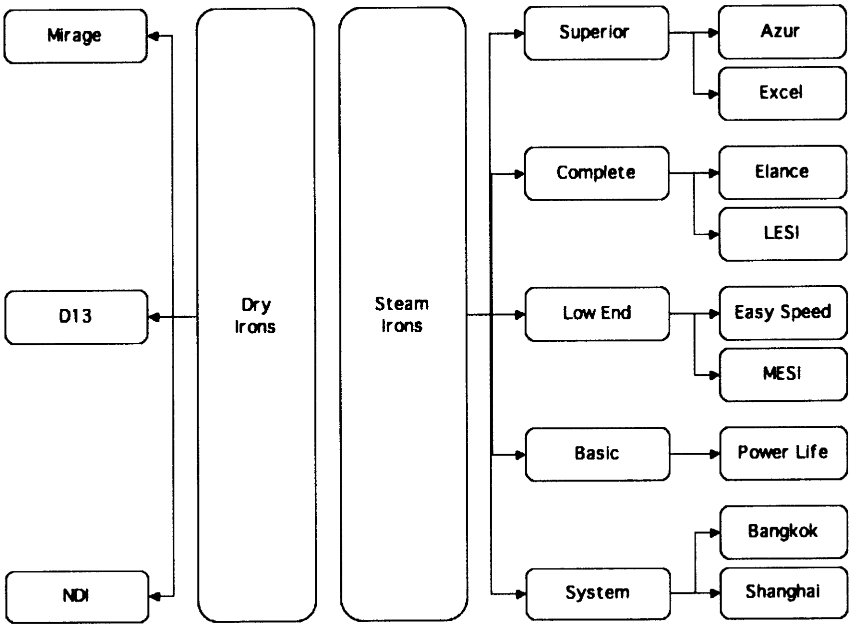

Figure 1.1: Product classification tree

1.3 Production process flow

Dry iron SPs and steam iron SPs share two production processes initially in their manufacturing process plans and are processed on shared production stages i.e. Heating Element (HE) and Die Cast (DC). Dry iron SPs are routed to their dedicated Part-A (PA) stage, which is the final process for some dry SKUs but some of them are directed towards Auto Coat (AC) for further processing. The finished SPs are stored in Finished Goods Store (FGS). This generic flow for dry irons SPs is depicted in Figure 1-2.

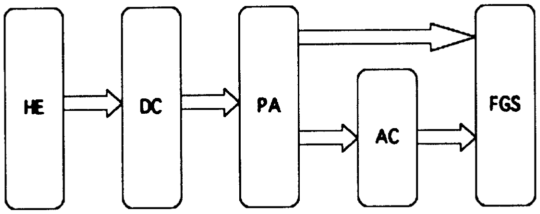

Figure 1-2: Dry iron SPs production flow diagram

All the steam iron SPs require additional processing at Steam Promoter (ST) after DC, which is a shared stage before they are directed towards respective Part-A (PA) stages dedicated on the basis of steam iron SKU families. Two of the six steam irons family's SPs are sent directly to their dedicated Riveting & Sealing (R&S) stage and rest of them require processing at AC, also a shared stage, before they are processed at their dedicated R&S stages. One of the four steam irons family's SPs processed at AC requires additional processing at Solgel (SG). SG also processes a common part named Iron Plate for steam iron SPs, classified on the SKU family basis, and is fed directly to their R&S stages. The finished sole plates from R&S lines are taken to be stored in FGS. The generic steam iron SPs flow on the production floor is depicted in Figure 1-3.

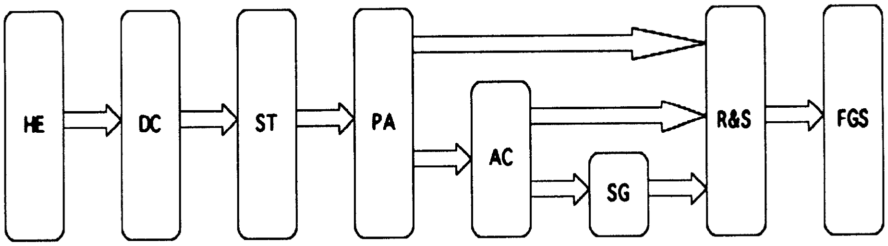

Figure 1-3: Steam irons SPs production flow diagram

1.4 Demand management

PDA produces SP assembly for an assembly plant in Batam, Indonesia and some satellite factories in Europe and China where the irons are assembled. Demand from assembly plant is met through daily shipments where as satellite factories demand is fulfilled by weekly shipments.

1.4.1 SP assembly demand management

National Sales Organization (NSO) using Advanced Planning Optimization (APO) tool and collaboration with Logistics Management Team (LMT) provides monthly demand forecast for coming year by November of current year. This monthly forecast is revised on monthly basis with a horizon from next month up till end of the year. It also provides weekly demand orientation values for next 52 weeks with rough estimates for weeks beyond current year. The demand management process is described as a sequence of activities which are explained in point 1 to point 6 below.

1) Monthly production schedule (MPS). Factory planner prepares the MPS by the end of 3rd week of current month for rest of the months in current year at finished goods level, based on the monthly forecast. Factory planner considers the actual demand and only the final process capacity while preparing the MPS. The factory planner tries to maintain the quarterly production contribution to the annual demand based on her judgment of historic demand data and input from the factory planner at assembly plant in Indonesia. The first version of the MPS serves as the basis for a manufacturing manager who is responsible for developing stock building plan as explained in section 2.1.1. 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) Monthly demand constraints. MPS is provided to the commercial planner to communicate monthly production constraints for each product model, which assist him to confirm the orders. Some products models have variants and commercial planner is given the flexibility to change the monthly demand of variants within aggregate production constraints for the corresponding product model.

3) Weekly constraint list. Production planner provides a weekly constraint list to factory planner based on his anticipated stock values for the coming week to constraint the factory planner weekly production schedule (WPS) values for next week.

4) The constraints set in step 3 are sent to the commercial planner as a reference for next weeks order placement.

5) Weekly order placement. Commercial planner places finished goods order every week for next 18 weeks among which 1-week order is confirmed while 17-weeks are tentative, considering the constraints provided by the production planner.

6) Weekly production schedule. Factory planner converts the orders placed by the commercial planner in step 5 into confirmed WPS for next week and tentative WPS for week following next week. Hence the confirmed order for next week serves as the basis for WPS and Shipment Plan (with a 2 days lead to WPS) at finished goods level for production planner.

Production planner takes into account the next week WPS, first two days order of the following week for assembly plant and weekly satellite factories requirement to develop the daily production plan for different production stages in the factory. He has to do some production leveling on his experience to match demand with capacity while ensuring on-time deliveries. He considers the leveled finished goods requirements, quoted lead-times of upstream stages, and individual stages work-in-process and finished inventory levels to develop the daily production plan for all the stages excluding ST. The entire demand management process flow is depicted in figure 1-4.

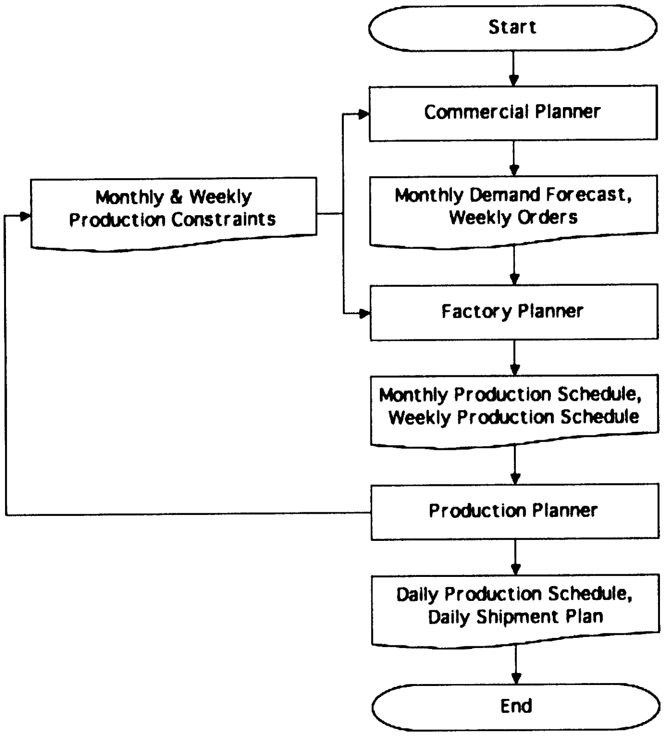

Figure 1-4: Demand management process flow chart

During the high demand season, the production requirements are decoupled from the shipment schedules because the factory builds up stock for the high runners towards the end low demand season. Production planner usually tends to run larger lots of every model in sequence 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 six steps described above.

1.4.2 Semi Knocked Down (SKD) parts demand management

This factory also supplies some Semi Knocked down (SKD) parts (some components that are added at R&S stage and procured from suppliers and SP work-in-process) to satellite factories in Europe and China. A manager responsible for managing SKD demand 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 production planner so that he can plan accordingly.

CHAPTER TWO: PROBLEM STATEMENT

This chapter describes the main problems unveiled about the current PDA production system and objectives of our project.

2.1 Demand seasonality and stock building

PDA Singapore experiences peak demand around the third quarter of each year during July to October, when assembly plant and satellite factories in anticipation of the Christmas sale, place advanced orders. This demand is higher than the effective capacity of the factory. The low season starts from November, and continues through January to June in the following year. The factory plans 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 it 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 Singapore factory capacity alone cannot cope with the demand.

The stock building plan is of paramount importance as the production requirements are extracted from it during the production ramp-up period rather than the daily shipment requirements. The capacity of the last production stage is examined to determine if the monthly demands, as projected in Monthly Production Schedules serving as shipment plans, can be satisfied with monthly production. Any excess demand is shifted backwards to earlier months. These adjusted demand values for the last stage in earlier months 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 would serve as the input source for us to perform production requirements seasonality and characteristics analysis and calculations.

However, this stock building practice only ensures the satisfaction of the demand, without taking into account 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 SKUs and it would be the job of production planner to stock high runner variants based on these monthly target. A more efficient and accurate way of making a stock building plan may need to be explored. It is known that a student from senior batch of MEng in Manufacturing program solved this problem but management couldn't pursue the implementation as the person mentoring and supervising the student, left the company and the spreadsheet that had embedded logic of proposed linear program is not available anymore.

2.2 Production control

The daily production planning carried out by the production planner serves as the benchmark for production stages during rest of the week. It is found that this plan only controls five out of the seven production stages in the factory, namely HE, DC, AC (same for PA), SG (for sole plates only) and R&S while ST department supervisor has to control production based on his judgment of the upstream work-in-process level, stock level and the capacity. Production planner conducts a daily meeting with the production supervisors to follow up on production targets and shipments. This process is shown in Figure 2-1 where the block horizontal arrows represents the material flow, the line arrows represents the planning signal sent from production planner to the individual departments, and the self-directed arrow represents self-planning of ST department.

The current production control mechanism results in problems such as unnecessarily high inter-stage WIP levels and stock-outs between stages. Moreover it does not provide ST stage any production plan, which leaves the whole production decision of this station to subjective human judgments, and often results in unreasonable ST inventory structure and varying inter-stage customer service level. The process involves a great deal of human interaction that leads to arguments and confusion during the actual production.

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

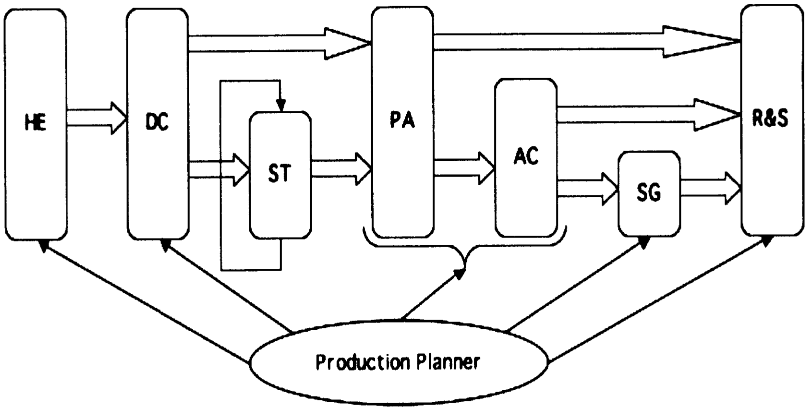

Figure 2-1: Current production control mechanism

2.3 Production scheduling and inventory control

This production system has a mix of dedicated and shared resources as already explained in the production process flow description in 1.3. Moreover the large SP variety with distinct process requirements adds to the complexity. The resource sharing observed in this system can be characterized in two forms; the first form is that one single production line is shared by more than one downstream production line for instance; ST is a single line and supplies to five PA lines and requires changeovers. The second form is that multiple SPs from same product family share one dedicated resource that also requires changeovers. These shared resources are subjected to simultaneous demand of multiple SPs that needs to be processed on downstream resources. The aggregate downstream requirements can be more or less than the resource capacity and thus it causes delays in first case and overproduction in later as supervisor's performance is judged on resource utilization.

The supervisors tend to follow the shipment plan finalized in the morning meeting, which is conducted to monitor the finished goods level and expedite production to meet the targets. Supervisors schedule their production relying on their experience resulting in unsynchronized schedules of individual stages. If there is a 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 to maximize the machine utilization, even if the downstream lines do not require those SPs and thus causing over production resulting in unnecessary inventories and deviations from the original production plan. Furthermore uncertain work-in-process levels and unsynchronized schedules can cause either the deviation of downstream stages from their plans and schedules or over production. As all the supervisors adapt this practice, it causes abnormal day-to-day non-uniformity of the work-in-process levels and the production stage lead-times for the released materials. The production stage lead-times are assumed as 1 day for planning purpose without any consideration of the interplay between demand variations and capacity. It can be concluded that discrepancy between planning assumptions and actual production practice leads to huge wastes and confusion in operation.

The careful investigation of all this leads us to the conclusion that this erratic system behavior is the result of unsynchronized production execution and inventory control between production stages. Hence, a production planning and inventory control approach is needed to control the inventory levels along the line. This approach should also help individual production stages to set sound production targets within their capacity constraints.

2.4 Project motivation

The production system at PDA 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 machines, 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, our internship team was divided into two groups each comprising of two students. Each group will focus on distinct parts of the PDA production system. For Xiaoyu Zhou [1] and author of this thesis, the focus is on the PA, AC, SG and R&S stages; while second group (i.e. Youqun Dong [2] and Yuan Zhong [3]) is working on upstream production stage i.e. ST.

AC is a single-flow line shared by all SPs that need to go through this process. The sharing of the line causes changeovers that usually take more than half an hour and make up a significant capacity loss. Since AC is a chemical coating process, various SP variants can be processed together based on their coating requirements. This allows AC supervisor to utilize the opportunity and schedule the production so that changeover time loss is minimum. AC is subjected to supply two R&S lines and serves as a final process for some dry iron SPs, and thus faces simultaneous demand from downstream, which is a challenging task to deal with. As already described in the problem statement part, production execution and inventory control is based on supervisor's judgment and thus causes problems like over-production and downstream line starvation.

PA and R&S are two similar processes and the SP flow between them can be characterized as 'Direct Flow' and 'Routed Flow' based on the SP process requirements. Some PA and R&S lines have a direct flow of SPs between them and have close production rates. It provides an opportunity to couple PA with R&S that means simultaneous production of same SP on the coupled-line. It will enable supervisor to easily schedule production of different SPs and higher work-in-process between the two lines can be avoided. Routed flow, which is through AC and SG, can be controlled by keeping stock of SPs between production stages to meet simultaneous downstream requirements and suitable inventory control approach needs to be proposed.

2.4 Project objectives

The main objective of this thesis is to develop an adequate production planning and inventory control framework for the PDA 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 inter-stage and customer service level. The results from inventory control policy should be verified through reliable means such as simulation and implementation.

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 to facilitate implementation of the proposed solutions.

4. Propose an approach to integrate shipment planning with the proposed inventory control policy with consideration of capacity and stock constraints.

The overall objectives resulted in some collaborative as well as individual work for group members. The proposal of inventory control policy and the design of visual management system is completed in collaboration with Xiaoyu Zhou [1], Youqun Dong [2] and Yuan Zhong [3]. The author of this thesis has individual focus on the verification inventory control policy results and an investigation of the effects of stock-outs on inventory levels. Moreover, the author has also proposed an approach and implemented in a spreadsheet interface for integration of shipment planning activity with proposed solutions. Xiaoyu Zhou [1] has focused on production leveling to reduce stock levels. Youqun Dong [2] has proposed a modified approach for long-term capacity planning and Yuan Zhong [3] has proposed the use of statistical analysis using ANOVA for demand seasonality.

CHAPTER THREE: LITERATURE REVIEW

This chapter comprises of theoretical background of basic concepts related to manufacturing systems and inventory control policies that will make the basis for problem analysis and calculations procedure.

3.1 Manufacturing 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 generally three typical ways of realizing pull production in a factory, namely:

(1) Supermarket pull system
(2) Sequential pull system
(3) Mixed supermarket and sequential pull system [6]

In a 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 the 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: 1-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 implement lean concepts in this factory, one of the most important topics is the implementation of a right inventory control policy. There has been extensive work done regarding inventory control policies. MIT lecture material of course 15.763 [7] introduces two basic inventory control policies for stochastic demand in general, one is continuous review policy (Q-R policy) and the other is periodic review policy (base stock policy).

3.2.1 Q-R policy

The main concept for this 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.

Reorder Point R,

$$R = \square L + z\sigma L^{1/2} = \text{expected lead} - \text{time demand} + \text{safety stock}$$

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

$$E[I] = \frac{E[I^-] + E[I^+]}{2} = \frac{Q}{2} + z\sigma L^{1/2} = \text{cycle stock} + \text{safety stock}$$

Q: Re-order quantity

$\square$: Demand rate

r: Review period in days

z: Safety factor

σ : 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 fixed 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,

$$B=\theta(r+L)+z\sigma(r+L)^{1/2}$$

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

$$E[I]=\frac{E\left[I(r+L^{-})\right]+E\left[I(r+L^{+})\right]}{2}=\frac{\theta r}{2}+z\sigma(r+L)^{1/2}=\text{cycle stock}+\text{safety stock}$$

Where the parameters are same as in Q-R policy except ‘r’ is the fixed review period.

3.2.3 Limitations of the conventional inventory control policies

The Q-R policy is suitable for dedicated resources whereas the production system studied in this thesis has production resources that are shared by multiple downstream resources. This can cause simultaneous replenishment signals from downstream resources 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.

3.2.4 Base-stock policy for multi-item line

Base-stock model proposed by Dr. Stephen Graves [8] deals with the limitations of conventional base-stocky policy for shared resources. 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

$$n=(k^2\sigma^2 \square \chi^2)/2\chi^2$$

k: Parameter associated with customer service level

σ: Aggregate standard deviation of demand

χ: Excess capacity relative to aggregate average demand

b) Daily aggregate production target

$$P_t \square \frac{W_t}{n} \square \frac{D_t}{n} \square \frac{\square n-1 \square P_{t-1}}{n}$$

t: Time period index (Day)

P: Daily production quantity

D: Daily demand quantity

W: WIP at the production stage

The daily production target for individual products can simply be expressed as,

$$P_{it} = \frac{W_{it}}{n}$$

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

$$R_{it} \square D_{it}$$

R: Material release quantity

d) Base-Stock for individual model

$$B_i \square E\square W_{it}\square\square E\square 1_{it}\square\square n\square_i \square k\left[n\sigma_i / \square 2n - 1\square^{1/2}\right]$$

$\square_i$: Average demand of item i

σ_i : Standard deviation of demand of item i

3.3 Visual management

Swain [9] defined visual management as “a method of creating an information-rich environment by the use of visually stimulating signals, symbols and objects”. In actual implementation, visual management could take the form of signs, lights, notice board, painted equipment and graphic displays. Whatever the form is, it serves the ultimate purpose of drawing people's attention and communicating important information during operation [9].

In lean manufacturing, the goal of visual management is simply generating meaningful signals, and facilitates 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 process. 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 FOUR: METHODOLOGY

4.1 Project Roadmap

As shown in Figure 4-1, the project roadmap shows the sequence of stages as with the specific activities involved at those stages. Rectangles represent project stages and ovals represent detailed activities of corresponding project stages, and the arrows represent the sequence.

