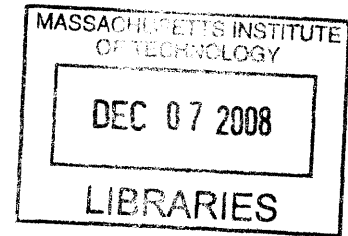


# Multiple-Part-Type Production Scheduling for High Volume Manufacturing (Token-Based Approach)

by

Sing Hng Ng

B.Eng. Chemical Engineering  
National University of Singapore, 2007



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## **Abstract**

Multiple-part-type production scheduling is a common industrial problem with no generalized solution. In this thesis, a systematic approach is presented to aid in the mentioned production decision making in an actual factory. This strategy involves first generating production targets by optimization followed by a real-time scheduling (token-based) method --- the Control Point Policy. Based on the simulation results, the proposed strategy is able to schedule the production effectively. In addition, it was demonstrated that there was a tradeoff between the amount of inventory and the number of changeovers.

**Keywords:** Multiple-part-type, production scheduling, optimization, token-based

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

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

## **Acknowledgement**

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Finally, I want to thank my team-mates, Mr Zhiyu Xie, Mr Kai Zhao Lee and Ms Xia Hua whom have accompanied me on this journey of learning and exploration.

## List of Figures

- Figure 1.1** *Process Flow Diagram*
- Figure 1.2** *Part types produce by each line*
- Figure 2.1** *Current Production Planning*
- Figure 2.2** *Demand Pattern*
- Figure 2.3** *Weekly Production Plan*
- Figure 3.1** *Multiple-part-type token-based system*
- Figure 4.1** *Methodology*
- Figure 4.2** *Demand versus Capacity*
- Figure 4.3** *Token-based CPP graphical interface*
- Figure 4.4** *Synchronization of production buffers with demand buffers*
- Figure 4.5** *Code at 'Job Release' Machine*
- Figure 4.6 (a)** *TTF evaluation with Stat-Fit for Simul8*
- Figure 4.6 (b)** *TTF distribution fitting*
- Figure 4.7 (a)** *TTR evaluation with Stat-Fit for Simul8*
- Figure 4.7 (b)** *TTR distribution fitting*
- Figure 5.1 (a)** *Cumulative production versus cumulative demand (Part-type A)*
- Figure 5.1 (b)** *Cumulative production versus cumulative demand (Part-type B)*
- Figure 5.1 (c)** *Cumulative production versus cumulative demand (Part-type C)*
- Figure 5.1 (d)** *Cumulative production versus cumulative demand (Total)*
- Figure 5.2** *Cumulative setup changeover frequency*
- Figure 5.3** *Relationship between changeover frequency and hedging levels*
- Figure 5.4** *Relationship between average inventory and hedging levels*

## List of Tables

<b>Table 1</b>	<i>Simul8 legend</i>
<b>Table 2</b>	<i>Simulation inputs</i>
<b>Table 3</b>	<i>Sample optimization output</i>
<b>Table 4</b>	<i>Token-based hedging levels with no lateness</i>
<b>Table 5</b>	<i>Quantity of lateness tested under different scenarios</i>
<b>Table 6</b>	<i>Revised Token-based hedging levels with no lateness</i>
<b>Table 7</b>	<i>Time-based parameters with no lateness</i>
<b>Table 8</b>	<i>Cost tabulation for time-based CPP</i>
<b>Table 9</b>	<i>Comparison of time-based and token-based CPP</i>
<b>Table 10</b>	<i>Comparison of proposed strategy with current strategy</i>

## List of Notations

$H^U$	=	Upper hedging level
$H^L$	=	Lower hedging level
TC	=	Total cost
IC	=	Inventory holding cost
MC	=	Extra cost of production on the manual line
E	=	Extra cost to produce unit quantity on the manual line
$P_{tmA1}$	=	Production on auto-line 1 of part-type m in time period t
$P_{tmA2}$	=	Production on auto-line 2 of part-type m in time period t
$M_t$	=	Manual-line production in time period t
$D_{tm}$	=	Demand for part-type m in time period t
$CP_{tm}$	=	Cumulative production on auto-lines for part-type m in time period t
$CM_t$	=	Cumulative production on manual line in time period t
$CD_{tm}$	=	Cumulative demand for part-type m in time period t
$I_w$	=	Cost to hold unit inventory for one week
$I_M$	=	Cost to hold unit inventory for one month
$C_{A1t}$	=	Capacity of auto-line 1 per time period
$C_{A2t}$	=	Capacity of auto-line 2 per time period
$C_{Mt}$	=	Capacity of manual line per time period

# Table of Contents

**ABSTRACT**

**ACKNOWLEDGEMENT**

**LIST OF FIGURES**

**LIST OF TABLES**

**LIST OF NOTATIONS**

<b>CHAPTER 1</b>	<b>INTRODUCTION .....</b>	<b>1</b>
1.1	COMPANY BACKGROUND.....	1
1.2	DESCRIPTION OF STATION A .....	3
1.4	THESIS OUTLINE .....	4
<b>CHAPTER 2</b>	<b>PROBLEM STATEMENT .....</b>	<b>5</b>
2.1	CURRENT PRODUCTION PLANNING .....	5
2.2	DEMAND PATTERN .....	6
2.3	OBJECTIVES .....	7
<b>CHAPTER 3</b>	<b>LITERATURE REVIEW .....</b>	<b>9</b>
3.1	DEMAND FORECASTING.....	9
3.2	OPTIMIZATION .....	9
3.3	CONTROL POINT POLICY .....	10
<b>CHAPTER 4</b>	<b>METHODOLOGY .....</b>	<b>13</b>
4.1	OVERVIEW .....	13
4.2	STEP 1 - CAPACITY EVALUATION .....	14
4.3	STEP 2 - OPTIMIZATION .....	15
4.4	STEP 3 - CONTROL POINT POLICY .....	20
4.5	DESCRIPTION OF SIMULATION MODEL .....	21
<b>CHAPTER 5</b>	<b>RESULTS AND DISCUSSIONS.....</b>	<b>29</b>
5.1	RESULTS OF OPTIMIZATION .....	29
5.2	SIMULATION RESULTS FOR TOKEN-BASED CPP .....	31
5.3	COMPARISON OF TIME-BASED AND TOKEN-BASED CPP .....	39
5.4	COMPARISON OF PROPOSED STRATEGY WITH CURRENT STRATEGY .....	41
<b>CHAPTER 6</b>	<b>RECOMMENDATIONS/FUTURE WORK/ CONCLUSIONS .....</b>	<b>43</b>
6.1	RECOMMENDATIONS.....	43
6.2	FUTURE WORK .....	44
6.3	CONCLUSIONS.....	45
<b>APPENDIX A</b>	<b>THE CONTROL POINT POLICY .....</b>	<b>47</b>
<b>APPENDIX B</b>	<b>ESTIMATION OF PERCENTAGE REJECT .....</b>	<b>48</b>
<b>APPENDIX C</b>	<b>ASSUMPTIONS FOR FIGURE 4.2 .....</b>	<b>49</b>
<b>APPENDIX D</b>	<b>VISUAL LOGIC FOR SIMUL8 MODEL .....</b>	<b>50</b>

# Chapter 1 Introduction

Multiple-part-type production scheduling for a manufacturing line is an important industrial problem. However, there is no generalized method to guide industry practitioners from deciding when to switch production from one part type to the other. The decision to change is complicated by several factors which include satisfying the demand and limiting the amount of inventory. These challenges motivate the investigation of a token-based approach for multiple-part-type production scheduling. An alternative approach which uses time as a yardstick for production control was discussed in the author's team-mate (Zhiyu Xie) thesis [1] and the results for both methods are compared before a recommendation is proposed to the company under study.

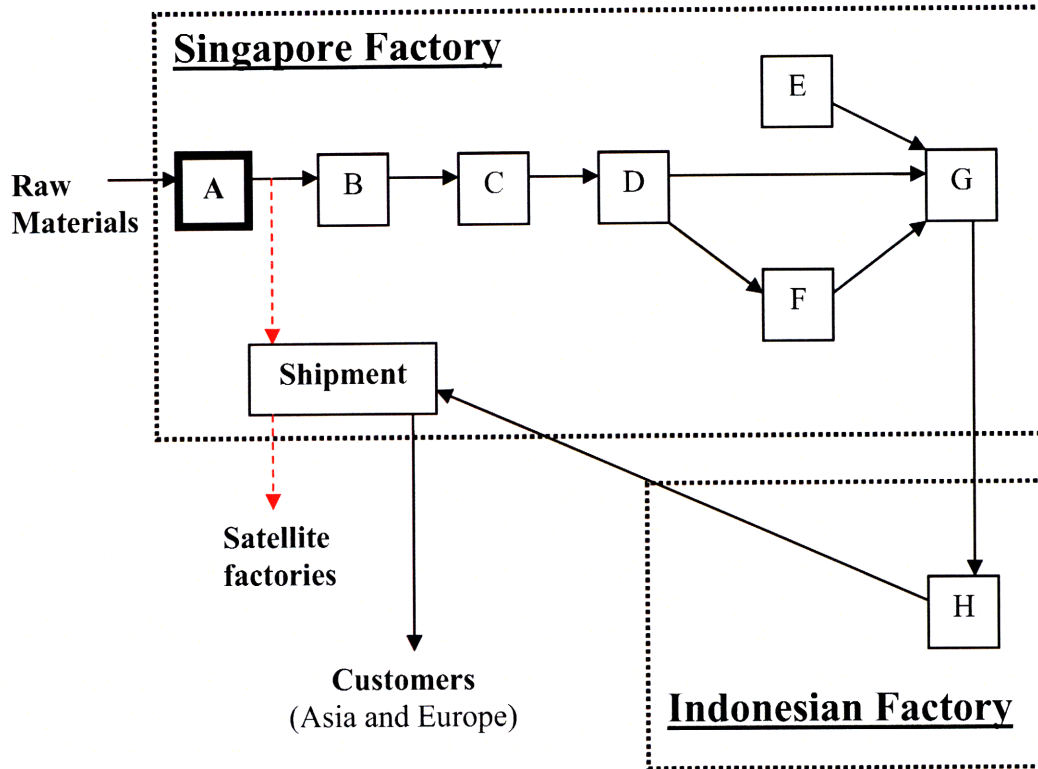
## 1.1 Company Background

Headquartered in Europe, the AILTER facility located in Singapore is a global manufacturer of product X. It produces more than 100 types of product X and supports the demand from both Asia and Europe.

In order to stay ahead of competition, the AILTER facility not only continues to develop better products but also takes active steps to stream-line its operation. One strategy which the AILTER facility adopted to reduce its operation cost was to manufacture the products in two different factories --- a Singapore factory and an Indonesian factory. Production starts at the Singapore factory where the product passes through 5 or 6 major stations. Next, the semi-finished product is shipped to the Indonesian factory where the labor-intensive final assembly operation is performed. The products which have been assembled at the Indonesian factory are the finished goods and will be shipped back to Singapore for distribution to the various geographical markets (*Figure 1.1*).

From the process flow diagram, one can observe that station's A production not only has to satisfy the immediate demand of Station B but it also has to support production of the

satellite factories (represented by the red dotted arrows). These satellite factories are part of the AILTER organization but are serving different geographical markets.

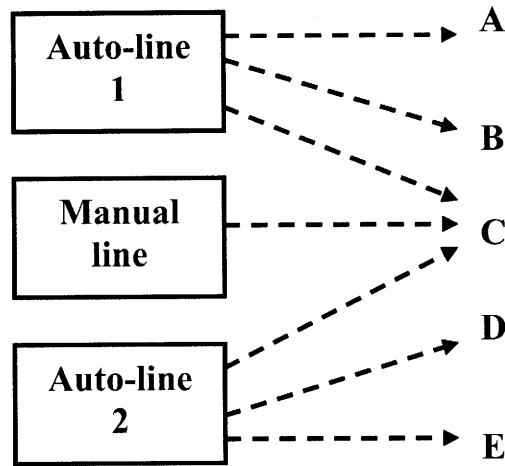


*Figure 1.1 Process Flow Diagram*

In this thesis, the scope of study is limited to Station A. There was a second team which worked on Station E at the same time. The team was made up of Xia Hua and Kai Zhao Lee and their theses [2], [3] are provided at the reference section. The main difference between Station A and Station E is their capacity relative to demand. Station A is capacity-constrained while Station E has large excess capacity relative to demand. As a consequence, the production decisions for these two stations are very different.

## 1.2 Description of Station A

Station A consists of two auto-lines and one manually-operated line (manual line for short). On auto-line 1, three part types can be produced namely part-type A, B and C. Similarly, auto-line 2 can produce three different products: part-type C, D and E. The manual line can only produce part-type C. A schematic representation of the part types each line can produce is shown in *Figure 1.2*.