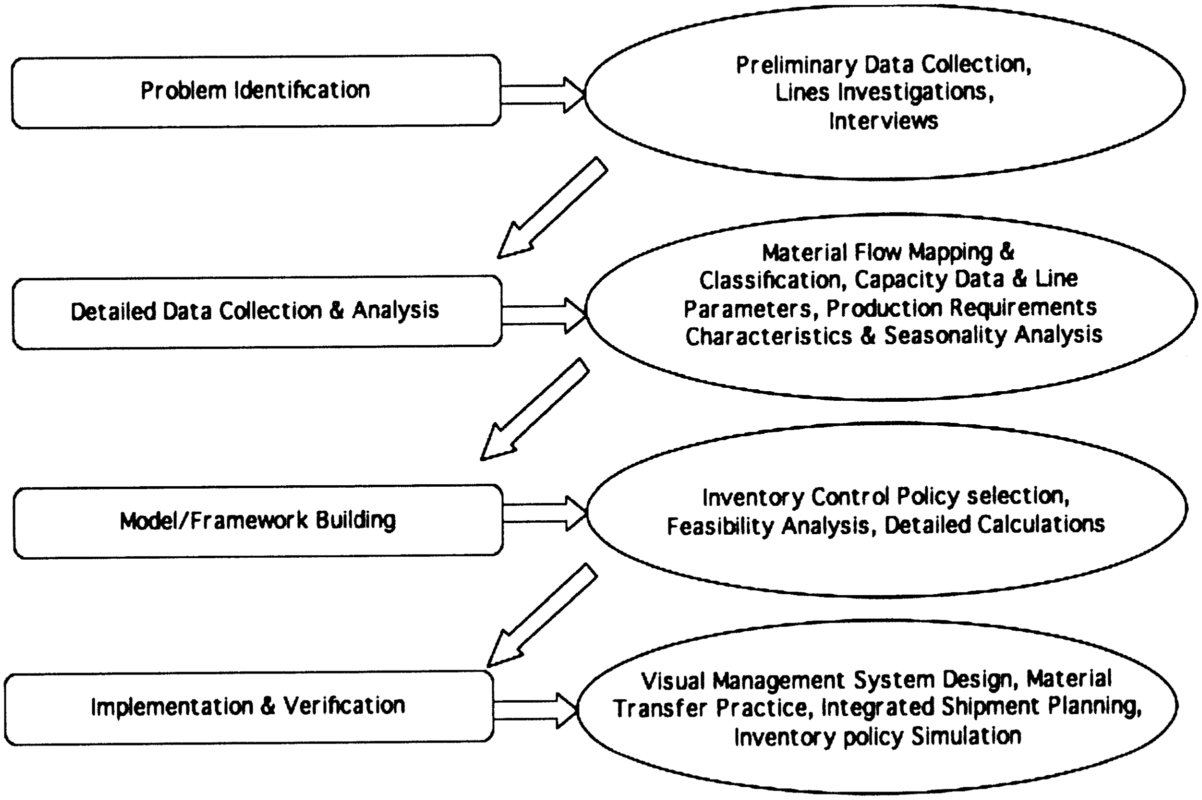

Figure 4-1: Project roadmap

4.2 Problem identification

We started the project work with the problem identification stage. We were initially briefed on what the management was intending to achieve in the future and we focused in depth on the production floor issues that were the biggest potential obstacles. We went on to understand the production process of the SP assemblies at PDA and conducted interviews with the production planner and supervisors. It helped us in identifying the issues that these people were facing. We looked at the inventory profiles from history and collected some real time data for comparison. The major issues identified have already been discussed in details in chapter 2.

4.3 Detailed data collection and analysis

Data relevant to the project was differentiated into two categories, structural data and quantitative data. Structural data includes material flow mapping, product categories, factory layout, and the value stream map of the factory. Quantitative data includes line performance parameters, historical demand data, demand forecast data and planned production data.

4.3.1 Production requirements seasonality analysis

As mentioned in 1.1, there are two product categories of this factory, dry iron SPs and steam iron SPs. Dry iron demand makes up about 30% where as steam irons demand is about 70% of the total annual demand. Since steam irons are mostly sold in America and Europe, Christmas have heavy impacts on the demand of steam irons SP product, which forms a distinct high demand pattern every year. Dry irons are sold mostly where the holiday effect is not so influential, so the demand for dry iron SPs is stable and consistent throughout the year comparatively.

As explained in section 2.1, PDA employs a stock building policy to cater this high demand peak during 3rd quarter of every year. The stock is build up in two forms, work-in-process at the bottleneck production stages and finished goods. The two product classes shares some production lines such as HE, DC and AC so their aggregate demand was taken into consideration for analysis. Moreover, the current year was an exception because some productions lines were to be shifted to another location during 3rd quarter of year. This required PDA to shut down the production lines and start stocking comparatively earlier.

This project work proposes implementation of a base-stock policy, as explained in section 4.5, to establish inventory levels between the production stages as a solution to the problems explained in Chapter 2. These inventory levels are much dependent on the demand characteristics. Since the finished goods demand at PDA has a pattern that suggests seasonality, PDA production contains the requirements with some seasonality as well. The seasonality of the production requirements should be identified as a combination of seasons with distinct characteristics so that corresponding inventory levels can be established for each production season. It will also provide PDA management an insight into the change of inventory requirements during a transition from one season to another and they can make operational decisions accordingly.

Analysis of Variance (ANOVA) is a statistical procedure based on hypothesis testing that quantifies the significance of group means difference. ANOVA was used to investigate the production requirements seasonality. Since stock building plan has monthly planned values, they can be plotted on time axis and eyeballing of the curve can give an intuition about the production seasons as expected for the current year. The approach was to compare various monthly groupings to form seasons and perform ANOVA. The grouping combination with highest mean difference significance as suggested by highest 'F' and lowest 'P' value in ANOVA table was selected.

4.3.2 Production requirements characteristics analysis

Once the production seasonality analysis identified the distinct production seasons, the daily production requirements characteristics i.e. mean and standard deviation were calculated for all SKUs in respective seasons. The source data of this data is the stock building plan as it is the best available estimate of planned production figures in current year. Since this plan is developed in previous year's December, it has aggregate planned weekly values on product family (and some models) basis. As already described in section 1.1, product models have various SKUs (final goods form of SPs). These model SKUs can have similar manufacturing sequence and are processed on same production resources but they can have distinct process requirements usually at later production stages resulting in different work-in-process. The following procedure was used to prepare demand data for analysis and calculations on SKU level for a particular season.

The first assumption is that the total annual demand of any SKU will not differ much from previous year to current year. Suitable estimates are made if there is any substitute product introduction or a product is terminated. The shipment data from previous year was analyzed for thus purpose and the SKU(s) demand contribution were estimated using the following formula,

$$\text{SKU Demand Contribution} = \frac{\text{Sum of SKU Shipments in year 2008}}{\text{Sum of all SKUs shipments in year 2008}}$$

It is to be noted that solution approach in this thesis is to deal with high runner SKUs production and controlling their work-in-process while providing room for low runner SKUs production control with existing approach because high runners SKUs chosen with the help of production planner, accounts for 97~98% of PDA production and thus it is appropriate to plan inventories for them only. Hence it required estimating requirement characteristics of individual high runner SKUs where as an aggregated estimate for low runner SKUs was needed. The following formula was used to extract the planned aggregate production requirements for high runner SKUs from given planned production requirements for product family (or model) on weekly level.

$$\text{High-Runner SKUs Planned AggregateWeekly Production Quantity} = \text{Sum of Family/Model High-Runner SKUs Demand Contribution} \times \text{Family/Model Planned Aggregate Weekly Production Quantity}$$

This high runner SKUs planned aggregate weekly production quantity can be divided into individual high runner SKU planned weekly production quantity(s) using the following formula,

$$\text{SKU Planned Weekly Production Quantity} = \frac{\text{SKU Demand Contribution}}{\text{Sum of Family/Model High-Runner SKUs Demand Contribution}} \times \text{High-Runner SKUs Planned AggregateWeekly Production Quantity}$$

Now the individual SKU requirements mean in the particular season can be determined as follows,

$$\text{SKU Daily Mean } (\square_{SKU}) = \frac{\text{Sum of SKU Planned Weekly Production Quantity in Season}}{\text{Total Production Days in Season}}$$

The daily production requirements are assumed to be independent and identically distributed (IID) thus aggregate weekly requirements standard deviation of high runner SKUs can be transformed to daily standard deviation using the following formula, Family/Model High-Runner SKUs Aggregate Daily Standard Deviation (σ_A) =

$$\frac{\text{Standard Deviation of High-Runner SKUs Planned Aggregate Weekly Production Quantity in Season}}{\sqrt{\text{Production Days in a Week for particular Season}}}$$

Since this estimate would be a pooled estimated of individual high runner SKUs, individual SKU's daily requirements standard deviation was needed and the production requirements of individual SKUs were assumed as independent and identically distributed. It suggests that the sum of variance of 'N' individual SKUs should be equal to aggregate variance i.e.,

$$\sigma_A^2 = \sigma_{SKU-1}^2 + \sigma_{SKU-2}^2 + \ldots\ldots\ldots + \sigma_{SKU-N}^2$$

Since the individual SKU means are different within family (or model) because of different demand contribution factors, assuming same standard deviation would not be proper because the SKU means can differ by magnitudes of scale. Assuming a same coefficient of variance within family (or model) sounds suitable and the calculations proceed as follows,

$$\sigma_A^2 = (CV_{SKU-1} \text{ x } \mu_{SKU-1})^2 + (CV_{SKU-2} \text{ x } \mu_{SKU-2})^2 + \ldots\ldots\ldots + (CV_{SKU-N} \text{ x } \mu_{SKU-N})^2$$

$$CV_{Family/Model} = CV_{SKU-1} = CV_{SKU-2} = \ldots\ldots\ldots = CV_{SKU-N}$$

$$\sigma_A^2 = CV_{Family/Model}^2(\mu_{SKU-1}^2 + \mu_{SKU-2}^2 + \ldots\ldots\ldots + \mu_{SKU-N}^2)$$

$$CV_{Family/Model} = \sqrt{\frac{\sigma_A^2}{(\mu_{SKU-1}^2 + \mu_{SKU-2}^2 + \ldots\ldots\ldots + \mu_{SKU-N}^2)}}$$

This common coefficient of variance along with individual SKU daily means can compute the individual SKU daily standard deviation using the following formula,

$$\sigma_{SKU} = CV_{Family/Model} \text{ x } \mu_{SKU}$$

4.4 Sole plate flow classification

Xiaoyu Zhou [1] and the author were assigned the work to deal with problems in the last four downstream stages i.e. Part A (PA), Auto Coat (AC), Sol Gel (SG) and Riveting & Sealing (R&S) in the production of sole plates (S). The problem identification section has covered in details our judgment of the problems with production and inventory control in general. This section will explain the approach of classifying the SP flow on production floor and form the basis of proposed solutions for two flow classes.

Figure 4-2 depicts the actual SPs flow within the last four production stages i.e. PA, AC, SG and R&S. Part-A (PA) stage has six SKU family specific production lines that are given the names as shown. For instance, PA-Dry is the dedicated line for dry SP processing. PA-PL/S can process SP for Basic and System families but System SPs can also be processed on PA-M, which is a manual line. AC is a single coating line and SG is a special coating line for Iron Plates (IP) and some SPs. Riveting & Sealing (R&S) stage has four SKU family-specific production lines and is usually the end process for most of SPs. All these lines are shared either by SPs of one or multiple SKU families depending upon the processing requirements and production line flexibility. A double arrow in the figure 4-4 represents multiple SP (either belonging to one family or more) flow from a production stage to another where as a single arrow represents family-specific IP flow from SG to corresponding dedicated R&S line.

Our task was to solve problems related to SP flow because IP flow from SG is controlled through a Kanban based inventory supermarket. SP flow in Figure 4-4 can be classified into two classes, and we named them as Direct Flow and Routed Flow. Although the two flow classes are different but the proposed solutions share some part in both situations. Later sections discuss the features of the two flow classes, potential differences in flow conditions and guidelines for solution.

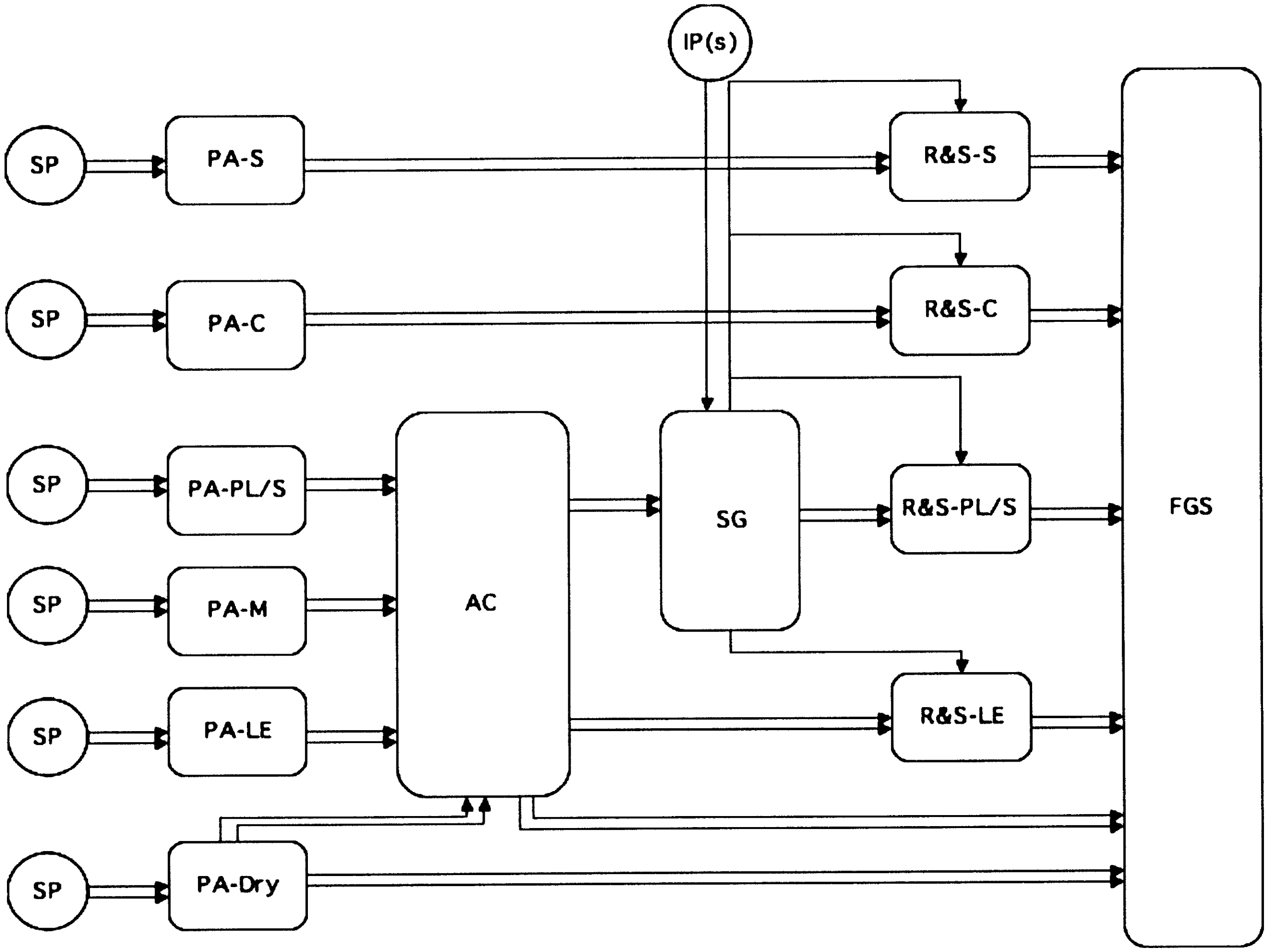

Figure 4-2: Stage specific SP flow

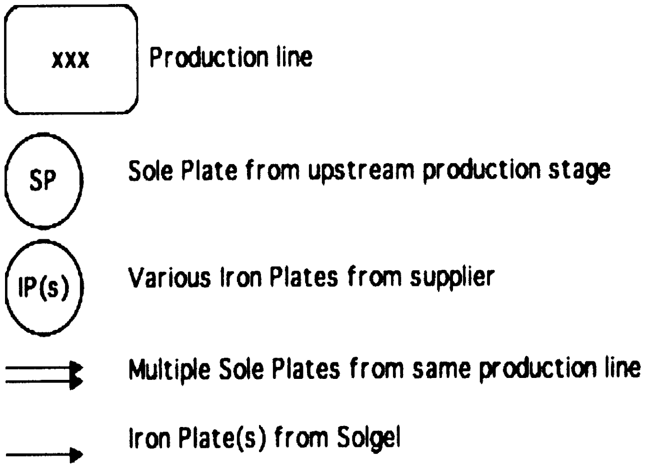

Figure 4-4: Legend for figure 4-2

4.4.1 Direct flow

A glimpse over figure 4-2 will identify a kind of flow, which appears direct between PA and R&S production stages and is named as 'Direct Flow' in this thesis and can be schematically drawn as in figure 4-3. It can be observed between PA-S to R&S-S and PA-C to R&S-C representing flow of Superior and Complete family SP flows respectively, which don't require any coating process neither at AC nor SG. Although there can be a simultaneous demand of more than one SPs that are processed on these lines, they operate on the same production schedule. For instance Azur 44I, Azur 44NI, Azur 46I and Azur 46NI are high runner SPs and are shipped to assembly plant on daily basis but their production sequence on PA-S and R&S-S can be kept similar since these lines can operate on single SKU configuration at a time. Moreover there are some SPs that are differentiated only at the R&S stage and thus shares work-in-process with other SKU SPs between these lines. The only difference between PA-S to R&S-S lines and PA-C to R&S-C lines is the capacity balance. PA-S is slower than R&S-S where as PA-C runs at equal pace with R&S-C.

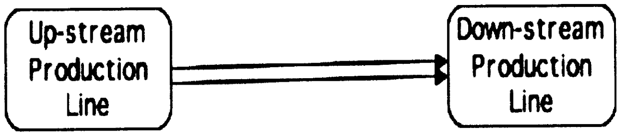

Figure 4-3: Direct flow of multiple SPs between two production lines

4.4.2 Routed flow

Further observation of figure 4-2 reveals another kind of SP flow on the production floor and is named here as 'Routed Flow', schematically depicted in figure 4-3. This kind of flow can be observed between various production stages for instance, SPs routed from multiple PA lines to AC and later directed either towards respective R&S lines or SG. There can be situations when multiple SPs demands are received from downstream production stages and there is a possibility of their starvation because the upstream production stage doesn't have work-in-process and is busy in processing other SPs or serving other lines. There are other issues as yield at SG and SP running sequence constraints that restricts processing of SP quantities lesser than certain batch sizes. It is impossible to run such shared lines on downstream production schedules and simultaneous requirements must be met for smooth operation.

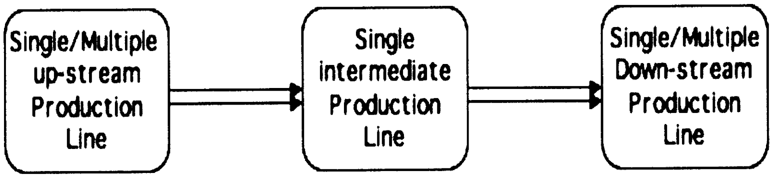

Figure 4-3: Routed flow of multiple SPs

4.5 Model building

A common model is proposed for controlling inventories of production stages in routed flow and with slight modification for production stages in direct flow. The model is first introduced and parameters are explained followed by explanation of control structure for routed flow (chain of production stages) and direct flow (coupled-line). Sub-sections will also cover explanation of capacity reserved for low-runner SKU SPs and a calculation procedure named as 'requirements pooling.

4.5.1 Model introduction

Dr. Stephen Graves [8] proposed a base-stock policy in, which is proposed for all production stages except Part A with direct flow. This policy specifies control rules and calculation of the inventory levels for each product manufactured on the same multi-item line.

Although this policy is able to govern multi-item lines and can be extended to multi-stage manufacturing system, one production stage that processes multiple products under this policy is chosen to explain how it works. Here is the list of important parameters that is used for the calculation:

- D: Demand
- R: Release of raw material
- P: Production quantity
- B: Base-stock level
- C: Line capacity

- W: Intra-stage inventory (inventory for raw material for the stage)
- I: Inter-stage inventory (finished goods inventory for the stage)
- t: Time period index
- i: Individual model
- n: Planned lead time
- χ : Excess capacity that is normally available at the production stage
- $\square$: Average aggregate demand
- σ: Aggregate standard deviation of demand
- k : Safety factor

I_t and W_t are aggregate inter-stage and aggregate intra-stage inventory; they can also be translated as finished goods inventory and raw material inventory at certain production stage. P_t and R_t are aggregate production and aggregate release quantities. Similarly the variables I_{it}, W_{it}, P_{it}, R_{it} are entities for individual model quantities. 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.

1) The balance equations for aggregated entities are:

$$W_t \square W_{t-1} \square R_t - P_{t-1} \qquad \text{Eq. 4-1}$$

$$I_t \square I_{t-1} \square P_{t-1} - D_t \qquad \text{Eq. 4-2}$$

The release rule is:

$$R_t = D_t \qquad \text{Eq. 4-3}$$

2) Eq. 4-1 to 4-3 can be easily extended to individual product types:

$$W_{it} \square W_{it-1} \square R_{it} - P_{it-1} \qquad \text{Eq. 4-4}$$

$$I_{it} \square I_{it-1} \square P_{it-1} - D_{it} \qquad \text{Eq. 4-5}$$

The release rule then becomes:

$$R_{it} \square D_{it} \qquad \text{Eq. 4-6}$$

3) χ and n are calculated by:

$$\chi \square C - \square \qquad \text{Eq. 4-7}$$

$$n=\square k^2\sigma^2 \square \chi^2 \square / 2\chi^2 \qquad \text{Eq. 4-8}$$

Assumption:

$$\chi \leq k\sigma$$

Otherwise n=1.

4) The production decision for individual model ‘i’ is given by:

$$P_{it} \square \frac{W_{it}}{n} \qquad \text{Eq. 4-9}$$

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

$$B_i \square E\square W_{it}\square\square E\square I_{it}\square\square n\square_i \square k\left[n\sigma_i / \square 2n-1\square^{1/2}\right] \qquad \text{Eq. 4-10}$$

For later calculation, E[W_{it}] and E[I_{it}] will be obtained for every high-runner SKU SPs at each production stage with consideration of reasonable requirements pooling.

4.5.2 Model control structure for routed flow

The base-stock inventory control approach described in previous section is adopted for all the involved production stages in routed flow i.e. PA, AC, SG and R&S and is schematically drawn in figure 4-4 to show the inventory control structure of production stages chain operation. A production stage is represented by a rectangle with two triangles inside representing intra-stage and inter-stage inventory across a machine represented by a circle. ‘D’ represents the aggregate demand of all the products and ‘R’ is the aggregate release quantities between two consecutive production stages. ‘P_i’ represents the aggregate production targets as set by linear production rule at stage ‘i’.

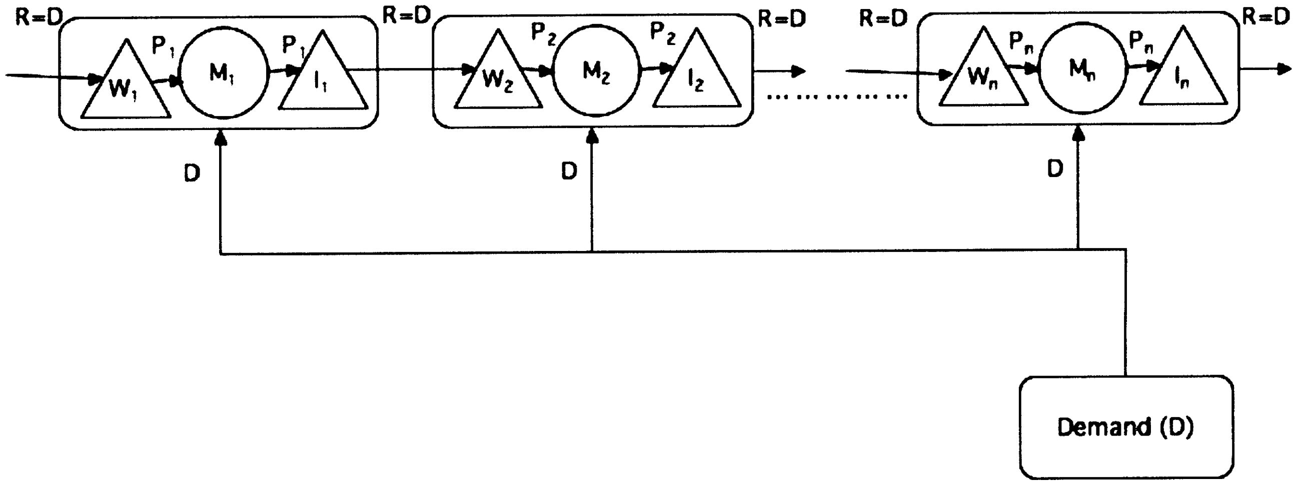

Figure 4-4: Base-stock multi-stage control structure

4.5.3 Model control structure for direct flow

The control structure for direct flow class of SP is a fusion of two approaches i.e. described base-stock policy applied across a ‘coupled-line’. The concept of a coupled-line is introduced specifically for direct flow and the idea avails the similar SP production schedules on involved lines as an opportunity. Since the involved lines can operate on one SP at a time, there are no simultaneous production requirements between them. It doesn’t mean that the coupled-line will be dedicated to one SKU only but it represents the fact that the two production stages coupled as a line would be dedicated to production of a single SP at a time and would switch to produce other SP once the production requirements of first are met. Coupled-line will employ a coupling stock (CS) between two lines and is calculated using the following formula, which is determined analytically (Refer to Appendix-B for the derivation of formula).

$$CS \square \frac{[CT_1 \square (T-1)\mathrm{x}UT_1]\mathrm{x}UT_2 \square [P_{\max}\mathrm{x}UT_2 - CT_1 - (T-1)\mathrm{x}UT_1]\mathrm{x}(UT_1 - UT_2)}{(UT_2)^2}$$

Where,

P_{max} = Maximum batch size
UT_1 □ Unit time of upstream line
UT_2 = Unit time of downstreage line
CT_1 = Cycle time of upstream line
CT_2 = Cycle time of downstream line
T= Container size

'Unit time' for downstream line can be defined as the time interval between two consecutive parts being loaded on it where as for upstream line it can be defined as the time interval between two successive parts being taken off from it. 'Cycle time' has the meaning of 'total time a part spent on the entire line'.

This coupling stock would enable the two lines to start production together and will prevent downstream line starving throughout production for a maximum batch size 'P_{max}', discussed in section 4.4.1. Base-stock policy is applied across this coupled-line to integrate it as a single production stage in the entire production stages chain. The effective capacity and lead time 'n' is considered to be the downstream line capacity as it would be responsible for meeting its downstream. This point is further discussed in section 4.5.3.2. The schematic inventory control structure for direct flow is illustrated in figure 4-5. 'D' is the demand for a particular SP to be processed on the coupled-line, 'R' is the released work-in-process from upstream of coupled-line and 'P' is the set production target for this SP.

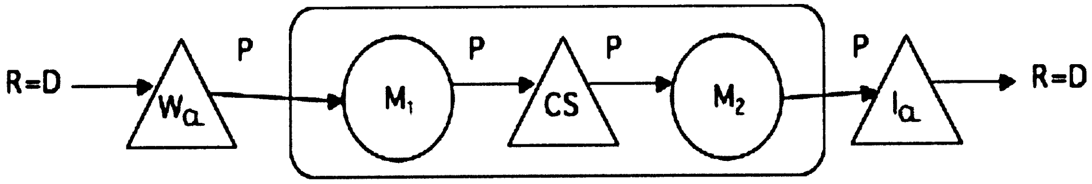

Figure 4-5: Base-stock across coupled-line

The changeover times for R&S lines i.e. the downstream lines in coupled-lines are usually more than the upstream PA lines. This enables the PA lines to replenish the consumed coupling stock before the line is setup for next SKU production.

4.5.3.1 Batch size consideration

Since the line-coupling concept may be applied over a combination of production lines with difference in capacities and production rates for instance downstream line can be faster than upstream line, production targets should not exceed a certain maximum value beyond which the coupling-stock will be exhausted and the downstream line would need to wait until the upstream line replenishes the stock. Hence it is required to set the coupling-stock value that will prevent disruptions in production up to a maximum batch size, which is higher enough to enable the coupled-line to deliver a desired service level. The maximum batch size 'P_{max}' that can be produced on the coupled-line at a stretch is determined to make it consistent with the service level that base-stock policy tends to ensure across the coupled-line. According to the base-stock policy in [5], expected production value of a production stage is the expected demand value over a certain time period i.e.,

$$E[P] \square \square_P \square \square_D$$

Standard deviation of the production values is related to standard deviation of the demand through following formula,

$$\sigma_P \square \frac{\sigma_D}{\sqrt{2n-1}}$$

Where 'n' is the lead-time for downstream production stage in coupled-line.. The maximum production batch size can be calculated to ensure a service level 'k' using following formula,

$$\mathrm{P}_{\max} = \square_P \square k\sigma_P$$

It can be expressed in terms of demand parameters as under,

$$\mathrm{P}_{\max} = \square_D \square \frac{k\sigma_D}{\sqrt{2n-1}}$$

P_{max} represents the maximum batch size for which the coupling-stock would last without any disruptions in supply between the two lines. Hence the two lines, even with a difference in production rates can start production together. The coupled stock would be replenished and consumed simultaneously and eventually reach its original value after the downstream line has consumed the required numbers of SPs while upstream line is replenishing the stock. This time difference can be used in the changeover of downstream line, which in this case (R&S stage) usually takes longer as compared to the changeover of upstream line (PA stage).

4.5.3.2 Coupled-line steady state

For the unbalanced coupled-line, it can be suspected that the capacity value used to calculate intra-stage and inter-stage inventory levels and coupled-line lead-time, as the downstream production line capacity is not appropriate. This suspicion holds significance if the planned production value for a day is greater than the daily capacity of upstream line (bottleneck production line) in coupled-line. Hence the coupled-line will not stay in steady state once the planned productions quantities are committed in excess to the bottleneck capacity. Therefore it needs to be ensured that such a scenario is never realized. This issue is addressed through 'capacitated shipment planning' approach and is discussed in section 4.7.2 this thesis.

The reason for using downstream production line capacity as the coupled-line capacity is the downstream requirements fulfillment through its production. The coupling stock in the coupled-line serves as a virtual addition to the upstream line capacity and the actual unbalanced coupled-line acts as balanced within certain limits i.e. up to a point (P_{max}) where a maximum demand corresponding to a certain service level can be fulfilled as explained in section 4.5.3.1.

4.5.4 Requirements pooling

It is known that some SKUs share work-in-process inventory at certain production stages i.e. the production stage processing doesn't differentiate the SP as for a particular SKU. At these shared production stages, downstream requirements of such SPs can be pooled to establish inventory levels. The pooling effect reduces the inventory levels and serves as 'risk pooling' of downstream requirements. This can be explained mathematically as follows.

Consider two production stages under base-stock control that are shared by two SKU SPs as depicted in figure 4-6. The upstream stage doesn't differentiate the two SPs, which are later differentiated at the downstream stage. If the two demands are assumed to be independent and identically distributed normal random variables i.e. $D_1 \sim N(\square_1, \sigma_1^2)$ and $D_2 \sim N(\square_2, \sigma_2^2)$. The pooled requirements for upstream production stage would be given by $D_T \sim N(\square_T \square \sigma_T^2)$ where $\square_T \square \square_1 \square \square_2$ and $\sigma_T^2 \square \sigma_1^2 \square \sigma_2^2$ by normal random variables definition.

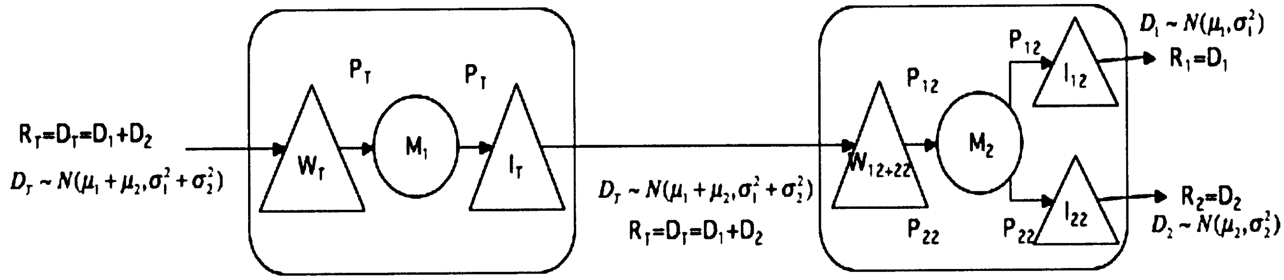

Figure 4-6: Requirements pooling of two SKU SPs on upstream stage

Another form of pooling at a production stage is the aggregation of production requirements characteristics of all the SKU SPs, regardless of their family/model type, passing through a production stage. Aggregate daily mean and aggregate daily standard deviation of the production requirements are required as input parameter for inventory calculations at each stage and can be obtained in a similar way as explained above. At a production stage, aggregate daily mean is the sum of all individual production requirements means and aggregate standard deviation is the square root of sum of squares of all individual production requirements standard deviations. It can be expressed mathematically for 'N' SKU SPs on a production stage as,

$$\square_{stage-Aggregate} \square \sum_{i}^{N} \square_{SKU-i}$$

$$\sigma_{stage-Aggregate} \square \sqrt{\sum_{i}^{N} \sigma_{SKU-i}^2}$$

4.5.5 Capacity considerations

It is decided that low runner SKUs production will be controlled by the existing method and room would be provided to accommodate them in parallel to the proposed base-stock control. Since low runners SKUs don't contribute much to the revenue as compared to high runner SKUs, it is preferable to meet the high runner SKUs requirements first. Therefore base-stock control is applied only for the high runner SKU SPs but low runners SKU SPs still need to be produced. Hence capacity values are modified to consider low runners demand and capacities are reserved at each production stage equal to the aggregate planned average production requirements of all low runner SKU SPs flowing through it. The following formula is used to extract low runner SKUs planned aggregate weekly production quantity from the stock building plan.

Low-Runner SKUs Planned AggregateWeekly Production Quantity = Sum of Family/Model Low-Runner SKUs Demand Contribution x
Planned Family/Model Planned Aggregate Weekly Production Quantity

Capacity at the final production stages i.e. usually R&S are reserved as the aggregate means for low-runners SKUs and is determined as,

$$\text{Low-Runner SKUs Aggregate Daily Mean } (\square_{LR}) = \frac{\text{Sum of Low-Runner SKUs Planned Aggregate Weekly Production Quantity in Season}}{\text{Total Production Days in Season}}$$

For upstream and intermediate production resources, same principle of requirements pooling as described in section 4.5.4, is used to reserve capacities for low runner SKUs but with a minor difference i.e. only the averages are added at upstream stages.

It should be noted that capacity figures obtained from manufacturing personnel are for 'effective capacity' and has considerations of minor line breakdowns, maintenance schedules, lunch & tea breaks and changeovers.

4.6 Model verification

It is observed that the inventory structure along the production lines is ever changing and the inventory levels are not appropriate to meet the requirements. At some stages they are higher when not needed whereas as at some stages, downstream lines are forced to deviate from production plans due to stock-outs. The inventory control policy proposed for this manufacturing system would ensure the placement of right stock quantities considering the requirements characteristics and capacity at production stages. However the inventory calculations for each stage are performed for a service level of 95%, i.e. stage is expected to meet the downstream requirements 95 out of 100 times on average. Since the stages are linked together through their inter-stage stocks (I) and the requirements are propagated simultaneously along the chain of production stages, a stock-out at any stage would result in base-stock level fluctuation of the immediate downstream stage. This can affect the performance of inventory policy and hence it should be verified that a chain of production stages, all controlled under same policy would deliver desired results and can be implemented as a viable solution to the problems stated in chapter 3. Coupling stock of a coupled-line with underline assumptions explained in section 4.5.3.1 about P_{max} and section 4.5.3.2 also needs to be validated.

4.6.1 Model simulation

Simulation was chosen as a tool to verify if the inventory control policy applied across the chain of production stages (with routed flow) would deliver desired results and investigate the effects of stock-out (and even simultaneous stock-outs) at any production stage(s) within the chain prior to the implementation. A simple simulation was also carried out to verify the service level ensured by coupling stock under P_{max} assumption. Moreover the operation of a coupled-line is explained with the help of a simple Excel based simulation graph, showing the simultaneous consumption and replenishment of coupling stock. Monte Carlo simulation was carried out on Crystal Ball software and specific models are explained in the sections following base-stock results for chain of production stages (routed flow) and coupled-lines (direct flow) to maintain consistency of discussion about results and their verification.

4.7 Implementation

This project was aimed at implementation of proposed solutions, which would eventually serve as an alternate mean of results verification and add value to PDA manufacturing operations. It was the implementation phase that brought practical challenges to our internship team because the manufacturing managers and supervisors were concerned about the feasibility of the proposed inventory control policy. The main challenge was to align the existing practice of material transfer between production stages and the integration of shipment planning to the proposed model. This phase involved team efforts and effective communication with the manufacturing personnel and resulted in the design of a Kanban based visual management system and the proposal of a capacitated shipment planning approach.

4.7.1 Visual management system design

Setting up the inventory levels and production control rules were not enough for the factory to run and test the proposed inventory control policy and the line workers required a simple operating system to carry out operations accordingly. A proposal was put forward about a Kanban based visual management system to run the chain of production stages under the proposed inventory control policy, which was refined with immense feedback from line supervisors and manufacturing managers. The operational procedure of running this system is given in Appendix-C. The following sub-section will discuss the issue related to material transfer practice and the solution.

4.7.1.1 Material transfer issue

The base-stock policy introduced in this thesis requires release of material to a production stage in exact proportion to the demand it incurs but controlling the material flow in a Kanban system requires a demand quantity to be a definite multiple of container size. Exact numbers can be simulated and use in calculations for inventory modeling but pre-implementation analysis identified some discrepancy in the material transfer activities between different production stages on the floor. There are various transfer-batch sizes used depending on the available trolley and container sizes. It is found that exact material transfer is operationally infeasible because of constraints associated with existing practice. Allowing the use of existing material transfer-batch sizes and rounded up material release values to meet the downstream requirements has some issues as explained below,

It would imply that every time the demand is incurred, more material will be pushed towards downstream stage that will eventually increase its base-stock by significant extent. Moreover, production targets are proportional to the intra-stage stock (W) of a production stage and may result in capacity violations with higher 'W' values. This scenario can be avoided by monitoring the excess transfer and considering it in the calculations for production targets and later material release quantities. It would require skills, more than that of a worker operating a simple Kanban system, such as computer literacy and will lose the basic aim of visual management.

It is known that shipments are made in standard pallet sizes and production planner tracks excess shipments. This fact in conjunction with a simple investigation of the current transfer batch sizes yields some opportunities for simpler solutions that are easy to implement and yet conserve the model accuracy. Table 4-1 lists down the current transfer batch and shipment pallet sizes between production stages covered in this project work. The cells with format 'xxx->xxx' represents the suggestion to change the existing transfer-batch size from quantity on the left of the arrow to the right, because PDA already has such trolleys/containers available and more trolleys/containers are ordered for new facility. The numbers are suggested so that they are factors of shipment pallet size and facilitate Kanban cards operation. This will enable standardized demand values and corresponding exact material transfer-batch size propagation along the production stages and conserve 'release quantity (R) equal to demand value (D)' requirement of the base-stock model.

Table 4-1: Material transfer-batch sizes

Family	SKU Name	DC/ST	PA	AC	SG	R&S	Shipment
Dry	Mirage Linish 230V	600	600	-	-	-	600
Dry	Mirage Linish 230V SKD	600	4224 -> 4200	-	-	-	4224 -> 4200
Dry	Mirage Coated 230V	600	200	4224 -> 4200	-	-	4224 -> 4200
Dry	Mirage Coated 230V SKD	600	200	4224 -> 4200	-	-	4224 ->4200

Dry	D13 (New) Linish	600	600	-	-	-	600
Dry	D13 (New) Coated	600	200	600	-	-	600
Dry	D13 Coated (New)-SKD Indonesia	600	200	4224 -> 4200	-	-	4224 -> 4200
Dry	NDI Coated (New) - (SKD) Indonesia	600	200	4224 -> 4200	-	-	4224-> 4200
Low End	Easy Speed - Linish (LE)	840 (ST)	200	-	-	160->150	600
Low End	Easy Speed - Coated (LE)	840 (ST)	200	200	-	160->150	600
Low End	Easy speed HE 230 PA	840 (ST)	200	200	-	-	600
Low End	Easy Speed - Gold Coated (HE)	840 (ST)	200	-	-	160->150	864
Low End	E3.3/5/6K (Sumber Terang) ST	840 (ST)	150	-	-	160	480
Complete	E3.3/5/6K (Sumber Terang) PT	840 (ST)	150	-	-	160	480
Complete	Powerlife Coated version - HV	840 (ST)	200	200	192->200	160->150	600
Basic	Powerlife SS	840 (ST)	200	200	192->200	160->150	600
Basic	Azur4400_Ionic	840 (ST)	150	-	-	160	480
Superior	Azur4400_Non Ionic	840 (ST)	150	-	-	160	480
Superior	Azur4600_Ionic	840 (ST)	150	-	-	160	480
Superior	Azur4600_Non Ionic	840 (ST)	150	-	-	160	480
System	Bangkok_Non SOS (SKD/B)	840 (ST)	200	200	192->160	72/144->160	480B/720SKD->480
System	Bangkok_SOS (SKD/B)	840 (ST)	200	200	192->160	72/144->160	480B/720SKD->480
System	Shanghai Successor (SKD/B)	840 (ST)	200	200	192->160	72/144->160	480B/720SKD->480

For example, a SKU named 'Powerlife Coated version – HV' is transferred from SG to R&S in trolleys of size 192, from R&S it is taken to curing station in trolleys of size 160 and later shipped in packed pallets of size 600. It was observed that the trolley used at SG stage could be slightly modified to accommodate 8 more SPs on its top and the concerned manufacturing manager approved the idea. Moreover the trolley of size 160 at R&S has compartments that could be blocked to alter its size to 150 as well as trolleys of size 150 that were already used by other stages could be used instead. These simple recommendations enabled to transfer material in batch sizes that are factors of the shipment size i.e. 600. Hence the requirements can be triggered from shipment towards upstream production stages in standard values and definite number of Kanban cards can be flipped on Kanban board to signal replenishment. Youqun Dong [2] and Yuan Zhong [3] have resolved material transfer batch size issue and discuss implementation of Kanban system at ST stages.

4.7.2 Capacitated shipment planning

It was explained in section 1.4.1 about demand management process that the production planner has to provide constraints to the factory planner and commercial planner, based on capacity and stock levels, to bind the confirmed order quantities for coming week. Already established lead-times of 1 day for each production stage are used and the weekly production requirements are translated into production plans for individual production stages. Production plan tends to closely follow shipment plan particularly in low-demand season when there is no stocking at any production stage. Since the proposed inventory control policy provided planned lead-times for production stages and establishes inventory levels, existing practice of meeting the shipment requirements was no longer applicable for high-runner SKUs. Although SKUs demand is characterized into seasons but non-stationary effects coupled with forecast errors can sometimes render the stock building policy results ineffective and thus a check over committed shipment quantities is desired to maintain adequate service levels for final assembly plant and satellite factories.

An integrated approach was required to align the shipment planning of high-runner SKUs with the proposed inventory control policy where as the low-runner SKUs can be controlled with existing planning practices. Since the production targets depend on the intra-stage stock (W) and the lead-time (n) of a production stage, this feature of the inventory policy plays vital role in planning daily shipment quantities.