*Figure 1.2* Part types produce by each line

The production lines have a similar set of machines which do a sequential operation on the semi-finished product. There are a total of 8 machines for each line. For the auto-lines, parts are transferred from one machine to another via conveyor belts. An interesting observation on the auto-lines is that on some conveyor belts, parts are only allowed to take up discrete spaces on the conveyor belt; while on other conveyor belts, the parts are continuously pushed towards the downstream machine. If there is a supply disruption from the upstream machine, the disturbance will be propagated in the earlier case but can be minimized in the second scenario. Since a manufacturing buffer is defined as a storage space between machines which can absorb upstream fluctuations, the latter conveyor belts behave like a true manufacturing buffer but not the earlier. To simplify the simulation model building process, this thesis uses an equivalent machine to simulate the auto-line 1 behavior.

Another important attribute of the auto-lines is that they have high production rate with minimal labor as compared to the manual line. As a result, the unit production cost on the manual line is much higher than the auto-lines. In addition, the operation of manual line requires the employment of contract workers which require additional human resource planning. Consequently, the management is trying to avoid the operation of manual line. In fact, the management has labeled the operation of manual line as an 'illegal' operation. However, the author noticed that the manual line is frequently under operation on several visits to Station A. Clearly, the management has not enforced the "*No Work Allowed on the Manual Line*" rule which it has specified.

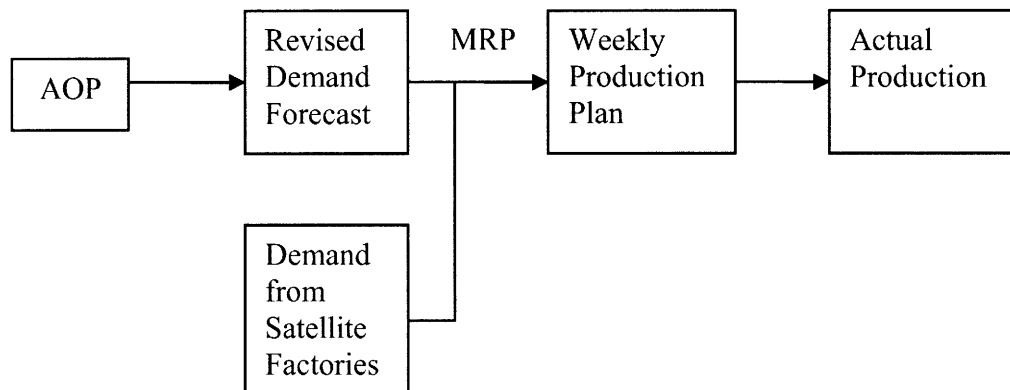
#### **1.4 Thesis Outline**

In this first chapter, a brief introduction of the company and the project is provided. Following in Chapter 2, the objectives of this thesis are stated explicitly. Chapter 3 provides a theoretical background of the techniques used for production scheduling. Next, Chapter 4 gives an outline of the proposed strategy. In Chapter 5, the results of the solution are shown. Finally, recommendations are provided in Chapter 6.

## Chapter 2 Problem Statement

### 2.1 Current Production Planning

Every September, the company projects its forecasted demand for the following year and records it on a document known as the Annual Operating Plan (AOP). At a regular time period, the company re-evaluates the inventories in its warehouses as well as the market conditions; thus a new demand forecast which has better accuracy than the AOP is obtained. At the same time, the factory anticipates production request from the satellite factories. After considering the total requirement from the two sets of demand forecast, the factory planner performs a material requirement planning (MRP) calculation to determine the weekly production plan. The weekly production plan is then used by the supervisor of Station A to plan for production whom schedules the production based on his experience. This process is illustrated in *Figure 2.1*.



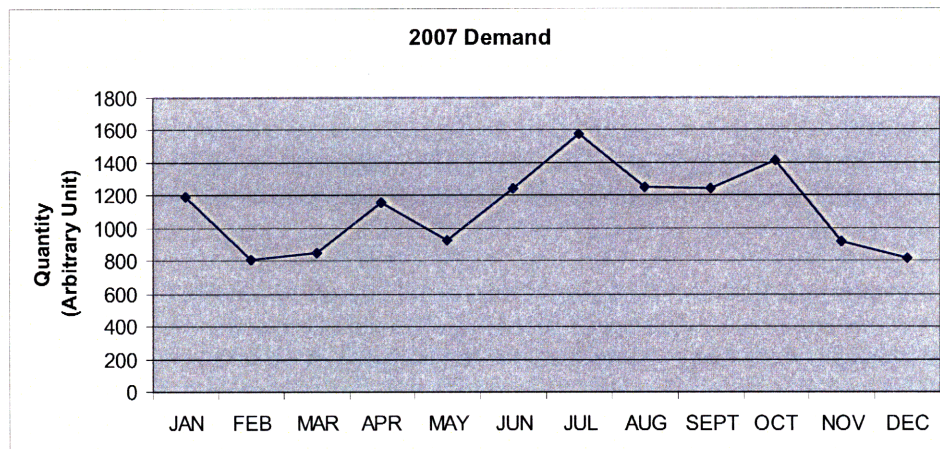
*Figure 2.1* Current Production Planning

Although the weekly production plan does not include the manual line, it is observed that in actual production, the manual line is frequently used to supplement the auto-lines' production. By observing the cumulative production of the auto-lines for each shift, one will notice that sometimes the production quantity by the auto-lines "magically" catch up with their respective targets. This is due to inputs from the manual line. The lack of production schedule for manual line makes human resource planning difficult because the requirement to operate the manual line is only known at the very last minute

## 2.2 Demand pattern

To facilitate coordination, all departments of the AILTER organization follow the AILTER calendar for planning. The AILTER calendar is a master calendar created by headquarter and stipulates how many weeks a month is made up of. According to the master calendar, the months of January, April, July and October are made up of 5 weeks in the year 2007. The remaining months have 4 weeks each. Thus, one will expect the demand quantity to be higher on the 5-week months.

Like most consumer products manufacturer, the AILTER facility observes a seasonal demand pattern. For illustration of the seasonal demand, the actual demand in the year 2007 is shown in *Figure 2.2*. From *Figure 2.2*, one can see that the demand during the third quarter is especially high. This demand peak is due to retailers placing advance orders in anticipation of Christmas.

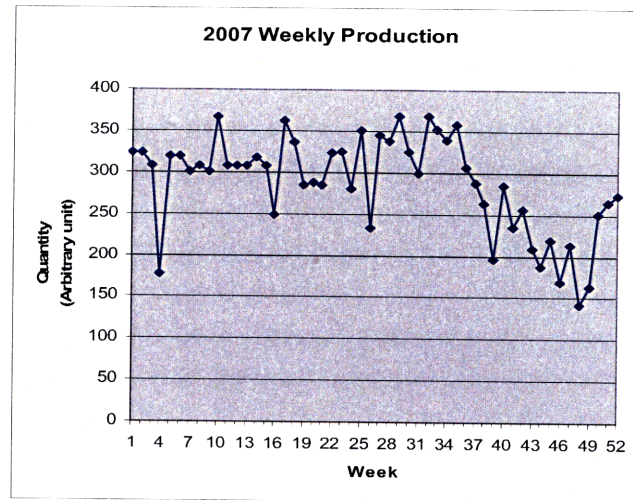


*Figure 2.2 Demand Pattern*

Since Station A has limited capacity, it is unable to satisfy the demand during the peak period. Thus, the factory has adopted a stock building strategy during the low demand period.

This decision is reflected in the weekly production plan (*Figure 2.3*). Besides having high production volume in the first three quarters, it was also observed that the weekly

production quantity exceeds the maximum combined capacity of the auto-lines (292 units). This suggests that the manual line was in operation during the first 36 weeks. In week 4, the low production is due to factory shutdown for Chinese New Year's celebration.



*Figure 2.3 Weekly Production Plan*

Another observation of the weekly production plan is that the auto-lines were not operated to their maximum capacity on the fourth quarter. This implies that there are opportunities to shift some production from the manual line to the auto-lines.

Additionally, it is questionable whether weekly production planning is the most ideal. If production planning is performed in an alternative manner, the loss production hours due to changeover may be decreased but at the expense of higher inventory holding cost. Thus, there is a trade-off between productivity and cost of keeping inventory

### **2.3 Objectives**

The main objective of this thesis is to develop a systematic approach for Station A to sequence its production so that it can satisfy its downstream requirements at an acceptable amount of inventory. In addition, this thesis will also address the following objectives:

- 1) To evaluate and demonstrate to the management whether it is necessary to operate the manual line. If the manual line is required for operation, this thesis will further propose a method to schedule production on the manual line.
- 2) To identify a cost-effective stock building strategy.
- 3) To suggest a method for distributing production of the common part type (part-type C) between the two auto-lines.
- 4) To evaluate the trade-off between the productivity and cost of holding inventory.

## **Chapter 3      Literature Review**

### **3.1    *Demand forecasting***

According to Simchi-Levi [4], there are three principles of demand forecasts.

1. The forecast is always wrong
2. The longer the forecast horizon, the worse the forecast
3. Aggregate forecasts are more accurate

Thus, it is challenging to develop a production scheduling technique based on forecasted demand. A conventional method to handle the demand forecast uncertainty is to keep a level of safety stock which corresponds to the service level desired. Evidently, there is a tradeoff between the amount of inventory (safety stock) and the demand fulfillment rate.

Since the demand forecast is generally more accurate at the short term, it can be specified more precisely. On the other hand, the longer term demand forecast can be aggregated over a longer time period to increase its accuracy. This strategy is employed in the proposed method and thus, demand forecast of different resolutions are used simultaneously for production decision making. For example, if we are considering a span of 12 months, the demand forecast is of weekly demand resolution in the immediate month, while the monthly forecasted demand can be utilized for the remaining eleven months.

### **3.2    *Optimization***

Optimization is defined as choosing the best of a set of alternatives in the MIT course “Manufacturing Systems” [5]. It has various applications which include scheduling.

There are usually three main components in optimization problems, namely the (a) *Objective*, (b) *Decision Variables* and (C) *Constraints*. The objective refers to the goal which we aim to achieve and that it is something which we wish to maximize or minimize. Since cost is the main driver for a manufacturing company, the objective which is of interest in this thesis is cost minimization. Next, decision variables refer to the parameters that can be changed to achieve the objective. Finally, constraints are relationships which determine the boundaries of the feasible solution set. Constraints can be due to physical limitations of the process such as capacity of a machine or that it can be arbitrarily limited by the user.

Although production scheduling is a continuous-time problem, it can be discretized and approximated as discrete-time problems. Thus, they can be roughly solved as *Non-Linear Programming* problems. Non-linear programming is a class of optimization which has continuous objective, decision variables and constraints.

For production scheduling, one input to the optimization algorithm is the demand forecast. As the time progress, better estimates of the demand are obtained. This results in changes in the forecasted value. A possible approach to handle these changes is to optimize with time as each new demand forecast is obtained.

### **3.3 Control Point Policy**

The Control Point Policy is a production scheduling strategy developed by Dr Stanley B. Gershwin, senior research scientist of the Laboratory for Manufacturing and Productivity, Massachusetts Institute of Technology. Its objective is to produce the required quantity at the right time and to keep work-in-progress (WIP) inventory limited. This is achieved using a set of control points which regulate the flow of material into and through the system [6, 7].

Control points regulate the material flow by limiting how far production is ahead of time and using buffers of limited size. The finite buffers prevent the WIP from being

excessive large. Additionally, the control points also consider which job should be performed first based on its priority.

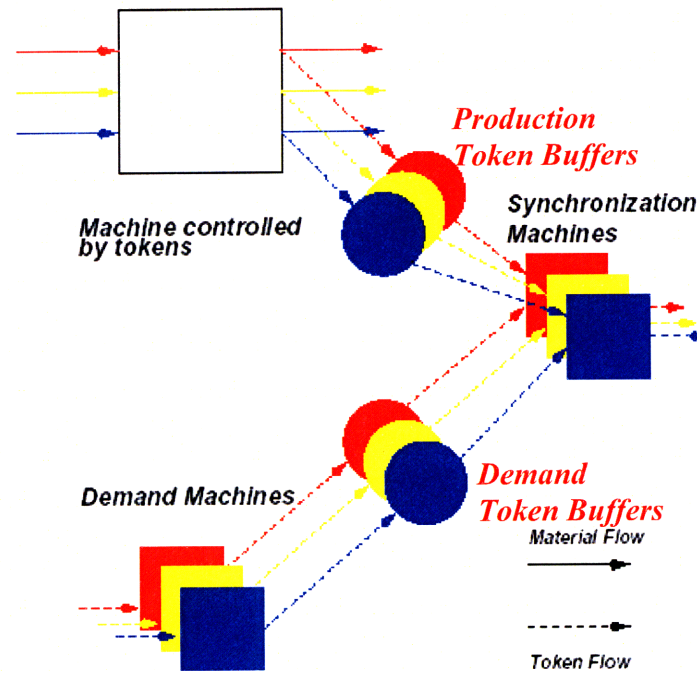
There are two versions of the Control Point Policy --- Time-based version and Token-based version. In the first version, the production scheduling makes use of the jobs specified due dates to decide the order of production. On the other hand, Token-based version regulates the buffer level for each class of inventory.