The very upstream production stages i.e. HE and DC are not included in the work done by Youqun Dong [2] and Yuan Zhong [3], whose works have focused on ST production stage only and therefore to ensure that HE and DC are able to supply ST (and PA lines for dry irons SPs), their operating stocks and capacities should be taken into account when shipment planning is carried out. Moreover, a portion of HE and DC production for some SKUs is outsourced to external suppliers and production planner was missing an integrated framework that can enable planning within constraints jointly formed by in-house and outsourcing capacities.

4.7.2.1 Goals and features

An integrated shipment planning approach is developed and implemented in spreadsheet based interface that has the following goals and features as needed by production planner,

1) Assessment of planned daily SKU shipment values for their feasibility in terms of corresponding aggregate production targets comparison with capacity of individual production stages. The solution should integrate anticipated stock levels and planned lead-times maintained under base-stock inventory control policy at ST, PA, AC, SG and R&S production stages. This will also include constraining shipment values across coupled-lines considering the bottleneck capacity.

2) Integration of in-house, out-sourcing capacities with operating stocks of HE and DC production stages to ensure smooth supply to ST (and PA for dry irons SPs) production stage.

3) Provide production planner an insight about manually leveling the load on production stages during shipment planning by considering the capacity of individual production stages.

4.7.2.2 Capacity and stock constraints

The backbone of capacitated shipment planning approach is the integration of individual production stages' capacities and stocks levels to constrain the maximum shipments quantities of all SKUs that can be committed by production planner. It is known by now that the production stages can be classified broadly either as those controlled under base-stock inventory control policy i.e. ST, PA, AC, SG & R&S or those which serves downstream stages by daily production and running stocks i.e. HE and DC. Hence the constraints applied on these two classes of production stages and stocks considerations are different.

4.7.2.2.1 Integrated constraints on stages controlled under base-stock

Since the shipment planning is carried out on weekly level because commercial planner confirms orders only a week before they are to be fulfilled, intra-stage 'W' stock levels would be available at the end of each week at all the production stages for all the SKU SPs that are processed on them. The planned lead-times of the production stages are also known after first phase of inventory calculations.

The aggregate production targets of 'J' SKU SPs at a production stage 'i' with planned-time of 'n_i' on a day 'k' as given by the base-stock policy can be expressed as,

$$\sum_{j}^{J} P_{i,j,k} \square \frac{\sum_{j}^{J} W_{i,j,k}}{n_i}$$

Where $\sum_{j}^{J} W_{i,j,k}$ is the sum of individual intra-stage stock '$W_{i,j,k}$' for all 'J' SKU SPs at a production stage 'i' on day 'k', which are recently updated after release of material from upstream stages. Since the material release quantity of a SKU SP is exactly equal to the demand '$D_{j,k}$' (i.e. downstream requirement and is exactly equal to the planned shipment quantity of the SKU), the aggregate production target on Day-1 for a production stage can be expressed in terms of last week ending intra-stage stock values for all SKU SPs i.e. $\sum_{j,k\square 0}^{J,0} W_{i,j,k}$ and is given by the following relationship,

$$\sum_{j,k\square 1}^{J,1} P_{i,j,k} \square \frac{1}{n_i}\left(\sum_{j,k\square 0}^{J,0} W_{i,j,k} \square \sum_{j,k\square 1}^{J,1} D_{j,k}\right)$$

Where '$\sum_{j,k\square 1}^{J,1} D_{j,k}$'is the aggregate demand of 'J' SKUs on Day-1. The aggregate production targets would be set by 'W' values on each day, which are updated by releasing material quantities equal to '$D_{j,k}$' of all 'J' SKU SPs passing through the production stage. The aggregate production target set for a production stage should be less than its daily capacity and this integrated capacity-stock constraint for Day-1 can be expressed as,

$$\frac{1}{n_i}\left(\sum_{j,k\square 0}^{J,0} W_{i,j,k} \square \sum_{j,k\square 1}^{J,1} D_{j,k}\right) \leq C_i$$

'C_i' represents the daily capacity of the stage 'i'. The aggregate 'W' value at the end of the Day-1 after production targets for all SKU SPs have been achieved can be expressed as,

$$\sum_{j,k\square 0}^{J,0} W_{i,j,k} \square \sum_{j,k\square 1}^{J,1} D_{j,k} - \sum_{j,k\square 1}^{J,1} P_{i,j,k}$$

Hence the aggregate production target of all SKU SPs on 'kth' day of the week can be generally expressed for stage 'i' as follows,

$$\sum_{j}^{J} P_{i,j,k} \square \frac{1}{n_i}\left(\sum_{j,k\square 0}^{J,k-1} W_{i,j,k} \square \sum_{j,k\square 1}^{J,k} D_{j,k} - \sum_{j,k\square 1}^{J,k-1} P_{i,j,k}\right)$$

The corresponding integrated capacity-stock constraint for stage 'i' for all the days in a week can then be generally expressed as,

$$\frac{1}{n_i}\left(\sum_{j,k\square 0}^{J,k-1} W_{i,j,k} \square \sum_{j,k\square 1}^{J,k} D_{j,k} - \sum_{j,k\square 1}^{J,k-1} P_{i,j,k}\right) \leq C_i$$

It should be noted that released quantities are assumed to be always fulfilled from upstream stage i.e. 100% of the time, which is not true in reality because of stock-outs as the upstream base-stocks are set to provide a certain service level. This assumption allows the planner to carry out worst-case planning i.e. the production requirements are kept within capacity for all the days considering there is no stock-out at upstream stage. In case of a stock at upstream stage, the supply may still be enough to achieve a production target set on real demand values and this point is further discussed in section 5.3.3 on simulation of base-stock policy on chain of production stages.

Similar constraints can be applied simultaneously at all the production stages under base-stock control and daily shipment values '$D_{j,k}$' can be set iteratively for a week so that no constraints are violated during planning at any of the production stage. This section only covered the production stages controlled under base-stock policy and the daily shipment quantities need further filtration through integrated capacity-stock constraints for HE and DC production stages, which are explained in section 4.7.2.2.3.

4.7.2.2.2 Integrated constraints on coupled-line

These constraints are the most critical aspect of an unbalance coupled-line to control as they have influence on the steady state of the coupled-line, with upstream line production rate being lower than downstream line. The first constraint should prevent exhaustion of coupling stock, which will cause disruption in production and is not desired. The second constraint should ensure that the aggregate daily planned production over a coupled line doesn't exceed the bottleneck line capacity i.e. upstream line at PA stage in our case because planned lead-time and capacity of downstream line at R&S stage (faster line) is used for calculating base-stock and it may mislead in planning phase. The two constraints are discussed as under following. For 'kth' day of a week, production target 'P' for a SKU SP 'j' on coupled-line 'i' is generally expressed as,

$$P_{i,j,k} \square \frac{1}{n_{R\&S}}\left(\sum_{k\square 0}^{k-1} W_{PA,i,j,k} \square \sum_{k\square 1}^{k} D_{j,k} - \sum_{k\square 1}^{k-1} P_{i,j,k}\right)$$

Where '$W_{PA,i,j,k}$' is the intra-stage stock at PA of the coupled-line 'i' and, $D_{j,k}$ is the shipment quantity of SKU 'j' and $n_{R\&S}$ is the R&S stage lead-time used for calculations purpose. As discussed in section 4.5.3.1, production target for any SKU SP should not exceed a maximum batch size' $P_{\max,j}$ '. The first constraint i.e. the daily production target of all individual SKU SPs for all days in a week is imposed as,

$$P_{i,j,k} \le P_{\max,j}$$

Or

$$\frac{1}{n_{R\&S}}\left(\sum_{k\square 0}^{k-1} W_{PA,i,j,k} \square \sum_{k\square 1}^{k} D_{j,k} - \sum_{k\square 1}^{k-1} P_{i,j,k}\right) \le P_{\max,j}$$

The second constraint is restricting the aggregate daily production targets of all 'J' SKU SPs set on a coupled-line 'i' for all the days in a week and is expressed as,

$$\sum_{i}^{J} P_{i,j,k} \le C_{PA}$$

Or

$$\frac{1}{n_{R\&S}}\left(\sum_{j,k\square 0}^{J,k-1} W_{PA,i,j,k} \square \sum_{j,k\square 1}^{J,k} D_{j,k} - \sum_{j,k\square 1}^{J,k-1} P_{i,j,k}\right) \le C_{PA}$$

Where C_{PA} is the bottleneck line i.e. PA stage line capacity. When the shipment quantities are planned, the joint effect of the two constraints explained in this section will prevent exhaustion of coupling stock and bottleneck capacity violation.

4.7.2.2.3 Supply and capacity constraints on HE and DC stages

It has already been stated that a portion of DC production is outsourced to external suppliers but only a limited number of SKU SPs can be outsource in case of in-house production capacity is not enough to meet the planned requirements. The only difference between HE and DC stages is that, all the machines at DC can make all type of SKU SPs where as HE has three machines (two automatic and one manual) which are dedicated to groups of SKU families. There are two types of constraints that are applied to DC and DC and HE and are named as 'supply constraint' and 'capacity constraint'.

The current planning practice considers 1-day lead-time for all production stages and since the base-stock policy is not applied on HE and DC, production planner will follow the old planning practice i.e. 1-day lead-time each for HE and DC. However it should be ensured at the start of planning cycle that HE would be able to supply to DC throughout the week and DC would be able to supply to ST (or PA for dry iron SPs) without any disruptions. Hence the planner needs to make decisions regarding the production targets at these two stages to maintain an adequate level of stock and prevent capacity violations. It is known that current planning cycle makes use of confirmed orders for next 1-week and tentative orders for first two days of 2nd next week for production and shipment planning. The capacitated shipment planning approach will make use of the same number of days for planning cycle but the confirmed orders will be considered as demand values for ST, PA, AC, SG and R&S. DC will operate on 6-days confirmed orders and 1-day tentative order while HE will operate on 5-days confirmed orders and 2-days tentative orders.

Let us first consider constraints at DC. There are two kind of SKU SPs defined at this production stage, ‘j’ will represent those SKU SPs that can only be produced in-house and ‘l’ will represent those SKU SPs that can be produced in-house as well as can be outsourced on daily basis. As a convention, ‘S’ will represent the stock value for a SKU SP at the start of day ‘k’. Considering 1-day lead-time for DC, the SKU SPs demands at DC for any day will actually be the confirmed demand quantities on next day at productions stages under base-stock control. The stock variables ‘S_{DC}’ for type ‘j’ SKU SPs can be generally expressed as,

$$S_{DC,j,k} \square \sum_{k \square 0}^{k} S_{DC,j,k-1} \square \sum_{k \square 1}^{k} P_{DC,j,k-1} - \sum_{k \square 1}^{k} D_{j,k}$$

Where k=0 for ‘S’ represents last week ending stock position and ‘P_{DC}’ represents the production decisions made at DC for SKU ‘j’ on day ‘k-1’. Similarly the stock variables for type ‘l’ SKU SPs can be generally expressed as,

$$S_{DC,l,k} \square \sum_{k \square 0}^{k} S_{DC,l,k-1} \square \sum_{k \square 1}^{k} IP_{DC,l,k-1} \square \sum_{k \square 1}^{k} OP_{DC,l,k-1} - \sum_{k \square 1}^{k} D_{l,k}$$

Where ‘IP_{DC}’ and ‘OP_{DC}’ represent the production targets set for in-house and outsourced production respectively for SKU SP ‘l’. The first type of constraint i.e. supply constraint is applied for all ‘J’ and ‘L’ SKU SPs on all the days in a planning week as,

$$S_{DC,j,k} \geq 0$$
$$S_{DC,l,k} \geq 0$$

This constraint will enable DC to supply to ST (or PA) without any disruptions. The second type of constraint i.e. capacity constraints are applied on the production targets for all ‘J’ and ‘L’ SKU SPs on all the days in a week as,

$$\sum_{j}^{J} P_{DC,j,k} + \sum_{l}^{L} IP_{DC,l,k} \leq C_{DC-IH}$$

Where ‘C_{DC-IH}’ is the daily DC in-house production capacity. Similar constraint is applied on the outsourced production for all ‘L’ SKU SPs as,

$$\sum_{l}^{L} OP_{DC,l,k} \leq C_{DC-OS}$$

Where ‘C_{DC-OS}’ is the daily DC outsourcing capacity. The production targets will be set by production planner to ensure that steady supply is maintained to stages downstream of DC and the shipment quantities finalized in previous section can be altered in case of lack of capacity at DC.

HE serves DC and 1-day lead-time is considered for it to supply to DC and hence the demand values at HE will be the next day production targets set at DC. HE stage has three machines among which one of the automatic machine can only produce two SKU family components (it’s a different component than SP and is used in SP at DC stage), which can’t be produced on rest of the two machines. The stock variables for those SKU family components represented by ‘m’ at HE can be defined as,

$$S_{HE,m,k} = \sum_{k=0}^{k} S_{HE,m,k-2} + \sum_{k=1}^{k} P_{HE-M1,m,k-2} - \sum_{k=1}^{k} P_{DC,j,k-1} - \sum_{k=1}^{k} IP_{DC,l,k-1}$$

Where '$P_{HE\text{-}M1}$' represents the production targets set at HE automatic machine 1 on day 'k-2' for component 'm' ($m \subset (j \cup l)$). Furthermore, there are some SKU family components (represented by 'n') that can only be produced on HE automatic machine 2 and their stock variables are expressed as,

$$S_{HE,n,k} \square \sum_{k\square 0}^{k} S_{HE,n,k-2} \square \sum_{k\square 1}^{k} P_{HE-M2,n,k-2} - \sum_{k\square 1}^{k} P_{DC,j,k-1} - \sum_{k\square 1}^{k} IP_{DC,l,k-1}$$

Where '$P_{HE\text{-}M2}$' represents the production targets set at HE automatic machine 2 on day 'k-2' for component 'n' ($n \subset (j \cup l)$). Finally, there are some SKU components (represented by 'o') that can be produced by automatic machine 2 as well as manual machine and their stock variables are expressed as,

$$S_{HE,o,k} \square \sum_{k\square 0}^{k} S_{HE,o,k-2} \square \sum_{k\square 1}^{k} P_{HE-M2,o,k-2} \square \sum_{k\square 1}^{k} P_{HE-MM,o,k-2} - \sum_{k\square 1}^{k} P_{DC,j,k-1} - \sum_{k\square 1}^{k} IP_{DC,l,k-1}$$

Where '$P_{HE\text{-}M2}$' and '$P_{HE\text{-}MM}$' represents the production targets set at HE automatic machine 2 and manual machine respectively on day 'k-2' for component 'o' ($o \subset (j \cup l)$). The supply constraints for HE are applied for all the days in a week as follows,

$$S_{HE,m,k} \geq 0$$
$$S_{HE,n,k} \geq 0$$
$$S_{HE,o,k} \geq 0$$

The capacity constraints for the production targets on three machines for all the days in a week are applied as follows,

HE Automatic Machine 1: $\sum_{m}^{M} P_{HE-M1,m,k} \leq C_{HE-M1}$

HE Automatic Machine 2: $\sum_{n}^{N} P_{HE-M2,n,k} \square \sum_{o}^{O} P_{HE-M2,o,k} \leq C_{HE-M2}$

HE Manual Machine: $\sum_{o}^{O} P_{HE-ML,o,k} \leq C_{HE-MM}$

Where 'C_{HE-M1}','C_{HE-M2}','C_{HE-MM}' represent daily production capacities of automatic machine 1, automatic machine 2 and manual machine respectively. Production planner will be responsible to set the production targets so that supply to DC from HE is maintained for entire week and the production quantities at DC can be altered in case of lack of capacity at HE. Hence the shipment quantities can be committed once all the constraints are satisfied at all the production stages.

4.7.2.3 Solution interface design

The integrated capacity and stock constraints are embedded in MS-Excel to provide production planner an interface to use the solution. The interface design has been given particular importance and is been developed with immense feedback from production planner. It is a simple to use tool and contains MS-Excel sheet that has areas allocated to individual production stages, which are further divided into subgroups of production lines for some stages such as PA and R&S to apply line specific capacity constraints. ST, AC and SG stages have only one production line and therefore constraints are applied on overall line capacity. HE and DC areas on sheet has sub-groups for in-house and outsourcing options. The constraints are enforced by means of 'conditional formatting' feature whereby cells are highlighted with colors incase the aggregate daily production targets at the corresponding stage violated capacity daily requirements. Hence it enables production planner to commit only capacity feasible shipment plan. The snapshot of this interface at R&S stage is provided in Appendix-D.

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CHAPTER 5: RESULTS & DISCUSSION

This chapter starts with discussion of production seasonality analysis results followed by the production requirements analysis results, which were carried out for the high demand season. These results served as input to the inventory model calculations and simulation for chain of production stages in routed flow and coupled-line of production stages in direct flow.

5.1 Production requirements seasonality analysis - Results

The aggregate monthly demand of all SKUs as predicted by the demand forecast is plotted with the aggregate monthly planned production of all SKUs at the finished goods level in figure 5-1. The source of this data is the latest stock building plan available, which was developed in previous year's December and is revised on monthly basis. This year is an exception for two reasons; first the demand values are not as high as compared to previous years demand values because of the economic recession and secondly the factory is shifting to another location.

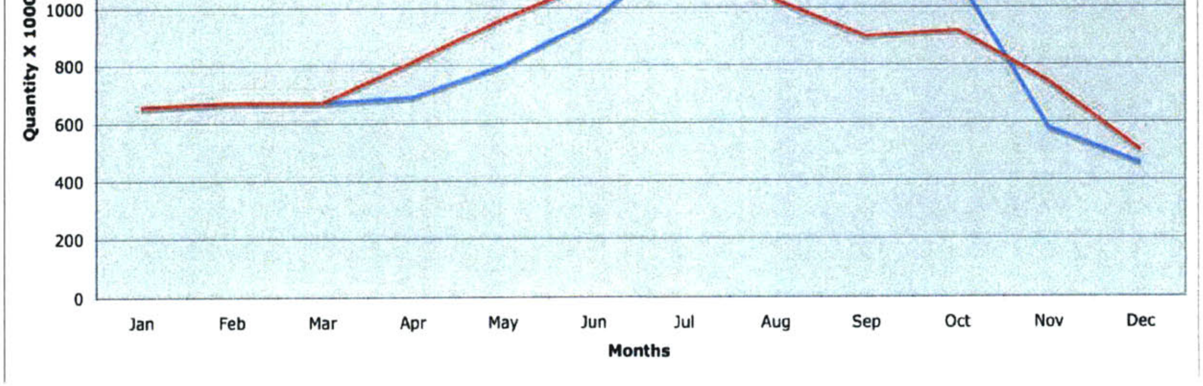

Figure 5-1: SKUs aggregate monthly demand versus SKUs aggregate monthly planned production

Since the demand values are not higher, it was found that monthly demands could be met with respective monthly production and no stocking would be required if the factory was not moving to another location, which caused shutdown of production lines and stocking for shifting period. It can be seen from figure 5-1 that the planned production values are exceeding the demand values from April to July and the stock was planned to serve requirements during the periods when the lines were shifted. It should be noted that not all the production lines were shifted simultaneously and therefore the planned production curve is continuous. In fact the peak in planned monthly production is higher than the peak in monthly demand i.e. during July, which represents the fact that demand was way too low and even excess production could be achieved within capacity. During the excess production period, daily production plans are decoupled from daily shipment requirements because of existing stock in finished goods form. The excess production in November and December, when the demand could be met by capacity alone is because of plant annual shutdown in late December and stock preparation for next year initial days demand. The stocking policy ensures the fulfillment of demand through out the year and this can be seen in the aggregate demand and planned production graph, figure 5-2, plotted as the running sum of aggregate monthly quantities. The production figures are always in excess as compared to the demand figures. Moreover it can be seen that the aggregate planned production is greater than the aggregate demand at the end of year. It can be attributed towards the company policy to fulfill maximum demand, to protect against any unexpected surge in demand and some stock preparation for next year demand during the plant annual shutdown in December.

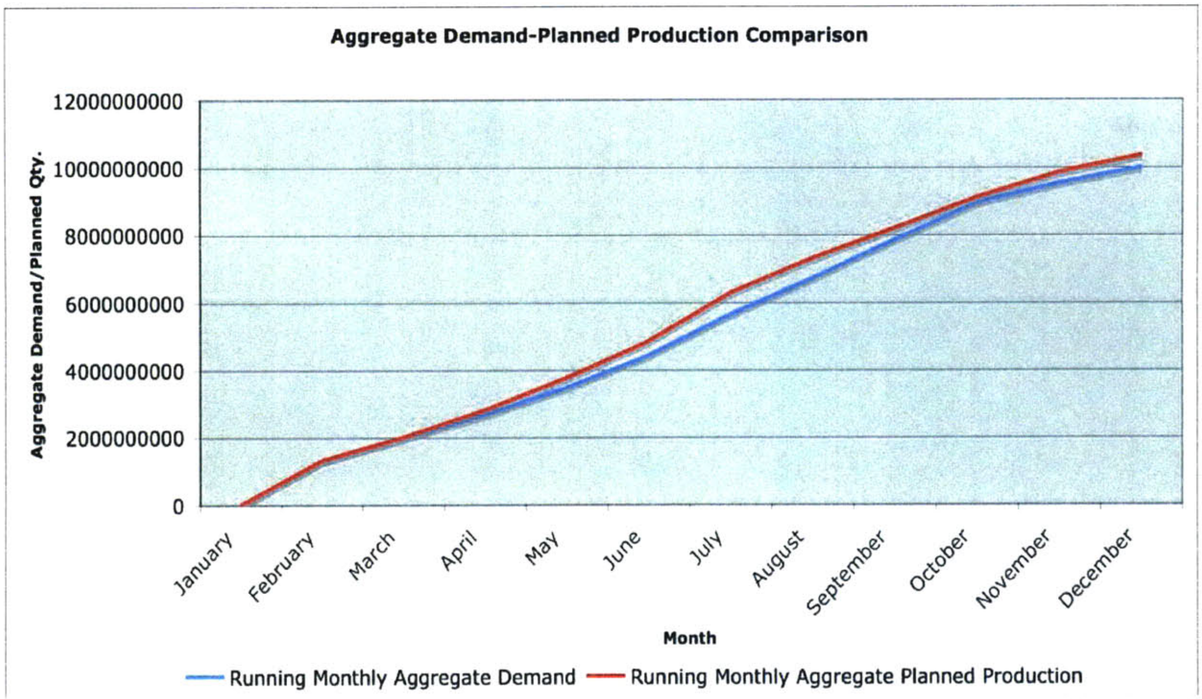

Figure 5-2: Aggregate demand versus aggregate planned production

It is worth investigating that if the production requirements have seasonal patterns because the production resources will be subjected to them. This finding would be useful because parameters of recommended inventory control policy and associated decisions can be modified at right point of time. ANOVA was carried out on the planned monthly production requirements and the results comparison is shown in table 5-1. It should be noted that there could be many seasonal groupings to evaluate but eyeballing the monthly production requirements curve in figure 5-1 identified the apparently significant monthly groupings and combinations were made with some shifting of months between seasons.

Table 5-1: Planned production seasonality - ANOVA results comparison

Combination	Season 1	Season 2	Season 3	F-Critical Value	F-Value	P-Value
1	Jan-Apr	May-Oct	Nov-Dec	4.256	8.295	0.0090
2	Jan-May	Jun-Oct	Nov-Dec	4.256	6.329	0.0192
3	Nov-Apr	May-Oct	-		17.400	0.0019
4	Nov-May	Jun-Oct	-		12.058	0.0059

The group means difference significance is measured by comparing the F-critical value to the combination F-value. Combination F-value should be greater than F-critical value to qualify as a combination with significant distinct seasons. The P-value is the measure of mean difference significance and the combination with smallest P-value would be considered the most significant combination with distinct seasons. There are two options of considering the number of seasons in a year, two-seasons and three-seasons. It would be operationally preferable to operate in two-seasons occurring alternatively. Two-season combinations included November and December to the months in first half of the year for analysis. Table 5-1 suggests combination 3 as the most significant seasonal grouping based on production requirements. ANOVA results for combination 3 are given in Appendix-A. This procedure can be recommended to PDA as a framework for planning associated with seasons and this thesis used these findings for analysis and calculations in requirements characteristics analysis and simulation work.

5.2 Production requirements characteristics analysis - Results

Although the production requirements seasonality analysis suggests May to October as a distinct and high demand season, these results were obtained in the middle of this season and the production requirements characteristics analysis was carried out on planned production values starting from July to October because the inventory levels were to be established for implementation phase. Production requirements characteristics analysis was performed following the procedure explained in section 4.3.2 and resulted in individual high runner SKUs daily mean and daily standard deviation for high demand season i.e. from July to October. These results are tabulated in table 5-2.

Table 5-2: Production requirements characteristics

Family/Model	SKU Name	SKU Demand Contribution (%)	Seasonal -Daily Mean (units)	Family/ Model CV	Seasonal -Daily Standard Deviation (units)
Dry/Mirage	Mirage Linish 230V	5.75	2246	0.57	1289
	Mirage Coated 230V	3.3	1290		740
Dry/D13-Batam	D13 (New) Linish	6.1	3206	0.85	2719
Dry/SKD	D13 Coated (New)-SKD Indonesia	3.66	1527	0.48	736
	NDI Coated (New) - (SKD) Indonesia	4.19	1745		841
Low End/Easy Speed	Easy Speed - Linish (LE)	2.67	1463	1.84	2693
	Easy Speed - Coated (LE)	2.11	1039		1912
	Easy speed HE 230 PA	2.55	1787		2750
	Easy Speed - Gold Coated (HE)	0.87	429		790
Complete/Elance	E3.3/5/6K (Sumber Terang) ST	2.69	953	0.64	606
	E3.3/5/6K (Sumber Terang) PT	10.66	3779		2402
Basic/Power Life/HV	Powerlife Coated version - HV	10.16	2241	0.88	1968
Basic/Power Life/Successor	Powerlife SS	20.73	4572	0.49	2226
Superior/Azur	Azur4400_Ionic	0.65	139	1	139
	Azur4400_Non lonic	6.37	1358		1358
	Azur4600_Ionic	3.24	691		691
	Azur4600_Non Ionic	7.38	1574		1574
System	Bangkok_Non SOS (SKD/BTM)	1.2	836	0.35	296
	Bangkok_SOS (SKD)	2.2	450		159
	Shanghai Successor	1.14	429		152

Table 5-2 contains daily means and daily standard deviation of individual high runner SKUs and their family/model common coefficient of variance (CV). CV is a measure of variability and can be used for comparison purpose. Low End/Easy Speed irons SPs has the most volatility i.e. CV=1.84, in production requirements whereas System irons SPs have the least i.e. CV=0.35. Assumption of common CV for a family/model sounds appropriate as most of the SKUs are sold in the same markets and share same features. It can be seen that the Dry iron SKUs have CVs usually less than 1 and represents stability in production requirements. It should be noted that these values are extracted from stock building plan, which has the planned aggregate weekly values either on SKU family or model basis and the production planner try his best to meet the targets that are more or less equal to the weekly mean (= number of production days per week x daily mean) of the production requirements. The actual variability may come from planner's tendency to run larger lots of SKUs in case of enough stocking for rest of the SKUs, raw materials supply and labor supply issues on production lines. The standard deviations of production requirements calculated in table 5-2 are introduced as input parameters for inventory calculations and can be considered as good representatives of variability in the SKU production requirements because they are scaled in proportion with magnitude of their mean production requirements. It is planned to establish robust inventory levels that can contain risk of similar magnitude such as unexpected surge in the production requirements.

5.3 Routed flow - Base-stock results

5.3.1 Model parameters

Inventory calculations for a production stage required production requirements characteristics of all the SKUs processed on it, effective capacity estimate and reserved capacity figures for low runner SKU SPs. The first phase of inventory calculations involved stage lead-time, slack capacity and aggregate demands mean & standard deviation estimates with requirements pooling consideration, which served as the input parameters for the model. Table 5-3 lists the results in tabulated form for all the production stages considered in this thesis. Daily effective capacity values at each production stage are obtained from production planner and capacity for low runner SKU SPs at each production stage is reserved and calculated according to procedure explained in section 4.5.5. Aggregate daily mean and aggregate daily standard deviation are calculated through procedure explained in section 4.5.4. Stage slack capacity and lead-times are calculated using the formula given in section 4.5.1.

Table 5-3: Production stage demand & capacity parameters

Production Stage-Line	Daily Effective Capacity – C (units)	Aggregate Low-Runner Mean/Reserved Capacity (units)	High-Runner Aggregate Daily Mean - □ (units)	Slack Capacity - χ (units)	High-Runner Aggregate Daily Standard Deviation - σ (units)	Lead Time - n (Days)
R&S-PL	8914	571	6813	1530	2971	5.63
R&S-S	3600	356	1715	1529	368	1
R&S-LE	10970	1076	2931	6963	3395	1
PA-PL/S	16290	927	8528	6835	2994	1
PA-LE	10970	1042	4718	5210	4370	1.56
PA-Dry	14571	1205	10014	3352	3294	1.81
AC	19575	2082	14458	2935	3878	2.88
SG	21400	12964	6287	2149	2256	2

It can be seen from table 5-3 that slack capacity has positive values for all production stage and thus provides flexibility of altering the production rate of a stage to meet requirements. Stage lead-time acts as a production smoothing factor and larger values implies greater smoothing. Production stages with 1-day lead-time have higher capacities relative to the aggregate average requirements at them and thus tend to have low inventory levels and observe virtually no production smoothing effect. This smoothing effect will be discussed shortly in section 5.3.3.4.1.

5.3.2 Inventory results

The second phase has the actual inventory calculations based on the parameters calculated in first phase, as explained in section 4.5.1. Table 5.2 tabulates expected intra-stage E[W], expected inter-stock E[I] and base-stock values for entire high runner SKUs range at the involved production stages in routed flow for a service level of 95% at each stage. The cells covering multiple SKUs represent pooled SP stock requirements since the corresponding production stage processing doesn't differentiate the SP.

Table 5-4: Base-stock results summary for routed flow

	R&S			P&A			SG			AC		
SKU Name	**I**	**W**	**B**	**I**	**W**	**B**	**I**	**W**	**B**	**I**	**W**	**B**
Mirage Linish 230V	-	-	-	2744	6415	9159	-	-	-	-	-	-
Mirage Coated 230V	-	-	-				-	-	-	1611	3710	5321
D13 (New) Linish	-	-	-	5020	5817	10837	-	-	-	-	-	-
D13 Coated (New)-SKD Indonesia	-	-	-	1359	2770	4129	-	-	-	1602	4392	5994
NDI Coated (New) - (SKD) Indonesia	-	-	-	1553	3166	4719	-	-	-	1831	5019	6850
Easy Speed - Linish (LE)	4443	1463	5906	5740	3647	9387	-	-	-	-	-	-
Easy Speed - Coated (LE)	3155	1039	4194				-		-	4162	2988	7150
Easy speed HE 230 PA	-	-	-	4972	3230	8202	-	-	-	-	-	-
Easy Speed - Gold Coated (HE)	1304	429	1733				-	-	-	1720	1234	2954
Powerlife Coated version - HV	5709	12625	18334	4902	6813	11715	-	-	-	4284	6446	10730
Powerlife SS	6458	24757	31215				4242	9147	13389	4846	13150	17996
Bangkok_Non SOS (SKD/BTM)	488	836	1324	608	1715	2323	703	3431	4134	803	4933	5736
Bangkok_SOS (SKD)	262	450	712									
Shanghai Successor	403	429	832									

It can be observed that inventories are pooled more at upstream production stages such as PA, AC and SG as most SPs are not differentiated at these stages. For example, the two Powerlife SKUs shares SPs at PA stage, which is the first process in production stages, considered in this thesis and their pooled inventory levels are shown in table 5-4.

From table 5-3, stage lead-time of R&S-LE is 1 day on which Easy Speed SKUs (in table 5-4) are processed. The intra-stage stock ‘W’ values of these SKUs at this stage are exactly equal to their mean production requirements (refer to table 5-2) because this 1 day lead time implies that the production targets are set exactly equal to the updated ‘W’ level and thus tends to process all the material within a day. Hence E[W] for such SKUs at this stage acquires values equal to their respective production requirements daily mean in a longer run of time.

The inventory levels of a production stage are directly proportional to its lead-time. For example, R&S-PL has a lead-time of 5.63 days and the SKU SPs process at this stage i.e. Powerlife Coated version and Powerlife SS has E[W] values equal to the product of their individual production requirements daily means and lead-time (5.63 days). It is because the production targets are set so that only a fraction (1/lead-time (n)) of updated ‘W’ value is processed in each day at the stage. It implies that higher lead-times cause higher ‘W’ values (and eventually higher base-stock ‘B’ levels).

The base-stock ‘B’ is also affected by the variability in production requirements, which is contained by keeping inter-stage stock ‘I’. The ‘I’ values are directly proportional to the standard deviation of production requirements and reduces with higher stage lead-times. From table 5-4, it can be observed at R&S (R&S-PL with lead-time of 5.63 days) stage that the SKU SPs E[I] values are much smaller as compared to their corresponding E[W] values.

5.3.3 Production stages chain simulation model

It is of paramount importance to verify the inventory calculations through reliable means to ensure that the inventory control policy would provide desired results and the effects of stock-outs should be studied. This verification is achieved through a simulation model of an entire production stage chain involved in manufacturing of two SKUs, named ‘Powerlife Coated Version’ and ‘Powerlife SS’ as depicted in figure 5-3. The chain simulation model integrates stocks of four production stages i.e. PA, AC, SG and R&S. The individual stocks are set to achieve a service level of 95%. The simulation period is set to be 120 days because the inventory calculation were done only for four months i.e. from July to October of the high demand season for the reason already explained in start of this chapter. This entire production stages chain is modeled to investigate stock-out effects propagation along the production stages, which couldn’t be observed if individual stages are simulated in isolation. Since the stocks are set for duration of a whole season usually lasting for half a year, a holistic picture of stock-out effects on production stages chain can look different from that proposed by an individual stage production stage results in term of stocks structure.

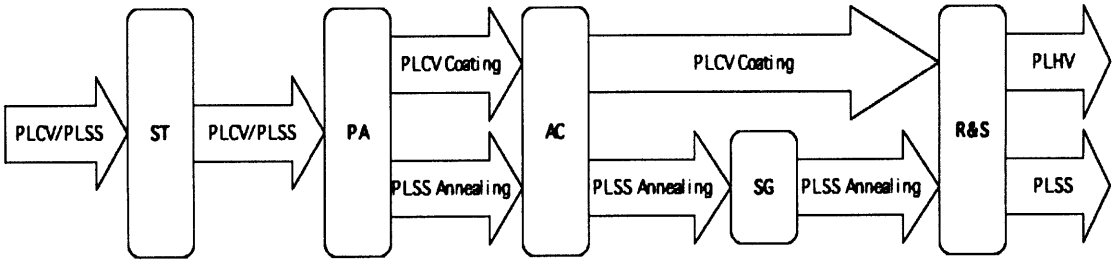

Figure 5-3: Simulation model material flow logic

As shown in figure 5-3, both SKUs share SP stock at ST and PA stage and therefore stocks of these two stages will be subjected to aggregate demand. Powerlife Coated Version is then processed at AC for coating while Powerlife SS is too processed on AC stage but for annealing and hence they don't share SP stock at this stage. Powerlife Coated Version is sent directly to the R&S stage whereas Powerlife SS requires coating at SG stage and is then processed at R&S stage (same line as that for Powerlife Coated Version). This SP flow logic was built into the model and each production stage was subjected to random number streams of size 120 (for 120 days representing production requirements of two SKU SPs) accordingly. A total of 10,000 runs were executed for better sampling results and the simulation work was carried out on Crystal Ball version 7.3.1.

5.3.3.1 Simulation goals

It was important to identify and state the goals of simulation explicitly so that simulation model assumptions were made in accordance with the requirements. Following is a list of core simulation goals desired,

1) Study the effects of stock-outs (including simultaneous stock-outs) at production stage(s) in terms of disturbance in base-stock level of immediate downstream production stage.

2) Verification of service levels promised at each production stage in general and final production stages in particular.

5.3.3.2 Simulation model assumptions

This simulation work was aimed at investigating effects of stock-out on base-stock and service levels and the model was formed with the following assumptions,

1) All production stages are controlled under proposed base-stock inventory control policy.

2) Individual production stages inventory levels are initially set to the calculated values in table 5-4 to provide a service level of 95% in isolation.

3) In case of a stock-out at a production stage, release quantity to the downstream stage would be exactly equal to the current 'I' level of the upstream stage because it is the maximum quantity it can provide at that time.

4) In case of a stock-out at a production stage, it will still try to retrieve material quantity equal to the requirements (demand of downstream), provided upstream stage can supply, so that its inter-stage stock 'I' can be replenished by setting higher production targets, which depends on the 'W' values updated after material is received from upstream stage. It is intended to protect possibility of consecutive stock-outs on following days that can be caused by lower 'I' values or base-stock reduction caused by stock-outs at upstream stage. The immediate effect of this assumption would be increase in base-stock of the production stage, which could only be lowered in case of stock-out at its upstream stage.

5) In case of a stock-out at upstream of a production stage that will cause less supply and reduced base-stock, production stage will try to set the production targets based on material release values equal to demand (requirements of downstream stage) to its 'W' stock, provided the supply is enough to achieve this target else the whole 'W' stock would be processed.

6) The goal of base-stock policy is to ensure that service level of a production stage is met and its base-stock is conserved. It can be noted that stock-outs at upstream of a production stage will cause reduction in its base-stock and hence the inventory structures in the entire chain can change similarly. Therefore, it is assumed that the total base-stock of the entire production

should at least be kept constant and conserve in the longer run. Hence the material release quantity to the first production stage (ST in this case) 'W' stock is controlled in exact proportion to the release from last production stages (R&S in this case) 'I' stock(s). In case of stock-out at R&S stage(s), it can only provide what is available in its 'I' stock(s) and hence ST's 'W' stock will be replenished with this quantity.

7) In case of a stock-out at a shared production stage with shared SP stock for example, PA stock is shared by the two SKUs in this model and supplies to AC for two different processes, a priority criterion is set to supply material to downstream stages in proportion to the weighted demand contribution of their SKUs unless the requirements at one of the downstream stage is less as compared to the supply share it can avail.

8) No backlog replenishment is considered and requirements are fulfilled with an intended service level of 95%.

9) Since Die Cast (DC) stage is not controlled under this policy, it is not included in the model and is assumed to meet ST's requirement 100% of time.

5.3.3.3 Simulation model input data

The model input parameters are classified as demand characteristics of the chosen SKUs as given in table 5.2, starting stock values as given in table 5.4 and stage lead-times as given in table5-3. Expected inventory levels for ST stage are taken from Youqun Dong [2] and Yuan Zhong [3]. These parameters are tabulated together in table 5-5 and serves as model input parameters.

Table 5-5: Simulation model input parameter

			ST n=3.46		PA n=1		AC n=2.88		SG n=2		R&S n=5.63	
SKU Name	**Mean**	**Standard Deviation**	**E[W]**	**E[I]**	**E[W]**	**E[I]**	**E[W]**	**E[I]**	**E[W]**	**E[I]**	**E[W]**	**E[I]**
Powerlife Coated Version	2241	1968	24989	6970	6813	4902	6446	4284	-	-	12625	5709
Powerlife SS	4572	2226					13150	4846	9147	4242	25757	6458

5.3.3.4 Simulation model results

This section will present results on the simulation model and covers discussion on inventory structure charts at productions stages, production smoothing effect and summary of stock-out results each in light of model assumptions and will focus on achievement of simulation goals. Inventory structure charts are drawn and values are taken from a single run of simulation for production smoothing comparison purpose and hence don't conclude the actual performance of the inventory policy in terms of stock-outs and service level.

5.3.3.4.1 Production smoothing effect

The recommended base-stock inventory control policy works on a linear production rule. It implies that the intra-stage stock 'W' of a production stage is converted into inter-stage stock 'I' in inverse proportion to its planned lead-time. Hence it can be said that production rule introduces flexibility in production rate of a production stage i.e. higher output would be expected for higher 'W' stock caused by introduction of higher release quantity of material 'R', which is in exact proportion to the demand 'D' (downstream requirements) and vice versa. Therefore a production stage appears to alter its production rate as per the requirements. This flexibility in production rate eventually contributes towards smoothing of output of a production stage. This smoothing effect is in direct proportion to the stage lead-time. It is explained through example of three production stages modeled for simulation in which R&S has lead-time of 5.63 days, ST has lead-time of 3.46 days and PA has lead-time of 1 day. This comparison will explain the production smoothing effect and its relationship with stage lead-time with discussion of three cases. Consider figure 5-4, if the line graph of intra-stage stock 'W' is compared with that of corresponding production 'P', it can be seen that the two differs much in terms of dispersion observed from day to day for a period of 120 days. This difference is chiefly caused by higher lead-time of this production stage i.e. R&S, highest in the chain of production stages in this simulation model. By eyeballing the figure 5-4 roughly from Day 30 to Day 50, it can be seen that 'W' undergoes a deep convex shape whereas corresponding 'P' undergoes only minor dishing.

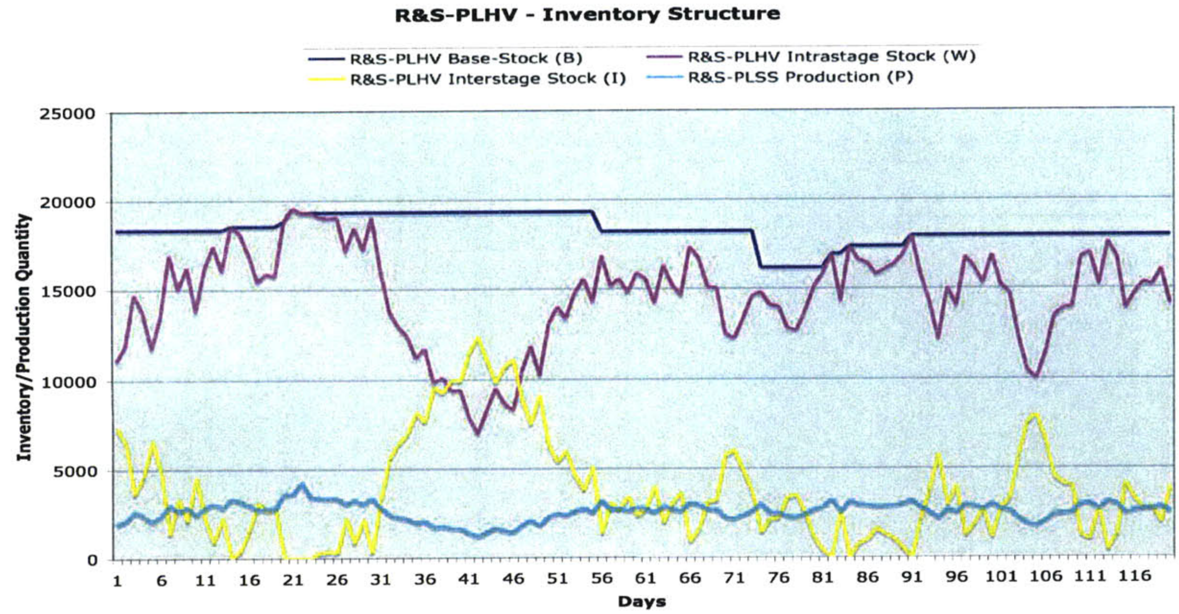

Figure 5-4: Inventory levels snapshot at R&S-PLHV

ST inventory graph as depicted in figure 5-5 is chosen to compare the effects of lead-time on production smoothing. It can be seen that the 'W' still has higher dispersion and the corresponding 'P' has lower but it has increased as compared to that of R&S. This relative decline in production smoothing can be attributed towards difference in lead-times, as ST has a lead-time of 3.46 days.