The time-based version of Control Point Policy will not be discussed in this thesis and that the interested reader is advised to refer to Zhiyu Xie's thesis [1] for additional details.

In the original Control Point Policy, the production scheduling strategy is developed for production lines which manufacture one part type. Since many production lines use in the industry produce more than one part type, Dr Gershwin has identified the importance of developing a more general strategy that is suitable for multiple-part-type production. This leads him to propose a modified form of the Control Point Policy known as the ***Control Point Policy with Setup Change Policy*** [8].

For the token-version of the Control Point Policy with Setup Change Policy (*Appendix A*), Dr Gershwin suggests that two types of token buffers are used. One type of token buffers call the *Demand Token Buffer* has infinite capacity. When a demand arrives, a KANBAN card (authorization card) is placed into its respective *Demand Token Buffer* and thus signals for production. There is a second type of token buffer known as the *Production Token Buffer* which has finite capacity. Once each job is completed, a Production card is placed into its corresponding *Production Token Buffer*. Since the *Production Token Buffer* has limited capacity, it will not allow a Production card to be added if it has the maximum number of Production cards. The result is that a new job cannot be allowed to work on until at least one production card is removed.

Each *Demand Token Buffer* is connected to its corresponding *Production Token Buffer* by a synchronization machine. Whenever there is a KANBAN card and a Production card present in their respective Token Buffers, the synchronization machine will immediately remove the two cards from their buffers. Thus, both the *Production Token Buffer* and the *Demand Token buffer* decrease at the same rate. A pictorial representation of the Token-based system is provided in *Figure 3.1*.



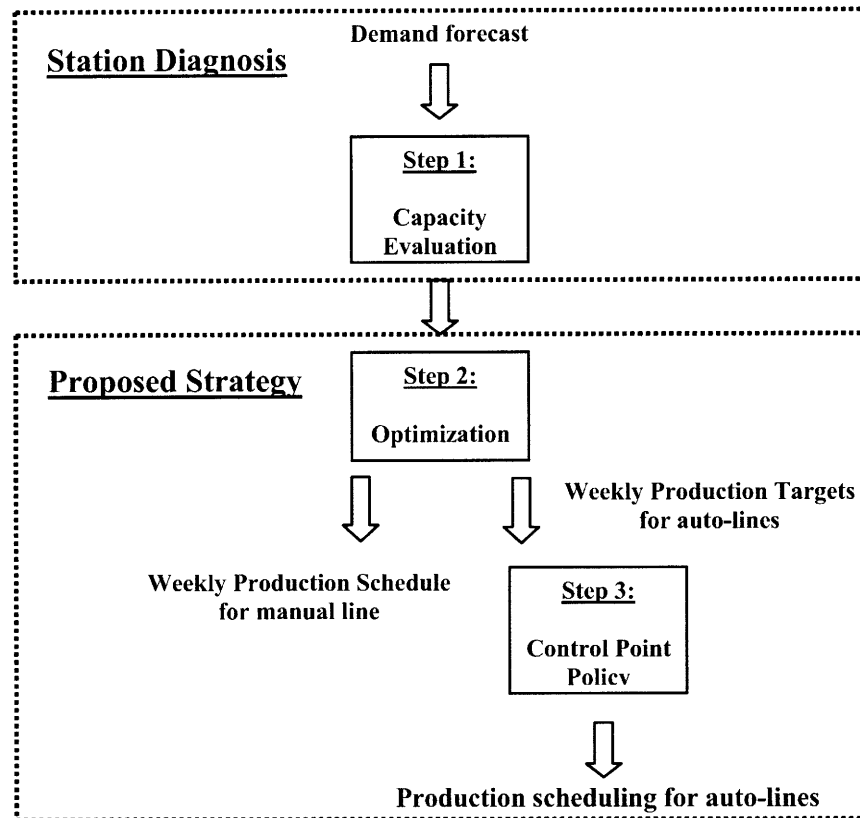
*Figure 3.1* Multiple-part-type token-based system [7]

Dr Gershwin further provides a set of rules which stipulates when to changeover and how much of each inventory to build. This is achieved using two buffer levels term the upper and lower hedging levels. First, the policy will select the highest priority part type with production level below its lower hedging level and manufacture it until the upper hedging level is reached. Next, it will perform a re-evaluation and identify part types that have buffer levels that are equal to or lower than their lower hedging levels. The highest priority part type which satisfies the above inequality is then selected for production. This is continued until all part types have buffer levels which equal to their respective upper hedging levels. Any further perturbation will cause the system to react in a similar manner.

## Chapter 4 Methodology

### 4.1 Overview

A three-step approach is taken to devise a production scheduling method for Station A. These steps are illustrated in the following flow diagram (*Figure 4.1*).



*Figure 4.1 Methodology*

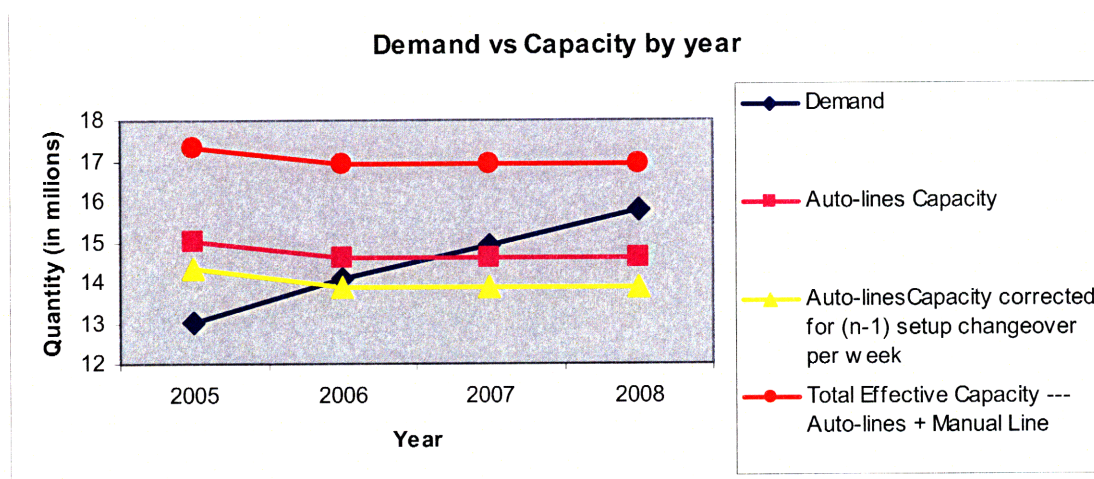
In the first step, a capacity evaluation was performed to understand whether production on the manual line is necessary to fulfill demand. Next, an appropriate optimization was set up to schedule production on the manual line (if necessary) and to generate the ideal production targets for the auto-lines. Utilizing the production targets obtained from *Step 2*, the Control Point Policy will then be used for real-time scheduling of the auto-lines.

## 4.2 STEP 1 - Capacity Evaluation

To evaluate whether it is necessary to operate the manual line to support the demand, a capacity evaluation was performed. Firstly, the forecasted demand data was corrected for probable reject amount (*Appendix B*) and then it was compared to the combined capacity of the auto-lines.

Since the auto-lines produce multiple part types, the capacity corrected for changeover was also compared to the demand. Currently, the management has stipulated that the number of changeover per week is equal to two for each auto-line per week. The management decision was based on minimizing the number of setup changeovers for each week.

The result of this study is illustrated in *Figure 4.2*. As observed, the demand is higher than the auto-lines capacity in the years 2007 and 2008. Thus, it is inevitable that the manual line needs to be operated.



*Figure 4.2 Demand versus Capacity<sup>1</sup>*

It can also be observed that there was a dip in capacity from the year 2005 to 2006. This was due to modifications on auto-line 1 to allow it to produce an additional part type. In the year 2005, auto-line 1 could only produce two part-types out of the three part-types it

<sup>1</sup> Refer to assumptions in Appendix C

can produce currently. Thus, the increased in production flexibility is at the expense of a reduction in capacity.

Due to the lower cost of production on the auto-lines, the author proposes that the auto-lines to be operated at maximum capacity throughout the year. This will be a consideration for the optimization algorithm discussed in *Section 4.3*. The excess demand has to be satisfied using the manual line or possibly by outsourcing.

By operating the auto-lines at full capacity in the fourth quarter, the estimated savings for reduction in production on manual line was estimated to be \$380,298. The increased in inventory holding cost was estimated to be \$18,718. Therefore, the net savings from this arrangement is approximately \$361,677.

### **4.3 STEP 2 - Optimization**

Optimization is used as a tool for the following:

1. To determine the quantity to be produced on the manual line
2. To aid in stock building decision during the low demand period
3. To distribute the production of part-type C among auto-lines 1 and 2
4. To generate weekly production targets for the auto-lines

Based on the forecast demand, a non-linear optimization problem is setup on Microsoft Excel Premium Solver. The optimization considers production for a twelve month period starting from October. October is chosen as the first month in the optimization because October is the end of peak demand period and that there are spare capacity on the auto-lines. Furthermore, demand forecast for the following year is only prepared in September.

In addition, the optimization utilizes the demand forecast of different resolutions. For the immediate month, the weekly forecasted demand data is used, whereas monthly

forecasted demand is used for the other months. The rationale for this arrangement is explained in *Section 3.1*.

To leverage on the more accurate demand forecast, *periodic optimization* as described in *Section 3.2* is used. At a regular time interval, the optimization problem is solved repeatedly. Since the demand forecast is updated on a weekly basis, the interval between each optimization is expected to be one week because the more frequently updated optimization can capture the actual market behavior better and thus allows for better production decision making.

### **Optimization Assumptions:**

The optimization problem was set up based on several assumptions. These assumptions are listed as follows:

- Auto-lines are operated at the maximum capacity throughout the year
- Inventory holding cost equals to 15% of the inventory cost per annum
- Unit inventory holding cost for the different part-types is assumed to be the same
- Production planning is of a weekly basis
- There are 2 setup changeovers for each auto-line per week
- The number of weeks in a month follows the AILTER calendar (either 4 or 5 weeks in a month)

It is important to point out that the inventory holding cost used in the optimization is comprised of the opportunity cost, interest payable for borrowed capital (example, from banks by the parent company) and other miscellaneous costs such as storage cost and inventory handling cost.

**Optimization Objective:** Minimize Total cost, TC

AILTER is a profit-driven organization. Thus, the objective of this optimization is to minimize the total cost, TC. The total cost is made up of the inventory holding cost (IC) and the extra cost to operate on the manual line (MC).

- Inventory holding cost, IC

Inventory holding cost, IC is equal to the quantity of inventory multiplied by the cost to hold unit inventory for all time periods.

For each time period,

Quantity of inventory

= Cumulative Production on Auto-lines + Cumulative Production on Manual line

– Cumulative Demand

$$= \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t$$

Define

$I_W$  = Cost to hold unit inventory for one week

$I_M$  = Cost to hold unit inventory for one month

Thus, the inventory holding cost for each time period is as follows:

- For the immediate month,

- Inventory cost per week = Quantity of inventory  $\times I_W$

$$= \left[ \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t \right] \times I_W$$

- For the other 11 months,

- Inventory cost per month = Quantity of inventory  $\times I_M$

$$= \left[ \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t \right] \times I_M$$

Hence,

Inventory holding cost, IC

= Inventory holding cost for immediate month, n  
+ Inventory holding cost for the other 11 months

$$= \sum_{t=n}^{n+4 \text{ or } n+5} \left[ \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t \right] \times I_W + \sum_{t=1}^{12} \left[ \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t \right] \times I_M \quad , \text{ where } t \neq n$$

- Extra Cost to produce on the Manual line, MC

Define

E = Extra cost for unit production on manual line relative to auto-line

Extra Cost to produce on the Manual line, MC

= Quantity produced on manual line  $\times$  Extra cost for unit production

$$= \sum_{t=1}^{12} M_t \times E$$

Therefore,

$$TC = \sum_{t=n}^{n+4 \text{ or } n+5} \left[ \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t \right] \times I_W + \sum_{t=1}^{12} \left[ \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t \right] \times I_M + \sum_{t=1}^{12} M_t \times E$$

Thus, the optimization objective can be described as follows:

**Minimize**

$$\sum_{t=n}^{n+4 \text{ or } n+5} \left[ \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t \right] \times I_W + \sum_{t=1}^{12} \left[ \sum_{m=1}^5 (CP_{tm} - CD_{tm}) + CM_t \right] \times I_M + \sum_{t=1}^{12} M_t \times E$$

### Decision variables:

The decision variables are the quantities of each part-type to be produced on the three lines for each time period.

Auto-line 1:  $P_{tmA1}$  for all t, m

Auto-line 2:  $P_{tmA2}$  for all t, m

Manual line:  $M_t$  for all t

### Optimization Constraints:

- Production cannot be negative.

Auto-line 1:  $P_{tmA1} \geq 0$  for all t, m

Auto-line 2:  $P_{tmA2} \geq 0$  for all t, m

Manual line:  $M_t \geq 0$  for all t

- 100% demand fulfillment

Cumulative production<sub>tm</sub>  $\geq$  Cumulative demand<sub>tm</sub> for all t, m

→  $CP_{tm} + CM_t \geq CD_{tm}$  for all t, m

*Note:  $CM_t$  is only non-zero for part-type C.*

- Production of auto-lines equal to their capacities

Auto-line 1:  $\sum_{m=1}^3 P_{tmA1} = C_{A1t}$  for all t

Auto-line 2:  $\sum_{m=3}^5 P_{tmA2} = C_{A2t}$  for all t

- Production on manual line cannot be larger than its capacity

$M_t < C_{Mt}$  for all t

#### **4.4 STEP 3 - Control Point Policy**

The results from optimization are based on deterministic data. The optimization assumes that the weekly production quantity is non-changing which is not true in the actual factory. Additionally, the optimization proposed in *Section 4.3* fixed the number of setup changeovers per auto-line to 2 times per week. This may not be the most ideal specification. Thus, the optimization results will only be used to determine the quantity of production on the manual line and to obtain the ideal weekly production targets for the auto-lines. For actual production scheduling on the auto-lines, the Control Point Policy is used to achieve the production targets obtained from the optimization. In this thesis, the Control Point Policy will only be developed for Auto-line 1. A similar strategy can be applied for Auto-line 2 but will not be discussed in this thesis.

Before the Control Point Policy can be used, it is important to identify the number and location of control points. For Station A, differentiation of the work-in-process inventory begins at the first machine. Thus, there is no opportunity to hold work-in-process inventory at any machine as a postponement strategy. Hence, only one control point at the beginning of each auto-line is selected.

Another aspect of the Control Point Policy is that the upper and lower hedging levels need to be specified. This is achieved with the help of simulation. For this thesis, Simul8 is selected as the simulation of choice. The reason for choosing Simul8 is that it is professional software designed for manufacturing. Thus, there are built-in functions like TTR/TTF, service time, changeover, buffer, machine which simplify the model building process.

Furthermore, this project is the application of a new concept to an actual factory. It is imperative that the ideas can be communicated to the management effectively. With the usage of graphical interfaces, it allows the management to better visualize the factory flow. Consequently, it enables us to present our case more strongly.

## 4.5 Description of Simulation Model

### 4.5.1 Simulation assumptions




In the Simul8 model, the following assumptions are made

1. Part-type priority:  $A > B > C$
2. Weekly demand from the downstream station (Station B) at the beginning of every week
3. At time zero, all buffers are at their upper hedging levels
4. Demand data is based on optimization result for the first 22 weeks of the year 2008

### 4.5.2 Simul8 Legend

The legend below is constructed to explain what the various images in Simul8 represent.

*Table 1 Simul8 legend*

Image	Description	Remarks
	Job release	<ul style="list-style-type: none"> <li>• Use to control how the jobs are released to the line</li> <li>• Job release corresponds to the actual demand</li> </ul>
Work Center 0 	Machine	<ul style="list-style-type: none"> <li>• Actual machine with user-specified inputs like TTR/ TTF, service time, etc</li> <li>• Allow the user to control the actual material flow through built-in functions and more importantly with codes</li> </ul>
	Physical buffer	<ul style="list-style-type: none"> <li>• Manufacturing buffer</li> <li>• Prevents propagation of disruption due to machine breakdown</li> </ul>



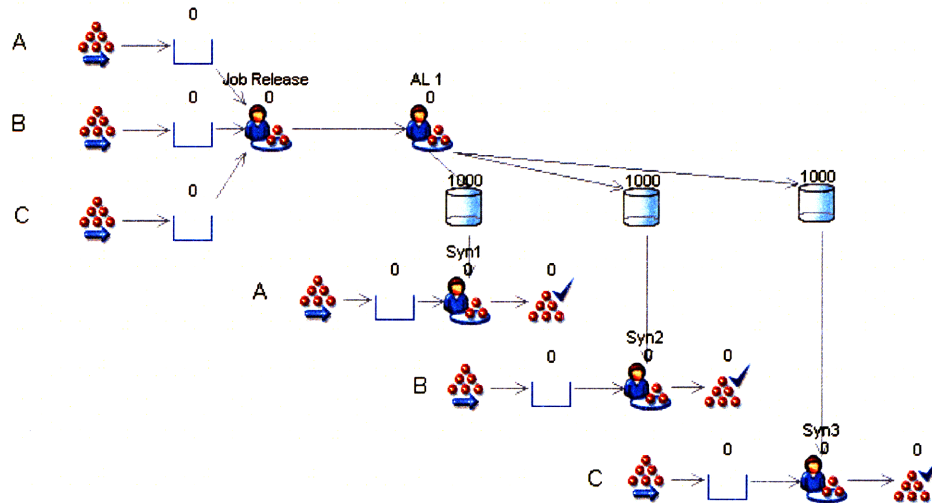
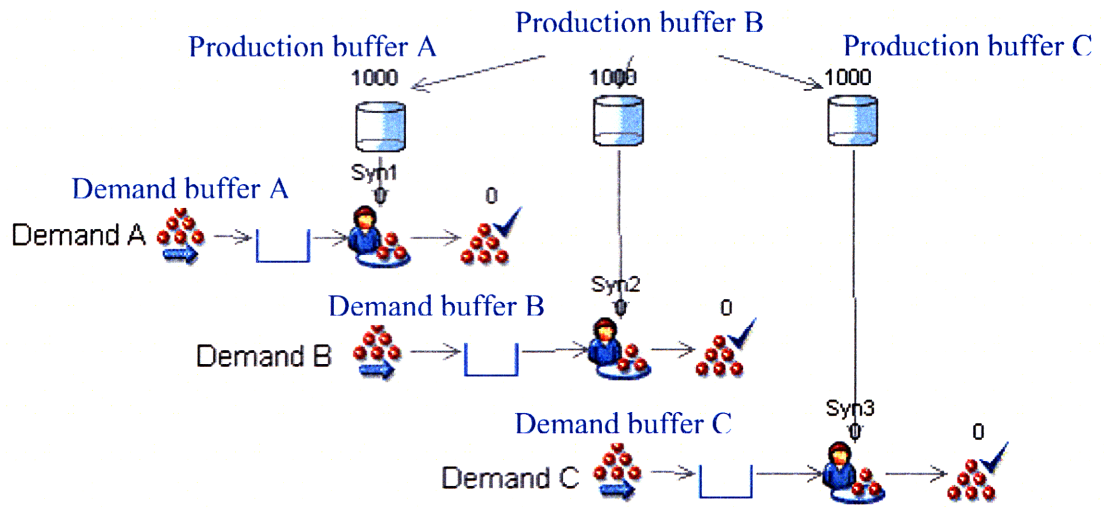
	Token buffer	<ul style="list-style-type: none"> <li>• Not physical buffer</li> <li>• Use to control how the job flows through the line</li> </ul>
	Work Complete	<ul style="list-style-type: none"> <li>• Collect the finished goods</li> </ul>

Figure 4.3 illustrates the graphical interface used for the token-based CPP implementation on auto-line 1.



**Figure 4.3** Token-based CPP graphical interface

The buffers with number ‘1000’ are the production buffers. They are connected to the synchronization machines labeled “Syn1”, “Syn2” and “Syn3” as illustrated in Figure 4.4.

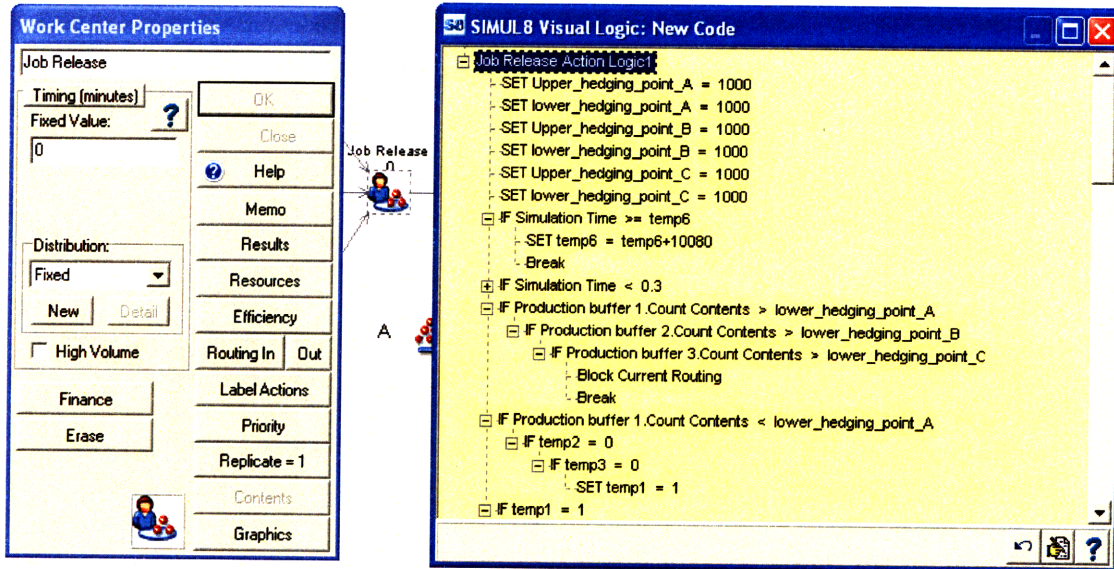


**Figure 4.4** Synchronization of production buffers with demand buffers

When demand A, B and C arrives, tokens (KANBAN cards) are added to their respective demand buffers A, B and C. Next, the workstations “Syn1”, “Syn2” and “Syn3” combine and remove tokens in the *Demand token buffers* with their corresponding tokens in the production buffers. This causes the tokens in the production buffers and demand buffers to decrease simultaneously.

### 4.5.3 Description of production scheduling logic

The Control Point Policy is implemented in Simul8 with the usage of 'Simul8 Visual Logic' at the 'Job Release' machine (*Figure 4.5*).



*Figure 4.5* Code at 'Job Release' Machine

The Visual Logic considers the following priority:  $A > B > C$ . Firstly, the algorithm searches for the various part-types that have reached their lower hedging levels. Next, the highest priority part-type is selected for production until its quantity equals its upper hedging level. The algorithm will then re-evaluate the various production token buffers and select the highest priority part-type with production buffer level lower than its lower hedging level for production. This process continues as the system aims to achieve the upper hedging levels for all the production token buffers. The Visual Logic algorithm is provided in *Appendix D*.

A minor difference of the simulation model from Dr Gershwin's Control Point Policy with setup change is that the setup token buffer is not considered. The reason for omitting this part of the policy is that there was no apparent advantage for its usage in this situation.

#### 4.5.4 Model verification and validation

There are 4 different scenarios where the auto-line is not producing a part. They are namely (a) daily preventive maintenance, (b) weekly preventive maintenance, (c) random line stoppage and (d) setup changeover.

Daily preventive maintenance is carried out daily except on Sundays where the line undergoes weekly preventive maintenance. The time for daily preventive maintenance is one hour and that for weekly preventive maintenance is scheduled for 8 hours per week.

On the contrary, random line stoppages are unplanned breakdowns and thus occur erratically. Using historical data of random line stoppages, the times to fail (TTF) and times to repair (TTR) were fitted using the 'Stat-Fit for Simul8' software. From the data analysis, the TTF was found to follow an Erlang distribution while the TTR follows a Pearson 6 distribution.

The detailed results from 'Stat-Fit for Simul8' for TTF and TTR are provided in *Figure 4.6* and *Figure 4.7*. Rank is defined as 'the relative rank of a continuous distribution, given by the Auto::Fit function, which indicates the relative goodness of fit of that distribution to the input data compared to the other distributions used.' In addition, the acceptance criterion as indicated at the last columns of *Figure 4.6(a)* and *Figure 4.7(a)* are also provided. The acceptance criterion is an indication, given by the Auto::Fit function, that the fitted distribution can be used rather than an empirical distribution.