It has been observed so far that production smoothing is significant for the last two cases just discussed above, the third case present the other extreme as shown in figure 5-6. PA has a lead-time of 1 day i.e. it has higher capacity as compared to the average aggregate production requirements and thus tends to convert the entire 'W' within a day. This fact can be seen from the overlapping of 'W' and 'P' graph in figure 5-6 and it shows virtually no production smoothing effect at this stage.

Hence it can be concluded that the higher the lead-time of a production stage, the smoother will be the production targets with less dispersion from day to day. Moreover the three inventory structures charts cited in this section present the fact that 'P' tends to follow trend of 'W' but with smoothing effect.

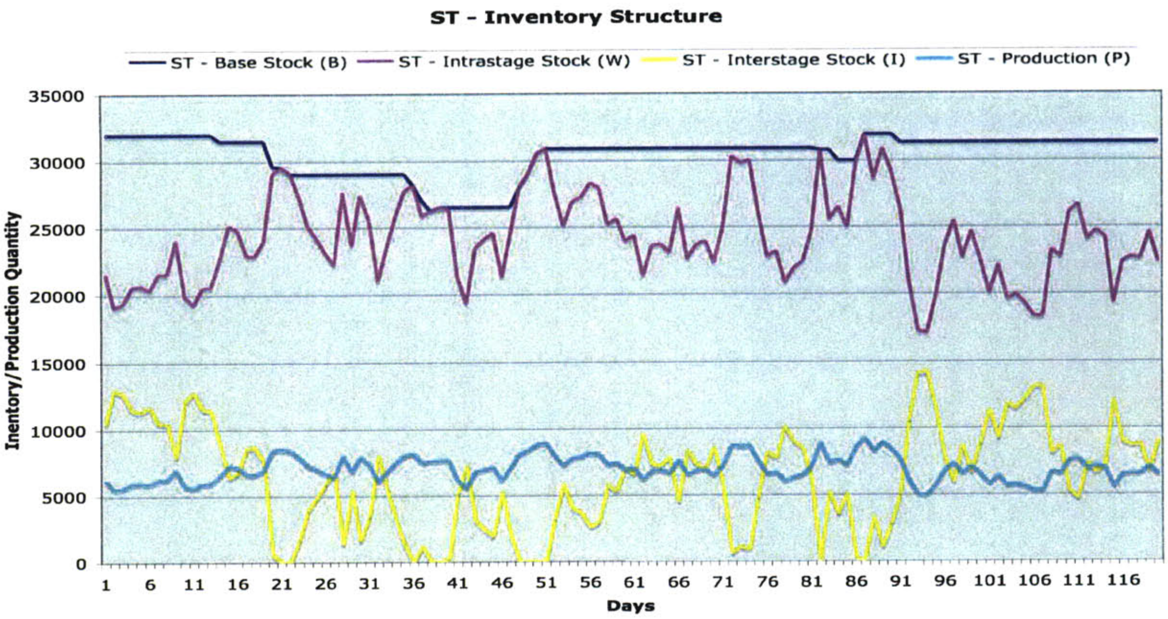

Figure 5-5: Inventory levels snapshot at ST

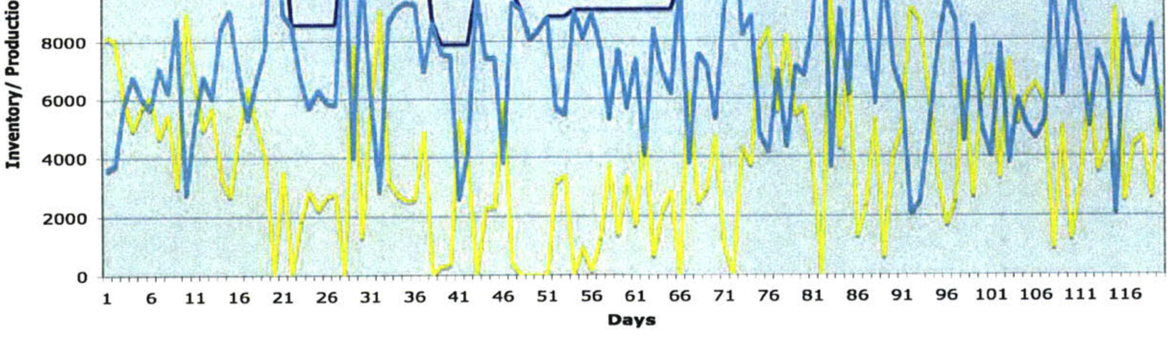

Figure 5-6: Inventory levels snapshot at PA

5.3.3.4.2 Stock-sharing & production targets deviation

A priority criteria was set during model simulation that in case of a stock-out at shared production stage with shared SP stock, downstream stages will be supplied material in proportion to the weighted demand contribution (32% for Powerlife Coated Version and 68% for Powerlife SS) of their SKUs unless the requirements at one of the downstream stage is less as compared to the supply share it can avail. PA inventory structure is shown in figure 5-6, in which the inter-stage stock 'I' goes to 'zero' in case of a stock-out. Since it is supplying same SP stock to AC but for two different processes, the release value to the AC 'W' for Powerlife Coated Version SP and Powerlife SS would be less as compared to AC requirements. Although it can not be observed just by looking at the charts, but all 'W' values in figure 5-7 and figure 5-8 the corresponding to stock-outs at PA in figure 5-6, are replenished with less material than what AC had required for each SKU and its 'I' had been depleted by higher values, provided it itself didn't have stock-out.

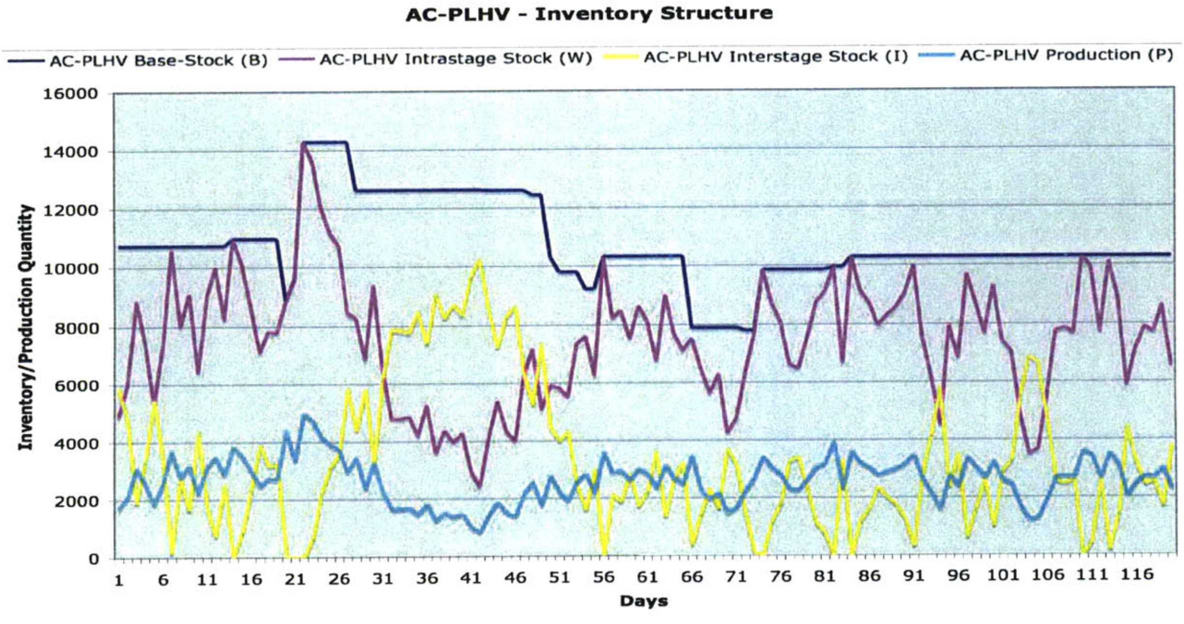

Figure 5-7: Inventory levels snapshot at AC-PLHV

The stock-out at PA may also cause deviation of AC from its production targets based on expectation of replenishment from PA in proportion to AC downstream requirements but model has been built with logic of setting the production target in case the supply is enough for conversion into 'I'.

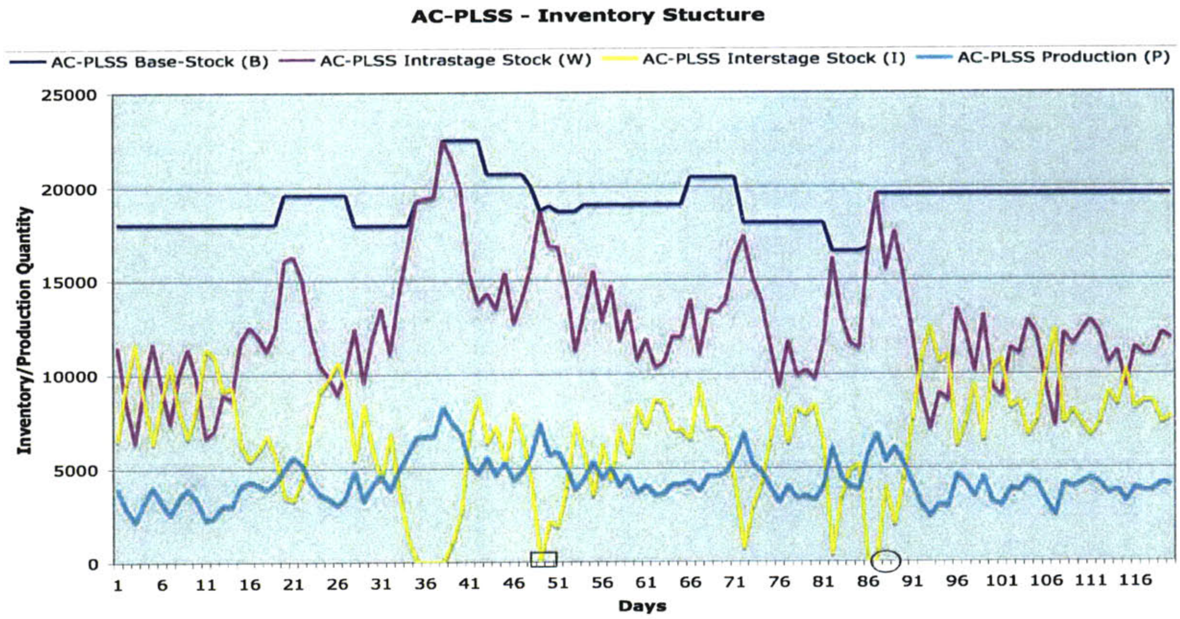

Figure 5-8: Inventory levels snapshot at AC-PLSS

5.3.3.4.3 Individual base-stock(s) fluctuations

As already discussed in section 5.3.3.2, it is expected that the individual stages base-stock levels would decline because of the stock-outs at their upstream stages. These levels can only be raised back, although not to the original values, when a stock-out occurs at a stage and its 'W' is replenished either with values equal to its downstream requirements or more than what it had in 'I' at the time of stock-out. Hence the model logic was built so that individual base-stock levels don't incur decline only. This aspect of model design is explained with the help of figure 5-8 and figure 5-9. AC supplies SP stock of Powerlife SS to SG and in case of a stock-out at AC for example at Day 87 as encircled in figure 5-8, would cause drop in 'W' of SG as encircled in figure 5-9.

The rise of base-stock is shown with the help of square drawn on figure 5-9, which represents increase in base-stock of SG at Day 49 when it had a stock-out. Although requirements at this particular day caused simultaneous stock-out at AC as well (shown in figure 5-8 and marked by a square) but the supply to SG was in excess to what SG supplied to R&S and therefore the net change in SG base-stock was positive.

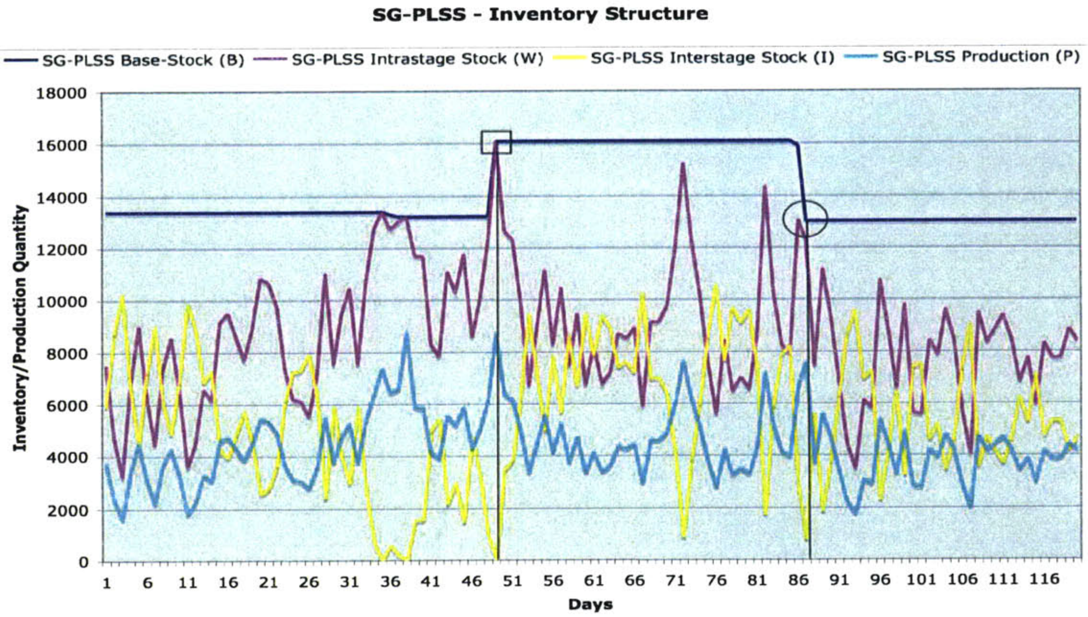

Figure 5-9: Inventory levels snapshot at SG-PLSS

5.3.3.4.4 Production stages chain base-stock conservation

It was explained in section 5.3.3.2 that to somehow contain the effects of individual base-stock fluctuations as described in section 5.3.3.4.3, total base-stock of production stages chain can be tried to keep constant in longer run. Hence the material released into the first stage of the chain i.e. to ST's 'W' would be equal to the depletion of R&S stage's 'I'. This particular assumption along with assumptions of meeting the production targets to the maximum extent as well maximum possible movement of material between stages to meet requirements can help in maintaining stage service levels as planned and conservation of individual base-stock to some extents. The overall impact of all these assumptions can be seen in figure 5-10 in which base-stock levels of individual stages are stacked together for a period of 120 Days. The total base-stock of production stages chain is able to held constant for the entire simulation period and the individual base-stocks don't fluctuate beyond certain limits.

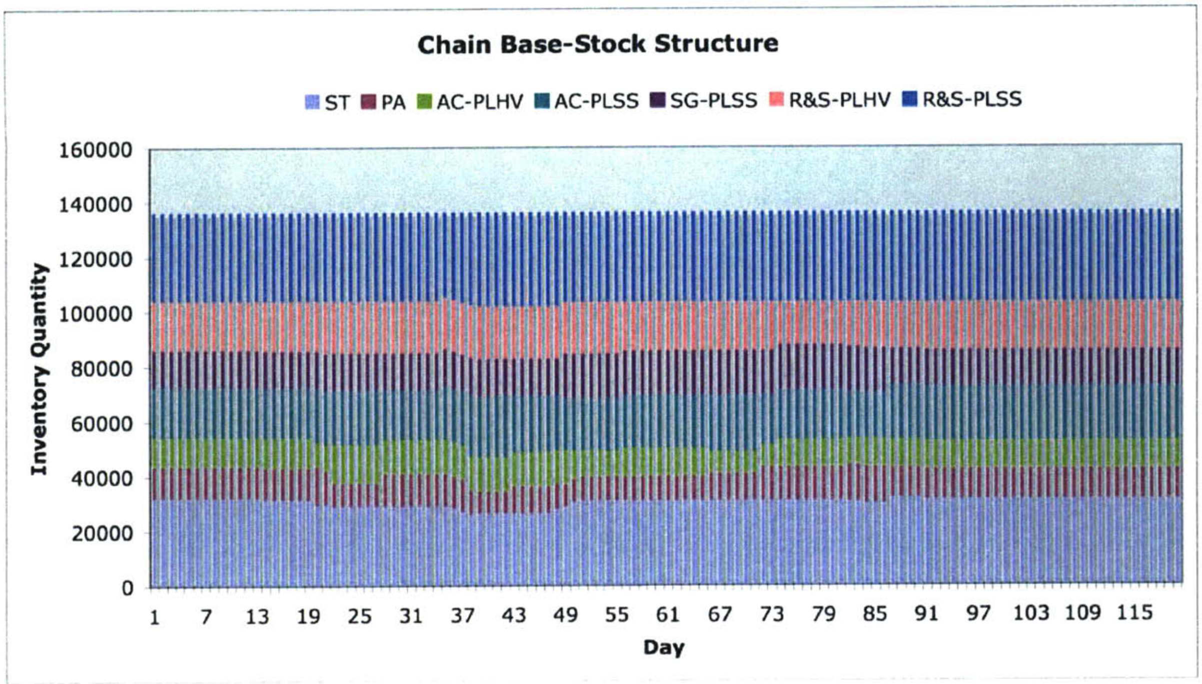

Figure 5-10: Chain base-stock conservation

5.3.3.5 Production stages chain performance

The ultimate goal of this simulation exercise is the performance of the chain of productions stages, all controlled under recommended base-stock inventory policy, which should be studied and verified to form basis for implementation of the work explained in this thesis. The main deliverable to the PDA management is the confidence in service levels this policy is claiming to provide. Hence the expected number of stock-outs at each production stage is estimated with considerations of all the stock uncertainty in the entire chain and corresponding service levels are calculated. The results are expressed on average level as well with a confidence level of 95% in table 5-6.

Table 5-6: Simulation model stock-outs summary

Stage-SKU	Average stock-outs	Average Service Level	Maximum Stock-outs with 95% Confidence	Service level with 95% Confidence
ST	10	91.67	18	85.00
PA	10	91.67	19	84.17
SG-PLSS	4	96.67	9	92.50
AC - PLHV	12	90.00	23	80.83
AC-PLSS	3	97.50	8	93.33
R&S-PLHV	11	90.83	21	82.50
R&S-PLSS	4	96.67	10	91.67

The average service level of ST and PA as achieved through simulation are low as compared to the committed ones. It should be noted that inventory calculations are carried out with consideration of requirements pooling effect and in reality it is also true that assembly plant doesn't demand for high quantities of both SKUs at the same time because of their own capacity constraints. Whereas the simulation model used two independent random streams of production requirements generated without any pooling effect and thus can be a reason of lower service levels.

However it is interesting to see that AC service levels for two SKUs are not identical which may cause some suspicion but it is quite clear from the fact that weighted demand contribution of Powerlife SS is 68% whereas it is only 32% for Powerlife Coated Version i.e. even less than half of Powerlife SS. Hence it can be perceived that in case of a stock-out at PA stage, Powerlife SS had more priority for supply as compared to Powerlife Coated Version. AC for Powerlife SS has a service level estimate that is even higher than committed which suggests that this priority criteria can be relaxed in real production environment and supervisors can make better decisions for supply in case of stock-outs.

Since AC supplies Powerlife SS to SG and Powerlife Coated Version to R&S stage, their service levels should be compared. It can be seen that SG has service level of more than 95% whereas R&S for Powerlife Coated Version has only 90%. The reason behind this can be connected to service levels of their upstream stages which influences level of stage base-stock fluctuations and eventually service level i.e. SG has supply with higher service level from AC whereas R&S has lower service level supply relatively. Hence it can be concluded that the stock-outs and service level of a stage has propagating effects on its downstream stages.

Although the service levels of all the stages are important but those of R&S stage are the crucial ones because it is the last stage in production process of SPs and its stock is meant to shipment for assembly plants and satellite factories. Hence the entire chain performance is reflected at this stage. It can be seen that R&S has even a higher than committed service level for Powerlife SS whereas it is lower for Powerlife Coated Version.

One parameter that can be adjusted in the simulation to improve overall results is the priority criteria based on weighted demand contribution because the variability in requirements of Powerlife SS (CV=0.49) is low as compared to Powerlife Coated Version (CV=0.88), which can influence the vulnerability of already fluctuated base-stock levels to stock-out. Hence by trial and error, a priority criterion was updated to supply PA stock to AC for Powerlife SS and Powerlife Coated Version in a proportion of 55% to 45% respectively in case of a stock-out. The results are quite satisfactory in terms of service level and are summarized in table 5-7.