## Time to fail (TTF)

### Auto::Fit of Distributions

distribution	rank	acceptance
Erlang(7.33e-002, 5., 7.26e-002)	99.8	do not reject
Gamma(7.33e-002, 4.46, 8.14e-002)	74.9	do not reject
Lognormal(-2.84e-002, -0.832, 0.363)	65.6	do not reject
Pearson 5(-0.162, 13.7, 7.57)	64.3	do not reject
Pearson 6(0.108, 2.26, 4.16, 29.5)	36.	do not reject
Beta(0.108, 1.43, 2.71, 8.1)	27.1	do not reject
Rayleigh(0.103, 0.268)	11.	do not reject
Weibull(0.103, 1.96, 0.376)	10.4	do not reject
Normal(0.436, 0.179)	3.5e-002	reject
Triangular(0.1, 1.43, 0.252)	0.	reject
Uniform(0.108, 1.43)	0.	reject
Exponential(0.108, 0.329)	0.	reject
Chi Squared(0.108, 1.01)	0.	reject
Power Function(0.107, 1.51, 0.623)	0.	reject

Figure 4.6 (a) TTF evaluation with Stat-Fit for Simul8

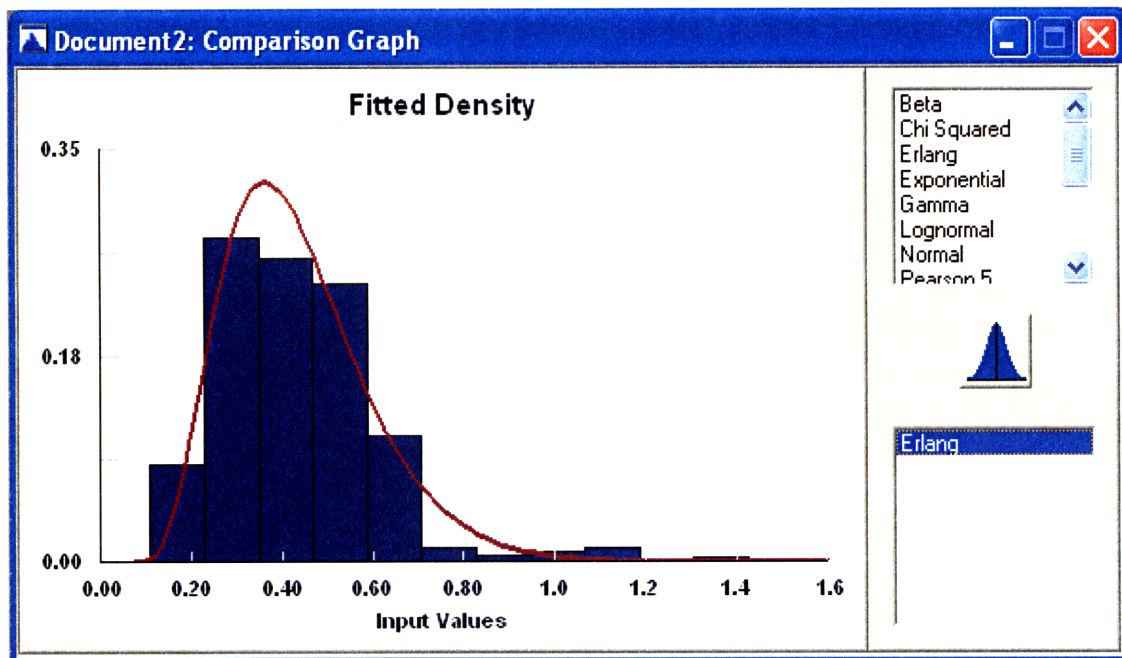


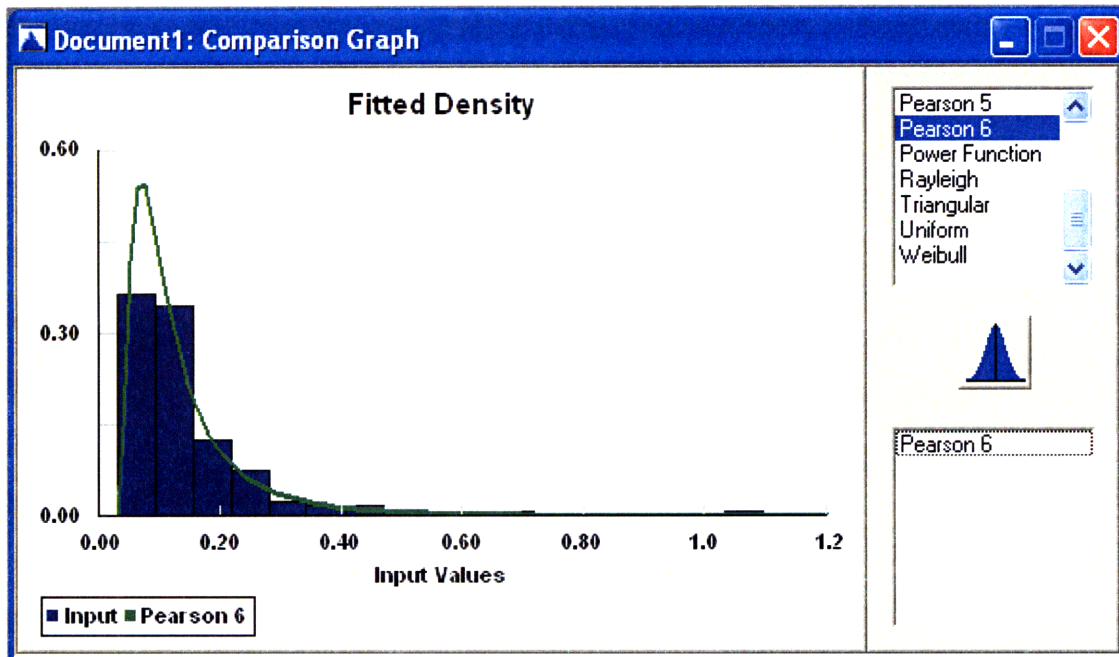
Figure 4.6 (b) TTF distribution fitting

## Time to Repair (TTR)

Auto::Fit of Distributions

distribution	rank	acceptance
Pearson 6(2.87e-002, 4.08e-002, 4.56, 2.5)	100.	do not reject
Pearson 5(1.2e-002, 2.4, 0.2)	97.5	do not reject
Lognormal(2.47e-002, -2.44, 0.824)	20.7	do not reject
Weibull(2.87e-002, 1., 0.122)	8.12e-004	reject
Exponential(2.87e-002, 0.121)	8.04e-004	reject
Erlang(2.84e-002, 1., 0.122)	5.89e-004	reject
Gamma(2.84e-002, 1.38, 8.85e-002)	5.67e-004	reject
Beta(2.87e-002, 34.8, 1.39, 394)	1.86e-005	reject
Normal(0.15, 0.141)	0.	reject
Triangular(2.53e-002, 1.1, 4.42e-002)	0.	reject
Uniform(2.87e-002, 1.09)	0.	reject
Rayleigh(-3.94e-002, 0.167)	0.	reject
Chi Squared(2.87e-002, 0.655)	0.	reject
Power Function(2.86e-002, 1.09, 0.387)	0.	reject

*Figure 4.7 (a) TTR evaluation with Stat-Fit for Simul8*



*Figure 4.7 (b) TTR distribution fitting*

Furthermore, the model changeover time was determined to be 4 hours per changeover and that the service time,  $\tau$  was determined to be 0.426 minute per part using historical data.

Thus, the following parameters are specified in the Simul8 model.

**Table 2** *Simulation inputs*

<b>Input</b>	<b>Distribution</b>	<b>Parameters</b>
Daily Preventive Maintenance	Deterministic	<ul style="list-style-type: none"> <li>• TTF = 1380 minutes</li> <li>• TTR = 60 minutes</li> </ul>
Weekly Preventive Maintenance	Deterministic	<ul style="list-style-type: none"> <li>• TTF = 9600 minutes</li> <li>• TTR = 480 minutes</li> </ul>
Random line failure	Yes	<ul style="list-style-type: none"> <li>• TTF               <ul style="list-style-type: none"> <li>○ Combination of 2 distributions                   <ol style="list-style-type: none"> <li>1. Erlang Distribution (Average = 0.363; K = 5)</li> <li>2. Fixed offset of 7.33e-2</li> </ol> </li> </ul> </li> <li>• TTR               <ul style="list-style-type: none"> <li>○ Combination of 2 distributions                   <ol style="list-style-type: none"> <li>1. Pearson 6 Distribution (<math>\alpha_1 = 4.56</math>; <math>\alpha_2 = 2.5</math>; <math>\beta = 4.08e-2</math>)</li> <li>2. Fixed offset of 7.33e-2</li> </ol> </li> </ul> </li> </ul>
Setup time	Deterministic	<ul style="list-style-type: none"> <li>• 4 hours per model changeover</li> </ul>
Service time, $\tau$	Deterministic	<ul style="list-style-type: none"> <li>• 0.426 minutes/part</li> </ul>

After the model parameters are specified, the simulation model was found to operate in a manner similar to that of the actual system. Besides checking that the simulation model performs the stipulated daily and weekly maintenance, the number of changeovers in the simulation model was controlled to be 2 times per week in accordance with the actual production. The average quantity of weekly output from the simulation model (153,164 units per week) was observed to be close to the average actual production quantity (152,966 units per week). Thus, the inputs specified in *Table 2* are verified to be suitable.

## Chapter 5 Results and Discussions

### 5.1 Results of Optimization

Due to the large number of variables in the optimization problem, it cannot be solved using the built-in 'Solver' function in Microsoft Excel. After evaluating various optimization software packages, it was found that the Microsoft Excel Premium Solver was the easiest to be used by the factory. Thus, the optimization was solved using the Microsoft Excel Premium Solver, 8<sup>th</sup> edition (trial version).

From the company, only the monthly demand forecasts for the first 5 months of 2008 were obtained with the exception of May 2008. For May 2008, both the demand forecasts at the beginning of the month and at the middle of the month were obtained. In addition, the December AOP for 2007 was also obtained. These values were used as inputs for the optimization.

To simulate *Periodic Optimization*, the optimization problem was solved repeatedly using the different sets of demand forecasts. For a time period which has passed, the production quantities are fixed while the forecasted demand is revised. The optimization only allows adjustment of production quantities for the subsequent time periods. For example, when the optimization of February is simulated, the production quantities for October, November, December and January are not allowed to change when the demand forecast is updated. Thus, only the production quantities (for both auto-lines and the manual line) in the month of February and the subsequent months are allowed to be altered.

A sample optimization result is provided in *Table 3*. One can find the quantity to be produced on the manual line on the right column. In addition, one may observe that the weekly production quantity on each auto-line is constant. This corresponds to the auto-lines' capacity.

Table 3 Sample optimization output

Optimization begins in October
Production Targets for auto-lines
Production Schedule for manual line

Month	Auto-line 1 Production			Auto-line 2 Production			Manual line Production
	A	B	C	C	D	E	C
Oct	215,054	94,864	454,912	91,483	450,358	85,184	116,855
Nov	161,863	94,297	355,704	51,901	411,918	37,801	246,516
Dec	115,723	90,114	406,027	157,605	316,073	27,942	0
Jan-wk1	37,734	28,999	86,232	3,059	120,452	1,893	59,223
Jan-wk2	37,481	29,122	86,364	3,102	119,054	3,249	59,328
Jan-wk3	36,953	29,386	86,628	3,102	118,331	3,972	59,336
Jan-wk4	36,425	29,650	86,892	3,102	118,331	3,972	59,344
Jan-wk5	35,981	30,022	86,964	3,102	118,331	3,972	59,352
Feb-wk1	19,671	7,335	125,960	36,481	0	88,924	0
Feb-wk2	18,968	8,582	125,417	109,232	0	16,173	0
Feb-wk3	20,307	8,531	124,129	89,296	35,079	1,030	0
Feb-wk4	21,226	9,033	122,708	3,819	112,985	8,602	0
Mar-wk1	31,552	51,151	70,262	31,385	92,856	1,164	0
Mar-wk2	34,678	26,111	92,178	15,454	102,628	7,324	0
Mar-wk3	36,068	17,225	99,673	13,638	107,106	4,660	0
Mar-wk4	27,639	25,501	99,826	6,496	111,585	7,324	0
Apr-wk1	77,290	24,530	51,146	105,466	9,649	10,290	0
Apr-wk2	35,158	31,294	86,514	56,764	62,203	6,438	0
Apr-wk3	35,158	26,026	91,781	62,032	56,935	6,438	0
Apr-wk4	29,891	20,759	102,316	46,229	72,738	6,438	0
Apr-wk5	34,034	21,294	97,638	40,779	84,626	0	0
May-wk1	31,659	53,782	67,525	99,184	0	26,221	0
May-wk2	37,584	30,538	84,844	34,261	81,464	9,680	0
May-wk3	18,209	22,512	112,245	18,700	95,297	11,408	0
May-wk4	30,862	30,800	91,304	0	116,682	8,723	40,207
Jun	190,300	132,000	289,564	171,367	292,671	37,583	105,569
Jul	278,102	159,500	327,228	209,617	359,934	57,474	252,000
Aug	231,298	99,000	281,566	167,118	292,315	42,187	252,000
Sep	212,300	88,000	311,564	200,343	248,917	52,360	163,416

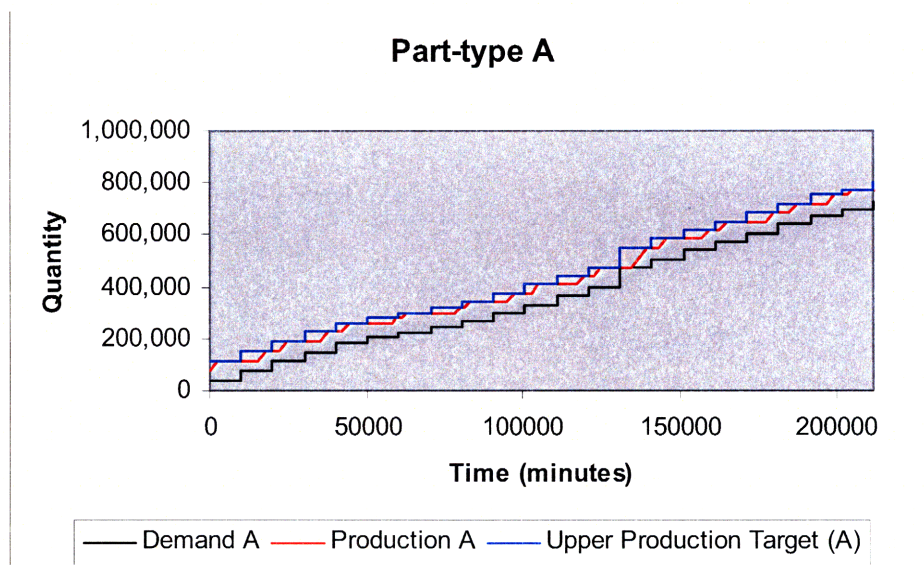
Sum of values equal to weekly capacity for auto-line 1

At this point, one can see that the optimization is multi-functional and that the size of the problem made the calculation challenging. On the other hand, Station E has only one line and that its capacity is almost always in excess of the demand. Thus, the stock-building decision on Station E can be performed by hand as demonstrated in Xia Hua' thesis [2] but is difficult to be calculated manually for Station A.

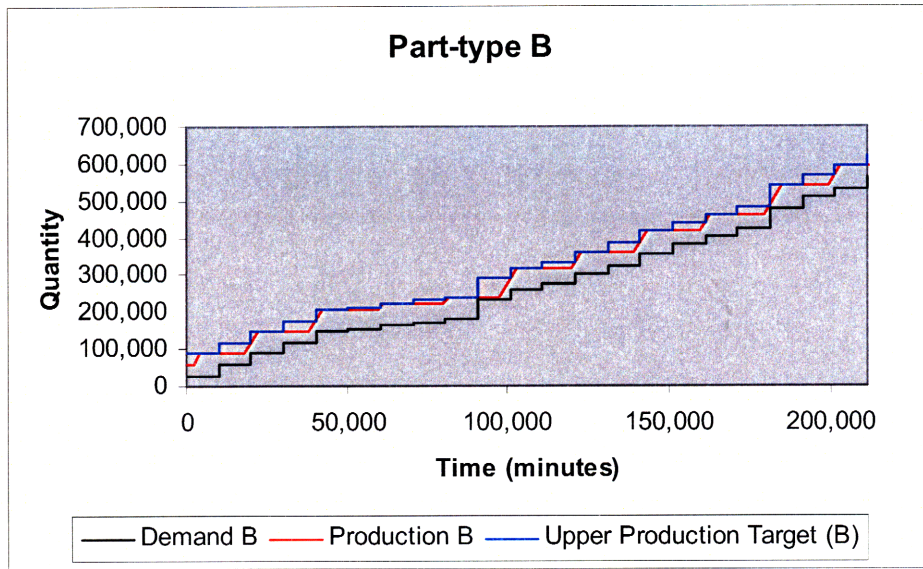
## 5.2 Simulation results for Token-Based CPP

### 5.2.1 Sample output of simulation model

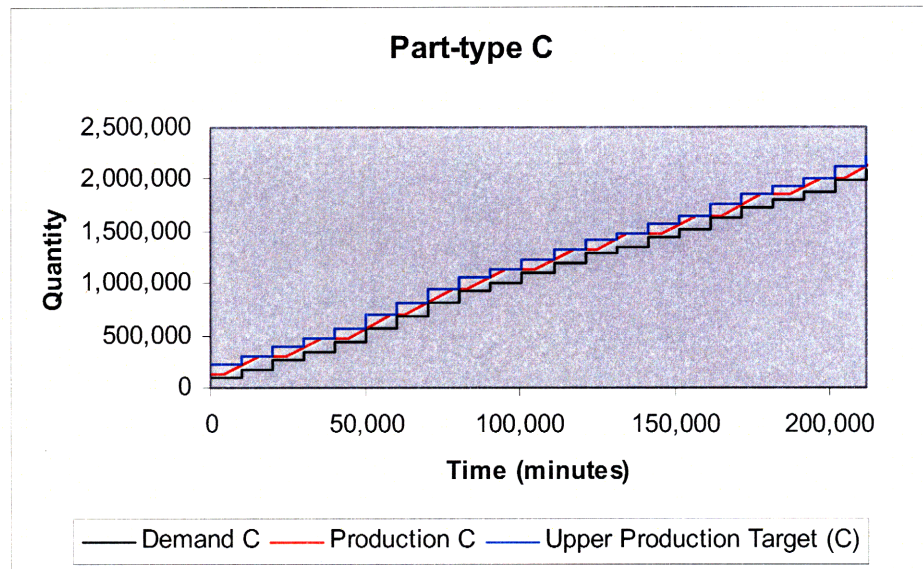
For ease of implementation, the hedging levels were set to be in lots of a thousand. During the initial testing, the upper and lower hedging levels were set to be equal. Next, the hedging levels for each of the part-type were adjusted such that the production is not late. The minimum hedging levels for Part-type A, B and C were found to be 78,000, 60,000 and 133,000 respectively. Figures 5.1 (a), (b), (c) illustrate the cumulative production versus the cumulative demand for each of the part-type when the above hedging levels were used.



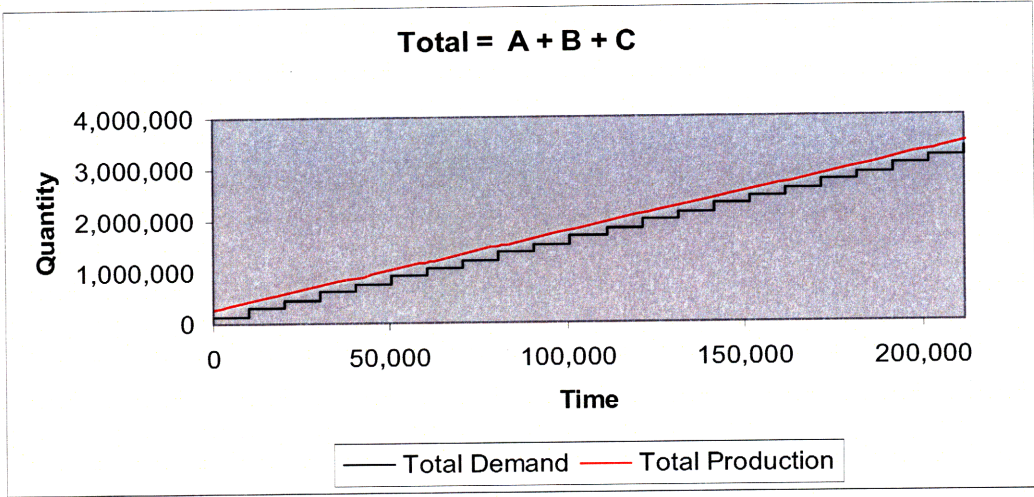
*Figure 5.1 (a) Cumulative production versus cumulative demand (Part-type A)*



*Figure 5.1 (b) Cumulative production versus cumulative demand (Part-type B)*



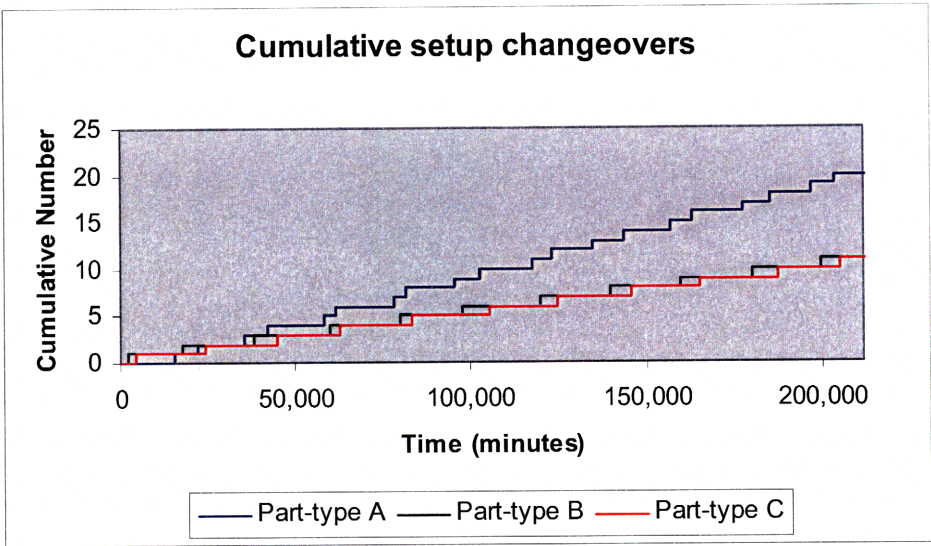
*Figure 5.1 (c) Cumulative production versus cumulative demand (Part-type C)*



**Figure 5.1 (d)** Cumulative production versus cumulative demand (Total)

As observed in Figure 5.1, the cumulative production is always higher than the cumulative demand when there is no lateness. The area between the cumulative production curve (red line) and the cumulative demand curve (black line) is the inventory held at Station A. In addition, the upper production targets (as indicated by the blue lines) are also provided.

The cumulative number of setup changeover for the 3 part-types is illustrated in Figure 5.2.



**Figure 5.2** Cumulative setup changeover frequency

From Figure 5.2, one can also observe that the total number of changeovers over the 22 weeks period is 44 times. This corresponds to 2 changeovers per week. Keeping the upper and lower hedging levels to be equal and then increased their values from 78,000, 60,000 and 133,000; it was observed that the number of changeovers remains unchanged. The reason for this result is that optimization has controlled the total weekly demand to close to the quantity which the line can produce in a week. In addition, the first model to be produced in a week corresponds to the last model that was produced in the previous week.

### 5.2.2 Adjustment of hedging levels

In order to decrease the number of changeovers, the upper hedging levels were set to be different from the lower hedging levels. The differences in upper and lower hedging levels were first set to be equal to their respective average daily demand for the 22 weeks. Specifically, the average daily demands are equal to 6,000, 4,000, and 13,000 for part-types A, B and C respectively. In addition, the lower hedging levels were kept unchanged. If the new hedging levels were found to result in lateness, both the upper and lower hedging levels were added with their average daily demand quantity. For example, the lower hedging levels were first set to be 78,000, 60,000 and 133,000 (for A, B and C respectively). Next, the upper hedging levels were obtained by adding their average weekly demand which give 84,000, 64,000 and 146,000. These hedging levels were tested but found to result in lateness. Thus, both the upper and lower hedging levels were increased by their average daily demand ( $H^L$ : A = 84,000, B = 64,000 and C = 146,000;  $H^U$ : A = 90,000, B = 68,000 and C = 159,000). This process was repeated until the hedging levels which yield no lateness were obtained.

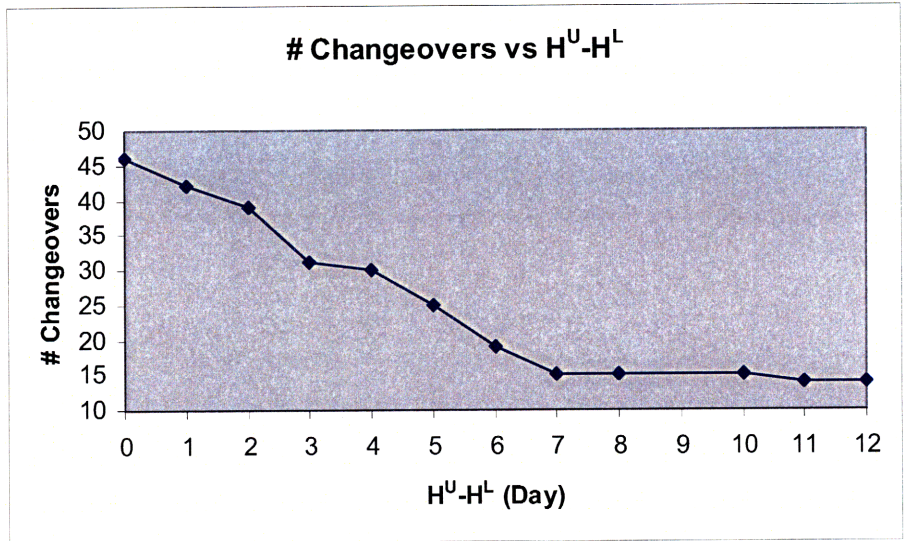
The results for upper and lower hedging levels that are more than one day apart were also calculated and that the result is provided in *Table 4*.