Table 5-7: Simulation model improved stock-outs summary

Stage-SKU	Average stock-outs	Average Service Level	Maximum Stock-outs with 95% Confidence	Service level with 95% Confidence
ST	8	93.33	15	87.50
PA	9	92.50	16	86.67
SG-PLSS	7	94.17	13	89.17
AC - PLHV	6	95.00	11	90.83
AC-PLSS	7	94.17	13	89.17
R&S-PLHV	7	94.17	12	90.00
R&S-PLSS	6	95.00	13	89.17

It can be noted that service levels are improved at each production stages with R&S stage providing almost 95% service level for Powerlife Coated Version and exactly 95% for Powerlife SS on average. It is interesting to note that even the service levels of ST and PA are improved. It can be attributed towards increase in material release quantities to 'W' of ST because comparatively less material was pushed in the chain in case of a stock-out at R&S stage, which was more likely in case of previous priority criteria. Hence the priority criteria modification enabled comparatively higher inventory levels for ST and improved service level, yet the total base-stock of production stages chain remained same (to its value in previous priority criteria) and conserved.

In real production environment, randomness in production requirements during high demand season is less because stock building enables decoupling of production plans from shipment plan and production planner tends to run larger but uniform batches of every high runner SKU for some definite period of time. During low demand season, production planner has the authority to negotiate shipment plans with assembly plant planner and can prevent stock-outs.

5.4 Direct flow – Base-stock results

This section will cover results and discussion about coupled-lines including the parameters used for calculations, coupling stock quantities along with base-stock results, a comparative study of inventory results of line coupling with original base-stock results and verification of service level 'P_{max}' can provide.

5.4.1 Coupled-line parameters

Table 5-8 provides the line parameters i.e. unit time and cycle time of PA and R&S stage and is taken from the line capacity data provided by production planner and was verified with time sampling on lines. PA is the first stage in the coupled-line and R&S is the second. For example, it can be seen that cycle time of PA-Azur is smaller as compared to R&S-Azur and hence the coupling stock will start being replenished after 335 sec of start of production and the rest of the parts will be collected with a time interval of 10.08 sec. Since coupling stock is consumed by downstream line, it will be depleted with a time interval of 9.16 sec. For Elance ST and PT, the two lines at PA and R&S stage are balanced and once the first part is collected from PA, consumption and replenishment can be observed at a same pace as the unit times are equal i.e. 7.76 sec.

Table 5-8: Coupled-line parameters

Stage	Parameters	Azur - 44I/44NI/46I/46NI	Elance ST/PT
PA	Unit Time (sec)	10.08	7.76
	Cycle Time (sec)	335	1200
R&S	Unit Time (sec)	9.16	7.76
	Cycle Time (sec)	1200	1200

5.4.2 Coupling stock results

Coupling stock calculations were performed according to the procedure explained in section 4.5.3 with maximum batch size consideration given in section 4.5.3.1 and the results are given in table 5-9. The base-stock results for ‘W’ and ‘I’ (for a service level of 95%) in upstream and downstream of coupled-line respectively, are calculated using R&S stage effective capacities and lead-times (R&S-Azur lead-time is 1-Day and R&S-Elance lead-time is 1.15 Days and are calculated using the formula given in section 4.5.1) for the reasons explained in section 4.5.3.2. Maximum batch size ‘P_{max}’ values are established to ensure that coupling stock would provide a service level of 95% between PA and R&S stages.

Table 5-9: Coupling stock summary

SKU	P_{max}	Coupled Line Intra-stage Stock 'W'	Coupling Stock 'CS'	Coupling Stock 'CS' (Rounded-off to container size - 150)	Coupled Line Inter-stage Stock 'I'	Total Inventory
Azur 44 Non Ionic	3599	1358	542	600	2241	4199
Azur 44 Ionic	369	139	218	300	230	669
Azur 46 Non Ionic	4172	2265	600	600	2597	6602
Azur 46 Ionic	1832		365	450	1140	
Elance ST	1831	5435	304	450	1008	10890
Elance PT	7259				3997	

It can be seen from table 5-9 that Azur 46 Ionic shares SP stock with Azur 46 Non Ionic and Elance ST with Elance PT at PA stage and hence the coupling stock for these SKUs can be kept at the relative maximum (of the two SKUs) i.e. 600 (>365) for Azur 46 Ionic and Azur 46 Non Ionic. P_{max} doesn't affect the coupling stock level for balanced lines and it only needs enough stock that can last up to the start of replenishment from PA stage. The coupling stock values are rounded-off to the nearest multiple of container/trolley size because movement between PA and R&S is not carried out as single-piece flow rather in batches of size 150.

5.4.2.1 Comparison with original base-stock results

The trade-off between introducing the concept of coupled-line operating under base-stock policy and PA and R&S stages operating independently under base-stock policy should be evaluated. The first aspect is the inventory reduction and is expressed in table 5-10, where it can be seen that a total of 16674 units are saved by introducing concept of a couple-line and recommended for lines at PA and R&S production stages for two SKU families i.e. Superior (Azur) and Complete (Elance).

Table 5-10: Coupled-line comparison with base-stock

SKU	PA - Base-stock	R&S - Base-stock	Coupled Line Total Stock	Inventory Reduction	Total Inventory Reduction
Azur 44 Non Ionic	3599	3599	4199	2999	16674
Azur 44 Ionic	368	368	669	67	
Azur 46 Non Ionic	5101	4171	6602	4051	
Azur 46 Ionic		1831			
Elance ST	9557	2103	10890	9107	
Elance PT		8337			

The second aspect is the performance of coupled-line in an event of a major breakdown at upstream stage i.e. PA during production, which will cause disruptions in supply to R&S stage. Independent base-stock control of the two stages has an edge over coupled-line because R&S

would draw required stock from upstream and won't be affected in short run if the major breakdown at PA lasts not more than a day. The inclination toward coupled-line concept is drawn more from operational aspect because same supervisor runs the two stages and the lines can be operated on synchronized production schedules, which will be an easy task since coupling stock enabled simultaneous production start on two lines. It prevents need to prepare stock and use of personal judgment in scheduling that usually causes unnecessary inventories.

5.4.2.2 Verification of maximum batch size

It has been stated that the coupling stocks of a coupled-line are established to deliver desired service levels that base-stock policy intends to provide across a production stage, which resulted in consideration of a maximum batch size 'P_{max}'. A simple simulation model on Crystal Ball was developed to verify that the maximum batch size values are established correctly. The simulation was carried out on Azur 46 Non Ionic with a mean and standard deviation of demand each as 1358 (CV=1) for a time period of 120 days (i.e. from July to October and consistent with time frame of inventory calculations) and a total of 10,000 runs were executed for better sampling. The maximum batch size 'P_{max}' value as given in table 5-9 was compared with the production target 'P' and the excess production targets were counted relative to the maximum batch size. The base-stock level of the coupled-line was set initially with 'W' and 'I' values given in table 5-10, which is calculated to provide a service level of 95% across coupled-line. Figure 5-11 depicts the histogram of the production targets excess count relative to the maximum batch size.

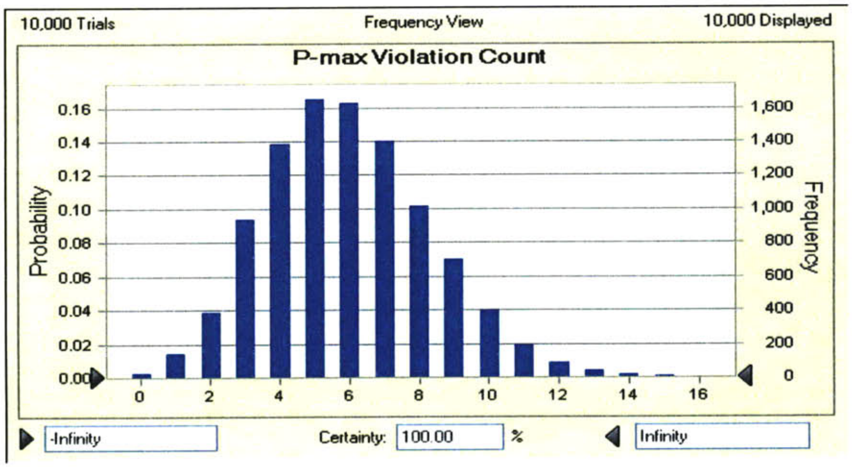

Figure 5-11: Histogram of production targets violation of P_{max}

Simulation model statistics shows that productions targets will exceed maximum batch size for only 5% of the time on average (8.34% of the time with 95% confidence) and there it can be concluded that 'P_{max}' accurately established for a service level of 95% (as explained in section 4.5.3.1

5.4.2.3 Coupling stock levels verification

Once the maximum batch size values are established according to the method explained in section 4.5.3.1, it should also be verified that the coupling stock would deliver desired performance i.e. it will not exhaust and cause disruptions in production, provided the upstream line doesn't experience a major breakdown. A simple MS-Excel based simulation is carried out on coupling stock of Azur 46 Non Ionic of size 600 (equivalent to 4 trolleys of size 150), which is subjected to the maximum production target that it can serve (i.e. maximum batch size of 3600 equivalent to 24 trolleys of size 150) and the performance is illustrated in figure 5-12.

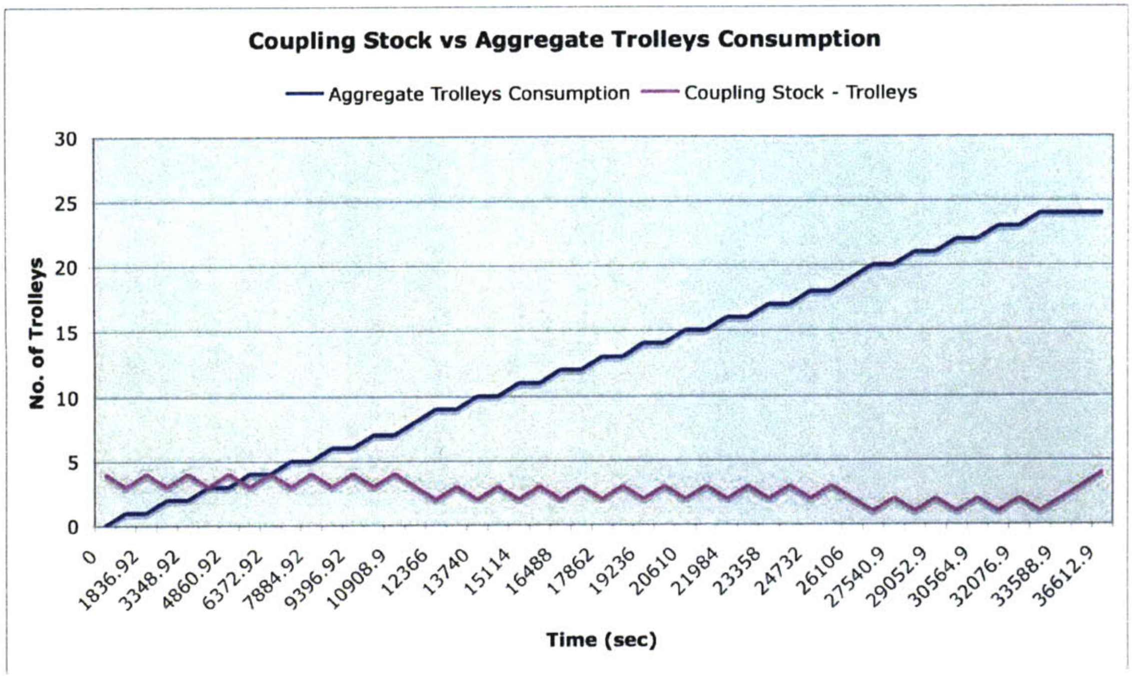

Figure 5-12: Coupling stock simultaneous consumption & replenishment

X-axis is representing the time-line marked for consumption of trolleys by R&S line and replenishment by PA line and Y-axis shows count of trolleys. It can be seen that a total of 24 trolleys are being consumed by R&S to meet a production target of 3600 while PA is simultaneously replenishing the coupling stock. The coupling stock graph never touches zero and rise back to its initial position of 4 trolleys once R&S has met its requirements. The minimum number of trolleys present at any instant was 1 and therefore it can be concluded that coupling stock would provide desired performance successfully under the assumptions stated for its feasibility.

5.5 Operational impact

This thesis is written at a time when PDA is undergoing implementation of the proposed solutions provided during internship work and management is keen to implement and extract value from a system it had put immense interest in. Management has evaluated the proposed solutions at every stage of project and provided feedback that added value to the work. The immediate impact, which appears most potential, is the improvement in PDA manufacturing operations practice. A complete solution in form of an inventory control policy that suits quite well to PDA production system is provided after verification through simulation work with a Kanban based visual management system and capacitated shipment planning approach that is established to integrate shipment planning practice with inventory control policy to ensure that the transition is smooth from current practice to new system.

Inventory structures on the production floor will be certain and allocated in right quantities to ensure inter-stage service levels are met. Production planning would be an easy task comparatively and decisions would be made with an insight into inventory levels and within integrated capacity constraints. Furthermore, visual management system will enable clear communication between productions stages for material consumption and replenishment signals and therefore production planner doesn't need to prepare plans for individual production stages once the planning phase has considered all the constraints.

The direct impact of the inventory control policy is setting up controlled inventory levels across production stages, which after comparison with the current inventory levels, turned out to be a major reduction in overall inventory levels of PDA. This comparison is depicted in figure 5-13 in which the anticipated inventory levels are derived from inventory calculations whereas current inventory levels are taken on average during June for the high runner SKU SPs. It can be seen that PDA is keeping high inventory levels at the finished goods stage i.e. R&S. The reason behind high stocks at last stage is the stocking of finished goods for serving requirements during production lines movement to another location, which makes current year an exception even though the demand figures are not as high as last year and could be met by capacity alone. The usual reason for stocking finished goods is to meet demand requirements in excess to capacity during high demand season. It is observed that the current inventory levels at intermediate production stages are ever fluctuating and thus cause uncertainty in service levels between production stages.

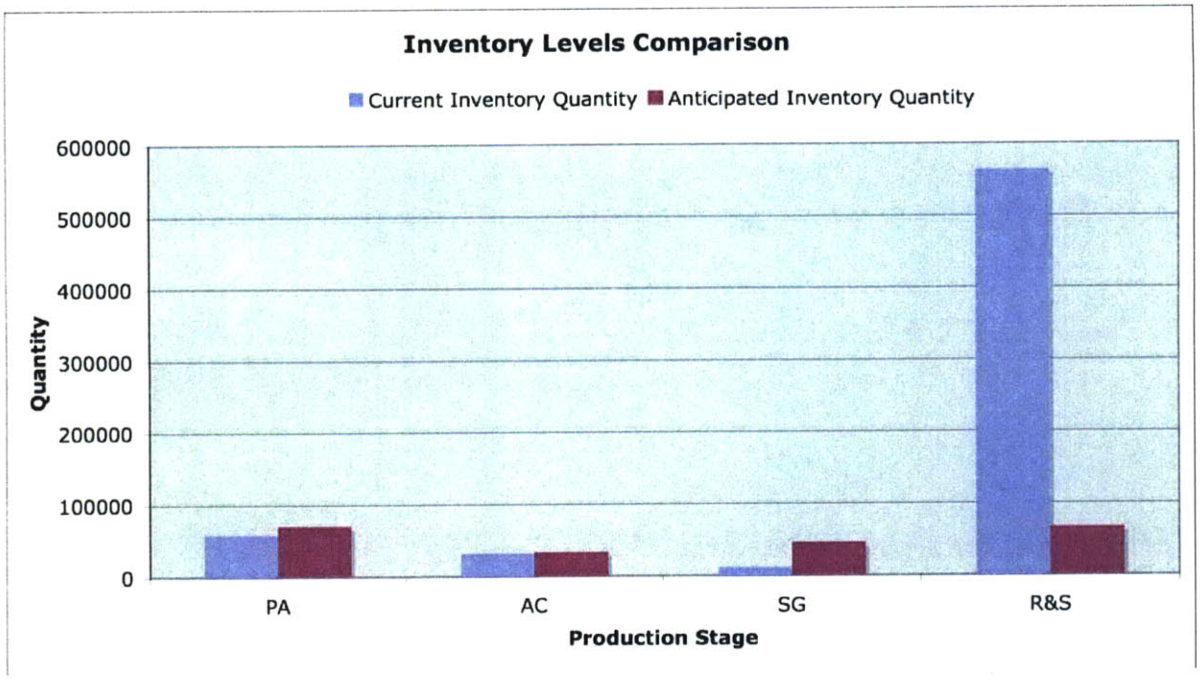

Figure 5-13: Inventory levels comparison

It can be seen that the anticipated inventory levels at R&S stage even with consideration of stocking are much lower as compared to current inventory levels and their contribution to total inventory levels is dropped from 84.6% to 30.9% as shown in figure 5-14. However, increase in inventories at intermediate stages can be seen and is explained as setting up of base-stocks to ensure adequate service levels between production stages. The overall reduction in inventory levels is estimated to be 67.4% across all the production stages. The reduction in finished good stock levels also indicate that PDA will have less customized inventories, which would be present in upstream production stages and increase PDA responsiveness to demand fluctuations.

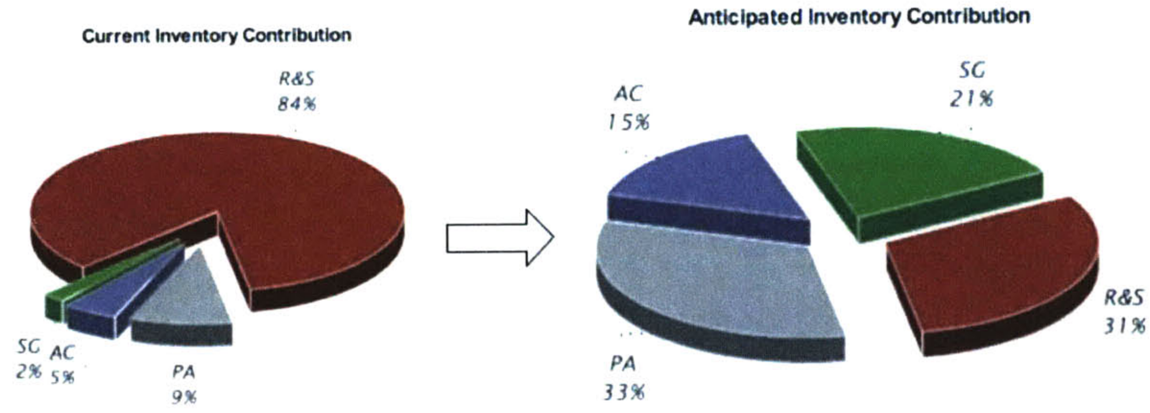

Figure 5-14: Inventory level contributions comparison

5.6 Financial impact

As shown in section 5.5, it is anticipated that overall inventory figures at PDA would be controlled and showed reduction from their current levels. This reduction resulted in financial savings because overall inventory holding costs would drop and increase cash in operations budget. This impact can be seen in figure 5-15 (inventory values are not shown because of information confidentiality but relative difference between values can be observed), which shows that proposed inventory control policy would reduce the cash blocked in inventories. An overall reduction of 74.3% is expected because the inventory levels at R&S stage are greatly reduced, which contribute 90.8% percent in current inventory values and is expected to contribute only 41.7% after implementation of the proposed solutions as shown in figure 5-16. Hence the proposed inventory control policy would help in restructuring the inventory levels and results in shifting the inventories to upstream production stages where the inventory costs are lower as compared to finished goods.

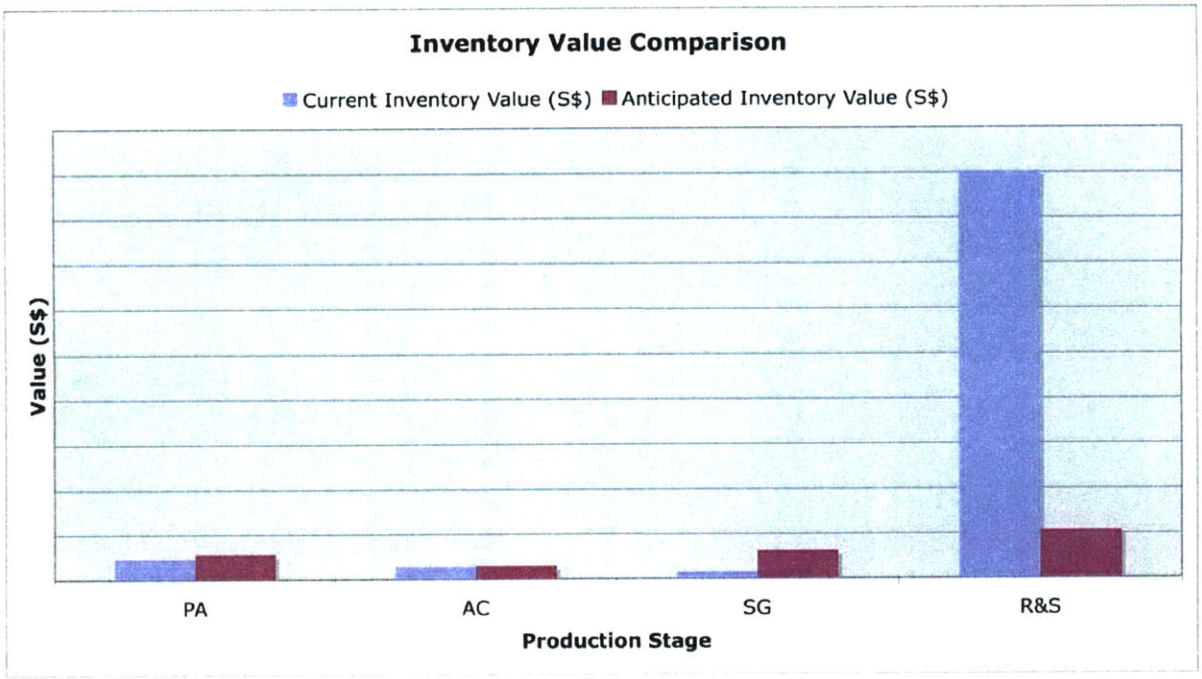

Figure 5-15: Inventory value comparison

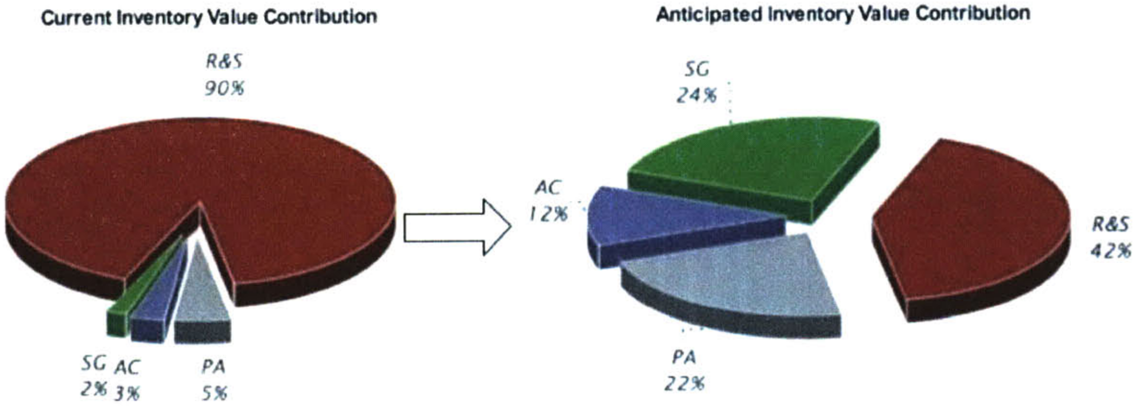

Figure 5-16: Inventory value contributions comparison

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CHAPTER 6: RECOMMENDATIONS, CONCLUSION & FUTURE WORK

6.1 Recommendations

The project work presented in this thesis resulted into solutions that were verified and improved with PDA management feedback. The following recommendations are made for smooth transition from current production planning and inventory control practice to the proposed ones and obtain the benefits that are expected in form of inventory reduction and improved operational practices.