**Table 4** Token-based hedging levels with no lateness

$H^U - H^L$ (day)	Lower Hedging Level, $H^L$ (in thousands)			Upper Hedging Level, $H^U$ (in thousands)			Total number of changeovers for 22 weeks	Average weekly inventory
	A	B	C	A	B	C		
0	78	60	133	78	60	133	46	196,242
1	84	64	146	90	68	159	42	232,518
2	90	68	159	102	76	185	39	267,496
3	90	68	159	108	80	198	31	279,992
4	96	72	172	120	88	224	30	308,079
5	96	72	172	126	92	237	25	317,609
6	102	76	185	138	100	263	19	320,158
7	102	76	185	144	104	276	15	328,918
8	102	76	185	150	108	289	15	341,116
10	102	76	185	162	116	315	15	364,054
11	120	86	224	186	132	367	14	428,319
12	138	100	263	210	148	419	14	555,510

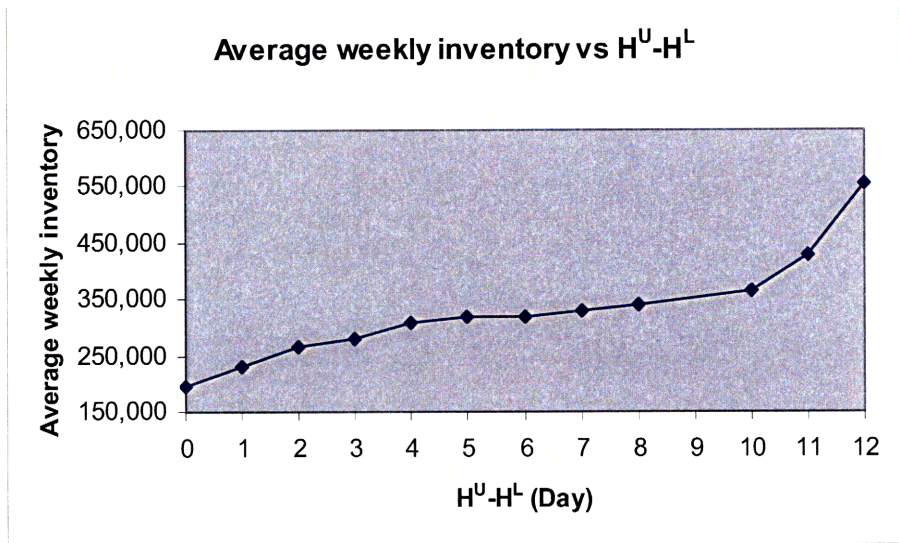
The tradeoff between average inventory and number of changeovers can be observed on *Table 4*. Generally, the number of changeovers decreases at the expense of higher average inventory. This finding is not surprising because when the number of changeovers decreases, each part-type needs to wait for a longer time period before its stock gets replenished. Thus, it will need to hold a larger quantity of inventory to satisfy the continuous demand.

From *Figure 5.3*, it can be seen that the number of changeovers decreases when the upper and lower hedging levels were further apart.



**Figure 5.3** Relationship between changeover frequency and hedging levels

Although the number of changeover can be reduced by increasing the difference between the upper and lower hedging levels, a larger amount of average inventory is required to fulfill demand as indicated in *Figure 5.4*



**Figure 5.4** Relationship between average inventory and hedging levels

From *Figure 5.3* and *Figure 5.4*, one can observe that when  $H^U - H^L$  is larger than 7, there is no significant reduction in changeover frequency even though the average inventory is higher. Furthermore, the upper hedging levels are already very high for  $H^U - H^L$  equal to 8.

Thus, further evaluation of scenarios where  $H^U - H^L$  is larger than 8 are not carried out in the subsequent sections.

### 5.2.3 Robustness study of hedging levels

The hedging levels presented in *Table 4* were based on 22 weeks of demand data. Due to the limited amount of demand data available, there was a concern that the hedging levels obtained may not be sufficiently robust. Thus, the sequence of the 22 weeks demand data was randomized and re-tested on the simulation model. In all, 8 scenarios were tested and the results of the quantity of lateness were tabulated in *Table 5*.

**Table 5** Quantity of lateness tested under different scenarios

$H^U - H^L$	Part-type	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Max
0	A	0	0	0	0	0	0	0	0	0
	B	0	0	0	0	0	0	0	0	0
	C	0	0	0	0	0	0	0	0	0
1	A	0	0	0	0	0	0	0	0	0
	B	0	0	0	0	0	0	0	0	0
	C	0	0	0	0	0	0	0	0	0
2	A	0	0	0	0	0	0	0	0	0
	B	0	0	3844	1532	0	2307	0	0	3,844
	C	0	0	0	0	0	0	0	0	0
3	A	0	0	0	0	0	0	0	0	0
	B	0	0	5084	5083	2782	0	0	276	5,084
	C	0	0	0	0	0	0	0	0	0
4	A	0	0	0	0	0	0	0	0	0
	B	0	11167	0	0	3372	16938	0	0	16,938
	C	0	0	0	0	0	0	0	0	0
5	A	0	0	0	0	0	0	0	0	0
	B	0	7167	0	0	0	18617	2963	0	18,617
	C	0	0	0	0	0	0	0	0	0
6	A	0	0	0	0	0	0	0	0	0
	B	0	16392	16626	3343	12432	24968	23962	0	24,968
	C	0	0	0	0	0	0	0	0	0
7	A	0	0	0	0	0	0	0	0	0
	B	0	12392	3596	0	8432	26968	0	8807	26,968
	C	0	0	0	0	0	0	0	0	0
8	A	0	0	0	0	0	0	0	0	0
	B	0	8392	8178	0	30543	14259	15962	0	30,543
	C	0	0	0	0	0	0	0	0	0

Based on the results in *Table 5*, only Part-type B is late using the hedging levels given in *Table 4*. This suggests that the hedging levels for Part-types A and C are relatively robust. For Part-type B, lateness was observed and that the maximum lateness generally increases when the difference between upper and lower hedging levels become larger. Thus, the hedging levels for Part-type B in *Table 4* were readjusted by adding the maximum quantity (round up to the nearest thousand) that is late to both their upper and lower hedging levels. The results for the new hedging levels were provided in *Table 6*.

**Table 6** Revised Token-based hedging levels with no lateness

$H^U - H^L$ (day)	Lower Hedging Level, $H^L$ (in thousands)			Upper Hedging Level, $H^U$ (in thousands)			Total number of changeovers (for 22 weeks)	Average weekly inventory	Total cost (for 22 weeks)
	A	B	C	A	B	C			
0	78	60	133	78	60	133	46	196,242	\$51,534
1	84	64	146	90	68	159	42	232,518	\$48,406
2	90	68	159	102	76	185	39	271,496	\$46,360
3	90	78	159	108	90	198	31	285,992	\$38,632
4	96	89	172	120	105	224	30	325,079	\$38,612
5	96	91	172	126	111	237	25	336,609	\$33,845
6	102	107	185	138	131	263	19	345,158	\$27,990
<b>7</b>	<b>129</b>	<b>103</b>	<b>212</b>	<b>171</b>	<b>131</b>	<b>303</b>	<b>15</b>	<b>355,918</b>	<b>\$24,215</b>
8	129	103	212	177	135	316	15	368,116	\$24,524

The total cost tabulated in *Table 6* includes the cost of setup (\$1012 per setup as provided by the company) plus the average inventory holding cost for the 22 weeks. As shown on *Table 6*, the lowest cost is obtained when the difference between high and low hedging levels are 7 days apart. It can also be observed that the costs for the last two scenarios are very close. Although this cost difference may not be statistically significant, the case of  $H^U - H^L$  equals 7 days is still preferred. This is because it is easier to implement when the upper hedging level is lower. Hence, the upper hedging levels of 171,000, 131,000 and 303,000 were selected for part-type A, B and C respectively. The lower hedging levels for part-type A, B and C was chosen to be 129,000, 103,000 and 212,000 respectively.

### 5.3 Comparison of time-based and token-based CPP

Table 7 is the result of time-based CPP obtained from Zhiyu Xie's thesis [1]. From the table, it can be seen that the total number of changeover decreases at the expense of higher average inventory. This result is similar to the token-based CPP.

*Table 7 Time-based parameters with no lateness [1]*

<b>U-L (Unit: day)</b>	<b>Parameters (Unit: day)</b>	<b>Average Inventory (unit: piece)</b>	<b>Total Number of changeovers</b>
0	U=8,L=8	114,810	44
1	U=10,L=9	175,429	41
2	U=17,L=15	297,308	31
3	U=20,L=17	379,070	25
4	U=24, L=20	467,685	22
5	U=29, L=24	549,530	18
6	U=30, L=24	572,092	16
7	U=31, L=24	590,914	16

The cost tabulated for the various scenarios for time-based CPP are shown in Table 8. The lowest cost which can be obtained by time-based CPP is \$30,714. This value is still larger than the cost that can be achieved by the token-based CPP (\$24,215).

*Table 8 Cost tabulation for time-based CPP [1]*

<b>U-L (Unit: day)</b>	<b>Parameters (Unit: day)</b>	<b>Inventory holding cost(\$\$) (January – May)</b>	<b>Changeover cost(\$\$) (January – May)</b>	<b>Total cost (\$) (January – May)</b>
0	U=8,L=8	2,914	44,528	47,442
1	U=10,L=9	4,453	41,492	45,945
2	U=17,L=15	7,547	31,372	38,919
3	U=20,L=17	9,623	25,300	34,923
4	U=24, L=20	11,872	22,264	34,136
5	U=29, L=24	13,950	18,216	32,166
<b>6</b>	<b>U=30, L=24</b>	<b>14,522</b>	<b>16,192</b>	<b>30,714</b>
7	U=31, L=24	15,000	16,192	31,192

Besides evaluating the time-based and token-based CPP based on their cost, other factors are also taken into account when deciding the more appropriate strategy for station A. These considerations are shown in *Table 9*.

**Table 9** Comparison of time-based and token-based CPP

	<b>Time-based CPP</b>	<b>Token-based CPP</b>
<b>Demand fulfillment</b>	Comparable	
<b>Inventory</b>	Comparable	
<b>Number of changeovers</b>	Comparable	
<b>Ease of implementation</b>	<ul style="list-style-type: none"> <li>• Need to forecast demand that may be far from present</li> </ul>	<ul style="list-style-type: none"> <li>• Does not require material planning</li> </ul>
<b>Uncertainty due to rejects</b>	<ul style="list-style-type: none"> <li>• Push system</li> <li>• May be difficult to anticipate the rejects quantity and type</li> </ul>	<ul style="list-style-type: none"> <li>• Pull system</li> <li>• Scheduling policy will react according to the type and quantity of rejects</li> </ul>

One important advantage of token-based CPP over time-based CPP is that it does not require the usage of a material planning schedule. Besides simplifying the production scheduling procedure, it can also prevent error that can arise from mistakes in the material planning schedule.

More importantly, it is challenging to forecast the quantity and part-type that will be rejected downstream. Since time-based CPP is a push strategy, it requires estimation of the part-types that will be rejected and thus may introduce a possible error. On the contrary, the token-based CPP is a pull strategy and that it reacts according to the type of reject. Consequently, it should react better according to the downstream rejects uncertainty.

After careful evaluation, the token-based CPP is recommended as the more appropriate production strategy for the auto-lines.

## 5.4 Comparison of proposed strategy with current strategy

To recap, the proposed strategy involves full production throughout the year and that production targets to be generated by optimization. The token-based CPP with upper hedging levels: A = 171,000, B = 131,000, C = 303,000; lower hedging levels A = 129,000, B = 103,000, C = 212,000 is then used for real-time production scheduling for the auto-lines.

Besides generating production targets, optimization is also used as a tool to distribute production of the common part-type among the 2 auto-lines, aid in stock building decision and to schedule production on the manual line.

A detailed comparison of the proposed strategy with the current strategy is provided in *Table 10*.

**Table 10** Comparison of proposed strategy with current strategy

	<b>Current Strategy</b>	<b>Proposed Strategy</b>
<b>Stock Building Strategy</b>	<ul style="list-style-type: none"> <li>• Auto-lines operate at full capacity during quarters 1-3</li> </ul>	<ul style="list-style-type: none"> <li>• Auto-lines operate at full capacity throughout the year</li> <li>• Consequently, it reduces the quantity required to be produce on manual line</li> <li>• Estimated cost reduction of \$381,177 per year</li> </ul>
<b>Operation of Manual line</b>	<ul style="list-style-type: none"> <li>• To help auto-lines achieve their production targets</li> <li>• Based on the experience of supervisor</li> <li>• Difficulty to arrange for labor</li> </ul>	<ul style="list-style-type: none"> <li>• Determined by optimization</li> <li>• Allow for better human resource planning</li> </ul>

<b>Distribution of Part-type C (common model) among the 2 auto-lines</b>	<ul style="list-style-type: none"> <li>• Based on the experience of supervisor</li> </ul>	<ul style="list-style-type: none"> <li>• Systematic approach with the help of optimization</li> </ul>
<b>Ease of implementation</b>	<ul style="list-style-type: none"> <li>• Requires the development of production schedule by factory planner</li> </ul>	<ul style="list-style-type: none"> <li>• Pull system --- Actual demand from downstream trigger production</li> <li>• External production schedule is not needed</li> </ul>
<b>Number of Changeovers</b>	<ul style="list-style-type: none"> <li>• 2 changeovers per week for each auto-line</li> </ul>	<ul style="list-style-type: none"> <li>• Reduce the number of changeovers by approximately half</li> <li>• Estimated cost reduction of \$52,624 per year</li> </ul>
<b>Inventory</b>	Comparable	

From *Table 8*, it is evident that the proposed strategy is better than the current strategy in multiple aspects. In particular, the quantity to be produced on the manual line can be reduced by operating the auto-lines at full capacity throughout the year. In addition, the production targets for manual line can be obtained earlier using optimization. This allows for better human resource planning and thus may help to resolve the current labor issue. At present, the operation on manual line is dependent on whether the auto-lines can achieve their targets. As a result, it is difficult to arrange for labor at the very last minute when it is realized that the operation of manual line is necessary. Another aspect to highlight is that the loss production hours due to changeover can be reduced by approximately half at the same amount of inventory if the proposed strategy is used. The estimated cost savings for the reduction in changeover is estimated to be \$52,624 per year.

## **Chapter 6      Recommendations/future work/ conclusions**

### **6.1    Recommendations**

First, the author recommends that the auto-lines be operated at their maximum capacities throughout the year. From the capacity evaluation of auto-lines, the total capacity of the auto-lines is smaller than the annual demand. Thus, there is a need to plan for production on the manual line. The amount to be produced on the manual line can be determined by optimization.

The token-based control point policy is recommended to sequence the production for the auto-lines. From the simulation results, the upper hedging levels: A = 171,000, B = 131,000, C = 303,000; lower hedging levels A = 129,000, B = 103,000, C = 212,000 is found to be appropriate for auto-line 1. A similar strategy can be employed to determine the hedging levels for auto-line 2.

The simulation assumes that all the production buffers are at their upper hedging levels at time zero. Hence, a strategy is required to ramp up the inventory to the stipulated levels. Since the auto-lines are already operated at their maximum production rate, it is necessary to utilize the manual line or to outsource the production to achieve the respective targets at the beginning.

Besides using outsourcing as a possible means to ramp up inventory at the initial stages, outsourcing may also be a viable option to handle the rising demand. From *Figure 4.2*, one can observe that the demand has been steadily increasing over the past years. If the trend were to continue, the total capacity of auto-lines and manual line may not be able to satisfy the increased demand in the near future. In addition, the excess demand may not be sufficient to warrant the installation of additional in-house production facility. Thus, outsourcing may be an attractive option if an effective contract can be negotiated with a supplier. If outsourcing is adopted as a production option, it can be factored into the optimization to decide the quantity and timing to outsource.

## **6.2 Future work**

In this thesis, optimization was used to distribute the common part-type among the two auto-lines. Next, each of the auto-line has a set of control point policy to guide in their production. This may not be the most ideal strategy. A generalized policy for multiple lines should be explored --- in this case, a control point policy that can help to schedule the various part-types among the two auto-lines. Besides the ease of implementation, the generalized strategy may react to (demand or production) uncertainties more favorably as both lines can help to counter any disruption encountered in any one line. As a result, it is possible that the disruption can be rectified more rapidly.

During the development of control point policy for Station A, one major challenge was to identify a good set of hedging levels. The strategy used in this thesis to determine the hedging levels is through extensive testing by simulations. Although there is nothing fundamentally wrong with this approach, the author believes that it will be helpful if the control point policy can also provide a set of guidelines to aid in hedging level selection. Thus, a possible future research topic is to develop a strategy for searching an appropriate set of hedging levels.

Next, it is questionable whether the scheduled daily and weekly preventive maintenances are the most appropriate. Although preventive maintenance can reduce the number of rejects and possibly maintain the machine lines' productivity, it results in lost production hours. For a capacity-constrained station like Station A, any opportunity to increase its productivity is critical. Hence, it is important to identify a better preventive maintenance schedule that perhaps is based on a fortnightly routine. More complex methodologies that possibly utilize the lines' output characteristics (reject percentage and productivity) to schedule preventive maintenance may also be interesting in this case.

### **6.3 Conclusions**

To conclude, this thesis has successfully developed a systematic method for multiple-part-type production scheduling at Station A. The strategy involves first obtaining production targets by optimization followed by a token-based, real-time scheduling approach --- the Control Point Policy --- developed by Dr Stanley B. Gershwin from MIT. From the simulation results, there is a distinct tradeoff between the inventory and the number of changeovers. After comparing the token-based strategy with the time-based strategy, the token-based strategy with upper hedging levels equal to 171,000, 131,000, 303,000 and lower hedging levels of 129,000, 103,000, 212,000 is finally recommended to the AILTER factory.

## Reference

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- 4 David Simchi-Levi, Philip Kaminsky, Edith Simchi-Levi. (2003). *Designing and Managing the Supply Chain*. New York: Irwin/McGraw Hill. (Page 35)
- 5 Stanley, B. Gershwin, Lecture notes, 2.854, 2004, MIT OpenCourseWare (URL: <http://ocw.mit.edu/OcwWeb/Mechanical-Engineering/2-854Fall-2004/LectureNotes/> date accessed: July 06, 2008.)
- 6 Stanley, B. Gershwin, The Control Point Policy - Summary, July 11, 2007, unpublished work
- 7 Stanley, B. Gershwin, Design and Operation of Manufacturing Systems: The Control Point Policy, IIE Transactions, Volume 32, Issue 10, October 2000 , pages 891 – 906
- 8 Stanley, B. Gershwin and Fernando Tubilla, Proposed Setup Change Policy, March 11, 2008, unpublished work

## Appendix A The Control Point Policy

Details of Control Point Policy with Setup Changeover [6]

### Assumptions and Definitions

- Setup time is measured in time units. The unit is arbitrary, but the units must be consistent with the units of time available for setups and setup time tokens (defined below).
- $S_{ij}$  = setup change time from type  $i$  to type  $j$ . By convention,  $S_{ii} = 0$ .
- The current time is  $t$ .
- During one week, the time available for setups is
  - The total shift time – the total operation time – the total expected down time (repairs and maintenance) – a safety time.
- The allowable setup fraction  $f_s$  is the time available for setups divided by the total shift time.  $f_s$  is given by

$$f_s = 1 - \left( \frac{r+p}{r} \right) \sum_i \tau_i d_i = 1 - \sum_i \left( \frac{\tau_i}{e} \right) d_i$$

where  $p = 1/\text{MTTF}$  is the failure rate of the machine,  $r = 1/\text{MTTR}$  is its repair rate,  $e = r/(r+p)$  is the efficiency of the machine,  $d_i$  = the demand rate for type  $i$  parts, and  $\tau_i$  = the operation time for a type  $i$  part.

- There is a setup token generator putting setup tokens into a setup token buffer at the rate of  $f_s$  tokens per time unit. Each token is worth one time unit of setup time. (Although we speak of tokens as though they are discrete items, the number of tokens is actually treated as a continuous quantity.)
- When a setup change from  $i$  to  $j$  occurs,  $S_{ij}$  tokens are removed from the setup token buffer.
- The setup token buffer is not allowed to go negative. This limits how frequently setups are allowed to occur.
- $x_i(t)$  is the number of tones in the type  $i$  production token buffer at time  $t$ .
- There are two hedging points for type  $j$ :  $Z_j^U$  and  $Z_j^L$  and  $Z_j^U > Z_j^L >> \max(d_i, d_j) S_{ij}$  for all  $i, j$ .

The detailed policy proposed by Dr Gershwin is as follows:

Assume the machine is producing part type  $i$  at time  $t$ .

1. Continue producing  $i$  until  $x_i(t) \geq Z_i^U$ .
2. Find the set of all  $j$  (which may include  $i$ ) such that:
  - There are at least  $S_{ij}$  setup tokens in the setup-token buffer.
  - $x_j < Z_j^L$ .If there is no such  $j$ , wait until there is. Do not continue producing  $i$ .
3. Set  $J$  to be the  $j$  with the highest priority. If there are more than one with the same highest priority, pick one.
4. Remove  $S_{ij}$  tokens from the setup token buffer.
5. Change setup to  $J$
6. Set  $i = J$  and go to Step 1.

## Appendix B Estimation of percentage reject

There are multiple value streams for the factory and that the complete details to calculate the quantity of system's rejects were not available. However, it was known that the annual production at Station A is very close to the actual annual demand. Thus, these values are used to estimate the cumulative percentage rejects downstream of Station A.

From the period between Week 5 – 52 of year 2007,

Total Demand = **12,701,500 units**

Total production (corrected for rejects) = **13,999,039 units**

Thus, the percentage reject  $\approx \frac{13,999,039 - 12,701,500}{12,701,500} \times 100\% = 10\%$

## Appendix C Assumptions for Figure 4.2

*Figure 4.2* was drawn based on several assumptions listed below:

1. Auto-lines are operational for 7 days/week.
2. 10% rejects included in demand (refer to *Appendix B*).
3. Capacity for 2006 – 2008 is assumed to be the same and has the value equal to that in May 2008.
4. At the time when this thesis was written, the year 2008 has not passed. Thus, the Demand for 2008 is estimated using the demand forecast obtained in May 2008.
5. Assume capacity of manual line = 252,000/month = 3 million/year.

## Appendix D Visual Logic for Simul8 Model

VL SECTION: Job Release Action Logic1

```
SET Upper_hedging_point_A = 171000
SET lower_hedging_point_A = 129000
SET Upper_hedging_point_B = 131000
SET lower_hedging_point_B = 103000
SET Upper_hedging_point_C = 303000
SET lower_hedging_point_C = 212000

IF Simulation Time >= temp6
  SET temp6 = temp6+10080
  Break
IF Simulation Time < 0.3
  Block Current Routing
  Break
IF Production buffer 1.Count Contents > lower_hedging_point_A
  IF Production buffer 2.Count Contents > lower_hedging_point_B
    IF Production buffer 3.Count Contents > lower_hedging_point_C
      Block Current Routing
      Break
IF Production buffer 1.Count Contents < lower_hedging_point_A
  IF temp2 = 0
    IF temp3 = 0
      SET temp1 = 1
IF temp1 = 1
  IF Production buffer 1.Count Contents < Upper_hedging_point_A
    IF Production buffer 3.Count Contents < lower_hedging_point_C
      IF Production buffer 2.Count Contents > lower_hedging_point_B
        Set Route In Priority Job Release , Store 1 , 90
        Set Route In Priority Job Release , Store 3 , 70
        Set Route In Priority Job Release , Store 2 , 50
      ELSE
        Set Route In Priority Job Release , Store 1 , 90
        Set Route In Priority Job Release , Store 2 , 70
        Set Route In Priority Job Release , Store 3 , 50
    ELSE
      Set Route In Priority Job Release , Store 1 , 90
      Set Route In Priority Job Release , Store 2 , 70
      Set Route In Priority Job Release , Store 3 , 50
  ELSE IF Store 1.Count Contents = 0
    SET temp1 = 0
    Break
ELSE
```

```

IF Production buffer 2.Count Contents < lower_hedging_point_B
  IF temp3 = 0
    SET temp2 = 1
  IF temp2 = 1
    IF Production buffer 2.Count Contents < Upper_hedging_point_B
      IF Production buffer 3.Count Contents < lower_hedging_point_C
        IF Production buffer 1.Count Contents > lower_hedging_point_A
          Set Route In Priority  Job Release , Store 2 , 90
          Set Route In Priority  Job Release , Store 3 , 70
          Set Route In Priority  Job Release , Store 1 , 50
        ELSE
          Set Route In Priority  Job Release , Store 2 , 90
          Set Route In Priority  Job Release , Store 1 , 70
          Set Route In Priority  Job Release , Store 3 , 50
        ELSE
          Set Route In Priority  Job Release , Store 2 , 90
          Set Route In Priority  Job Release , Store 1 , 70
          Set Route In Priority  Job Release , Store 3 , 50
        ELSE
          SET temp2 = 0
          Break
      ELSE
        IF Production buffer 3.Count Contents < lower_hedging_point_C
          SET temp3 = 1
          IF temp3 = 1
            IF Production buffer 3.Count Contents < Upper_hedging_point_C
              IF Production buffer 2.Count Contents < lower_hedging_point_B
                IF Production buffer 1.Count Contents > lower_hedging_point_A
                  Set Route In Priority  Job Release , Store 3 , 90
                  Set Route In Priority  Job Release , Store 2 , 70
                  Set Route In Priority  Job Release , Store 1 , 50
                ELSE
                  Set Route In Priority  Job Release , Store 3 , 90
                  Set Route In Priority  Job Release , Store 1 , 70
                  Set Route In Priority  Job Release , Store 2 , 50
                ELSE
                  Set Route In Priority  Job Release , Store 3 , 90
                  Set Route In Priority  Job Release , Store 1 , 70
                  Set Route In Priority  Job Release , Store 2 , 50
                ELSE
                  SET temp3 = 0
            ELSE
              Block Current Routing

```