1) Production requirements seasonality should be analyzed according to the provided framework and analysis of variance (ANOVA) should be carried out to choose the best monthly groupings that forms production seasons.

2) Production requirements characteristics for high runner SKUs should be extracted from stock building plan according to the proposed method during each production season.

3) Production requirements characteristics should be pooled for production stages (wherever applicable) as explained in this thesis and effective capacity of each production stage should be estimated with consideration of low runner SKU SPs production requirements.

4) Base-stock levels for production stages should be set up according to the proposed inventory control policy during identified production seasons with respective production requirements characteristics.

5) Production personnel should use the Kanban system to align operational activities with the inventory control policy requirements for delivery of its performance.

6) Production planner should use capacitated shipment planning approach to ensure shipment plans are feasible in terms of production capacity and stock levels.

6.2 Project wide conclusion

The MEng project at PDA Singapore aims to design a system for controlling inventory and directing daily production. After a thorough study of the factory' operation, the MEng 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 [2] and Yuan Zhong [3] focused on the bottleneck of the production system, the ST stage. Xiaoyu Zhou [1] and the author worked on PA, AC, SG and R&S stages, covering the end stages of various products. The implementation of systems designed by the two teams is expected 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 [3] 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 author studied the performance of the proposed base-stock model was using Monte Carlo 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 [2] and Yuan Zhong [3] simulation at ST stage also indicated that small batch sizes could be more cost-efficient in actual operation. Xiaoyu Zhou [1] and the author, 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 [2] developed a capacity planning optimization framework to handle excess demand during peak demand season. Xiaoyu Zhou [1] proposed a production leveling method functioning as a demand filter, which was shown to improve customer service level during simulation. The author developed an interface tool for production planner that enables integration of shipment planning and proposed inventory policy with capacity and stock considerations.

Based on the above results, the group recommends that PDA 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 PDA 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

There are few things that are identified as potential future work and are expected to improve the performance of the solutions presented in this thesis.

1) Study of SKUs demand correlation can help in identifying more realistic production requirement characters because the PDA customer, i.e. assembly plant has limited capacity and it demand supply of high runner SKU finished SPs on different days to level the load on its production resources. This thesis has set stock levels for a scenario where the entire range of high runner SKUs can be supplied together. This requirement can be relaxed in light of results provided by detailed demand correlation analysis and may result in further inventory levels reduction.

2) HE and DC production stages are not covered in the project work and the same inventory control policy can be extended to include these two stages for synergistic improvement.

3) SG production stage has issues related to production yield caused by smaller batch size and thus tends to accumulate requirements for 3-4 days. This can be studied in details and if feasible, suitable modifications can be made to the base-stock control of SG.

4) The base-stock levels are established using effective capacities (with considerations of average production time losses in changeovers, machine breakdowns and maintenance activities) and the simulation work didn't involve study of issues related to machine breakdowns in particular. Therefore, production lines reliability aspect can be incorporated in the simulation model and the results can be used to modify inventory levels.

5) Capacitated shipment planning approach can be extended to include planning for low runner SKUs production by making use of the reserved capacity. This integration would prevent the production planner from parallel planning of low runner and high runner SKUs production.

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APPENDICES

Appendix-A – ANOVA result

ANOVA: Single Factor - Production Seasonality Analysis						
SUMMARY						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Nov-Apr	6	4041.3164	673.5527333	10617.23675		
May-Oct	6	6319.2174	1053.2029	39082.53843		
ANOVA						
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F-critical***
Between Groups	432402.7472	1	432402.7472	17.40059168	0.001913695	4.96
Within Groups	248498.8759	10	24849.88759			
Total	680901.623	11				

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Appendix-B – Coupling stock formula derivation

'Unit time' i.e. UT can be defined as the time interval between two consecutive parts being loaded or unloaded on a production line. 'Cycle time' i.e. CT has the meaning of total time a part spent on the entire line.

Since it is desired that the two lines i.e. PA and R&S start production simultaneously, the initial values of the coupling stock say Q_1, should be enough to supply R&S until the first replenishment is made from PA. The time required by the first trolley of size 'T' to be processed by PA needs a total time, $CT_1 + (T-1) \text{ x } UT_1$ (It should be noted that the first part at PA would take CT_1 before it can be unloaded and the remaining (T-1) parts would be following the first part with a time interval of UT_1), during which R&S would be consuming stock with time interval of UT_2 between two successive parts consumption. Hence Q_1 should have a value as given by following relationship,

$$Q_1 \square \frac{CT_1 \square (T-1)\text{x}UT_1}{UT_2}$$

The coupling stock is established to even couple two unbalanced lines, i.e. with different production rates, PA is slower than R&S for Superior (Azur) family in our case, hence the coupling stock should also hold material for the difference in production rates to prevent R&S starvation within a certain limit i.e. a maximum batch size of $P_{\max}$. By the time R&S has already consumer Q_1, the maximum remaining requirements would be '$P_{\max}$ - Q_1' for which the production rates difference effect should be dealt with. The difference in time taken by PA and R&S to produce this remaining maximum requirement value can be expressed as $(P_{\max} - Q_1)\text{x}UT_1 - (P_{\max} - Q_1)\text{x}UT_2$, during which coupling stock should hold stock that can be consumed by R&S. This portion of coupling stock can be given by following relationship,

$$\frac{(P_{\max} - Q_1)\text{x}UT_1 - (P_{\max} - Q_1)\text{x}UT_2}{UT_2},$$

Or

$$\frac{(P_{\max} - Q_1)\text{x}(UT_1 - UT_2)}{UT_2}$$

Hence the total coupling stock value can be expressed as sum of the two requirements as follow,

$$CS \square Q_1 \square \frac{(P_{\max} - Q_1)\text{x}(UT_1 - UT_2)}{UT_2}$$

This relationship can be further derived purely in terms of unit times and cycle time in the following manner,

$$CS \square \frac{Q_1\text{x}UT_2 \square (P_{\max} - Q_1)\text{x}(UT_1 - UT_2)}{UT_2}$$

$$CS \square \frac{(\frac{CT_1 \square (T-1)\text{x}UT_1}{UT_2})\text{x}UT_2 \square [P_{\max} - \frac{CT_1 \square (T-1)\text{x}UT_1}{UT_2}]\text{x}(UT_1 - UT_2)}{UT_2}$$

$$CS \square \frac{CT_1 \square (T-1)\text{x}UT_1 \square [\frac{P_{\max}\text{x}UT_2 - CT_1 - (T-1)\text{x}UT_1}{UT_2}]\text{x}(UT_1 - UT_2)}{UT_2}$$

$$CS \square \frac{\frac{[CT_1 \square (T-1)\text{x}UT_1]\text{x}UT_2 \square [P_{\max}\text{x}UT_2 - CT_1 - (T-1)\text{x}UT_1]\text{x}(UT_1 - UT_2)}{UT_2}}{UT_2}$$

$$CS \square \frac{[CT_1 \square (T-1)\text{x}UT_1]\text{x}UT_2 \square [P_{\max}\text{x}UT_2 - CT_1 - (T-1)\text{x}UT_1]\text{x}(UT_1 - UT_2)}{(UT_2)^2}$$

Appendix-C – Kanban system design

The proposed base-stock control across a production stage makes replenishment and consumption decisions by use of parameters such as intra-stage stock 'W', inter-stage stock 'I', downstream requirements 'D' and stage lead-time 'n'. The Kanban system is designed to align role of these parameters in the consumption and replenishment decisions with physical material movement between and within production stages.

The design proposes use of a Kanban board and cards to reveal real-time stock levels of SKU SPs at the production stage and signal material acquisition (from upstream stage) and replenishment of inter-stage stock 'I'. The operation of the card movement for a SKU at a production stage is explained with the help of figure C-1, which has four sections and represents 'I', 'R', present WIP and 'P' levels. The total number of cards in R and 'WIP' section indicates the intra-stage stock 'W' level.

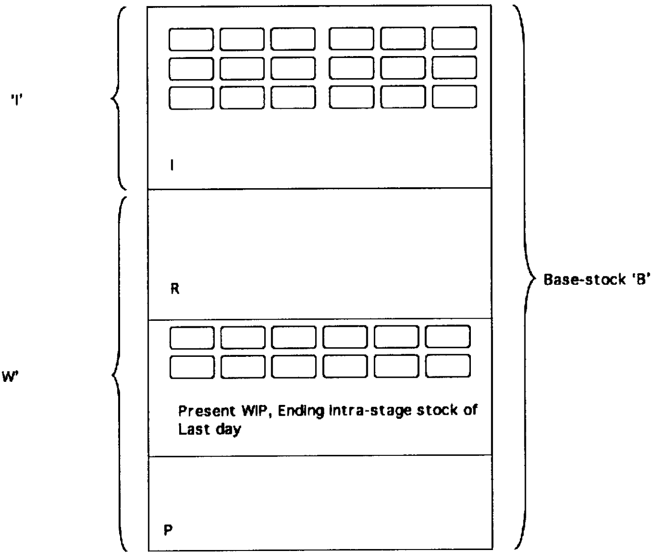


Figure C-1: Kanban board at the start of the day

The operation of card movement is summarized as under,

1) At the start of the day, downstream requirements 'D' are fulfilled from 'I' and equal number of cards on this section are moved to section 'R'. This movement is aligned with the base-stock policy requirements of material acquisition from upstream stage in exact proportion to the downstream requirements i.e. 'R=D'. This cards movement is the first step of Kanban operation that updates 'I' values for the day. This is depicted in figure C-2.

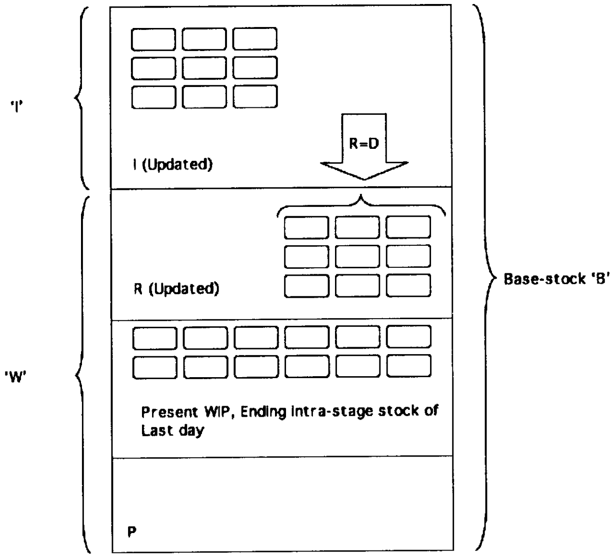


Figure C-2: Kanban board with updated-I

2) Production personnel/material handlers are required to replenish intra-stage stock 'W' of the stage by obtaining material quantity, indicated by the number of cards in 'R' section, from upstream stage. Material acquisition would make the board look as shown in figure C-3 with updated WIP levels.

3) Once the required material is obtained from upstream stage, production personnel would set the production targets based on the linear-production rule i.e. P=W/n and round-off the targets to the next multiple of container/trolley size used to store stage's finished SP stock. Number of cards equivalent to production target will be moved to the 'P' area. The updated board would look as in figures C-4.

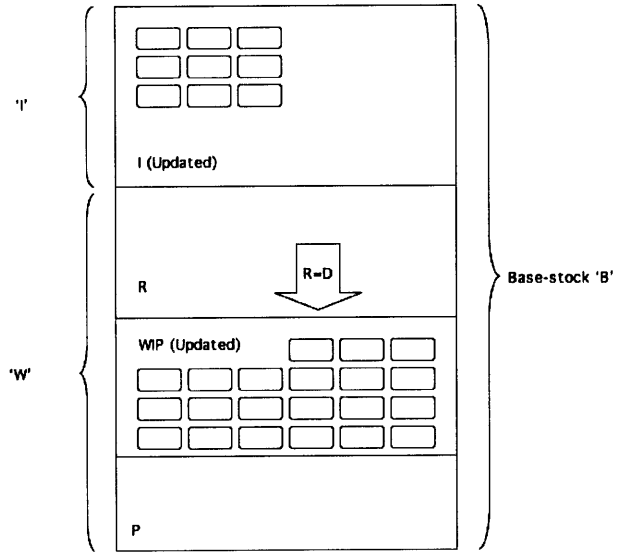


Figure C-3: Kanban board after material acquisition

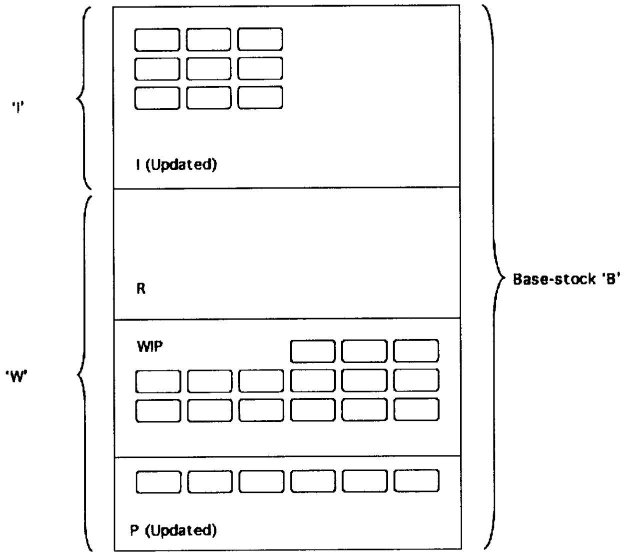


Figure C-4: Kanban board with updated-P

4) The cards from 'P' section to 'I' section will be moved in real-time when a container/trolley has been processed by the production stage. At the end of the day, when the production targets have been met, all the cards in 'P' section would have been moved back to 'I' section and the board would appear as shown in figure C-5.

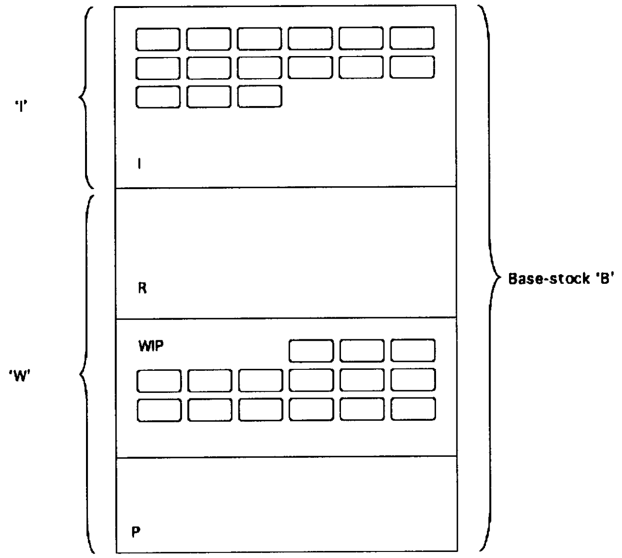
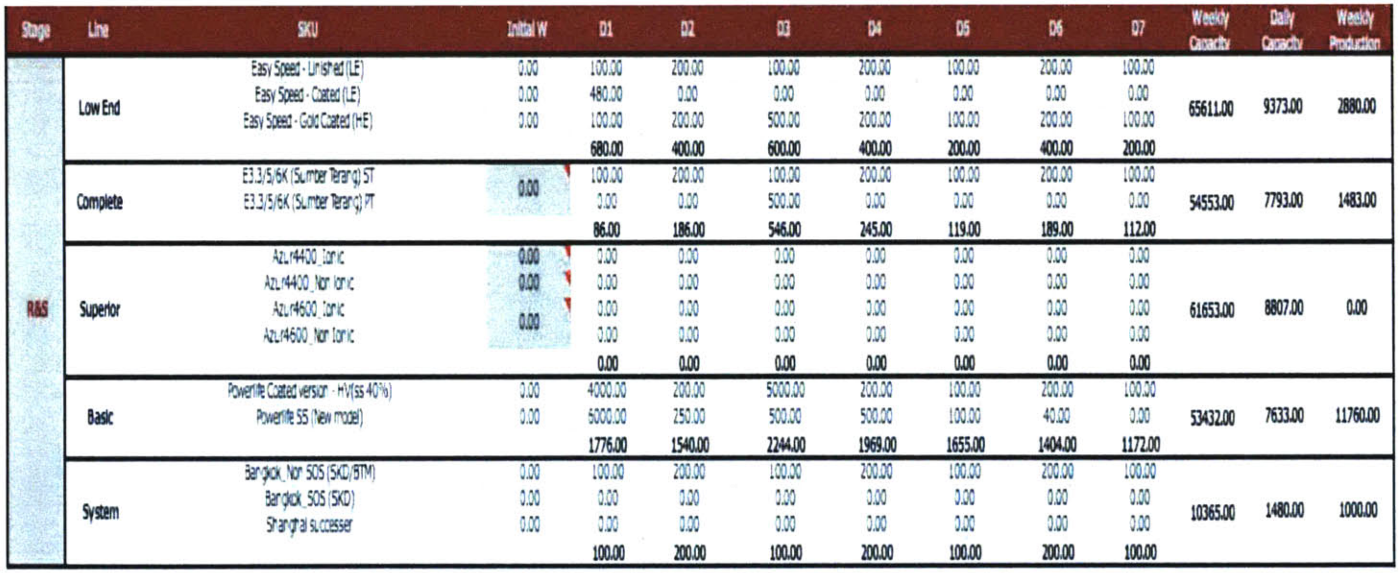


Figure C-5: Kanban board at the end the of day

Appendix-D – Capacitated shipment planning



Stage	Line	SKU	Initial W	D1	D2	D3	D4	D5	D6	D7	Weekly Capacity	Daily Capacity	Weekly Production
R&S	Low End	Easy Speed - Unfinished (LE)	0.00	100.00	200.00	100.00	200.00	100.00	200.00	100.00	65611.00	9373.00	2880.00
		Easy Speed - Coated (LE)	0.00	480.00	0.00	0.00	0.00	0.00	0.00	0.00			
		Easy Speed - Gold Coated (HE)	0.00	100.00	200.00	500.00	200.00	100.00	200.00	100.00			
				680.00	**400.00**	**600.00**	**400.00**	**200.00**	**400.00**	**200.00**			
	Complete	E3.3/5/6K (Sumber Terang) ST	0.00	100.00	200.00	100.00	200.00	100.00	200.00	100.00	54553.00	7793.00	1483.00
		E3.3/5/6K (Sumber Terang) PT		0.00	0.00	500.00	0.00	0.00	0.00	0.00			
				86.00	**186.00**	**546.00**	**245.00**	**119.00**	**189.00**	**112.00**			
	Superior	Azur4400_Ionic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	61653.00	8807.00	0.00
		Azur4400_Non Ionic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
		Azur4600_Ionic	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
		Azur4600_Non Ionic		0.00	0.00	0.00	0.00	0.00	0.00	0.00			
				0.00	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**			
	Basic	Powerlife Coated version - HV(ss 40%)	0.00	4000.00	200.00	5000.00	200.00	100.00	200.00	100.00	53432.00	7633.00	11760.00
		Powerlife SS (New model)	0.00	6000.00	250.00	500.00	500.00	100.00	40.00	0.00			
				1776.00	**1540.00**	**2244.00**	**1969.00**	**1655.00**	**1404.00**	**1172.00**			
	System	Bangkok_Non SOS (SKD/BTM)	0.00	100.00	200.00	100.00	200.00	100.00	200.00	100.00	10365.00	1480.00	1000.00
		Bangkok_SOS (SKD)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
		Shanghai successer	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
				100.00	**200.00**	**100.00**	**200.00**	**100.00**	**200.00**	**100.00**			

Figure D-1: Capacitated shipment planning interface snapshot