Reduce Cycle Time and Work In Process in a Medical Device Factory: Scheduling of Needle Hub Molding Machines

by

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Bachelor of Engineering (Computer Engineering)
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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Manufacturing

at the

Massachusetts Institute of Technology

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Professor of Mechanical Engineering
Chairman, Department Committee on Graduate Students
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ABSTRACT

Many manufacturing firms have improved their operations by implementing a work-in-process (WIP) limiting control strategy. This project explores the application of this concept to limit WIP and reduce cycle time for the Becton, Dickinson and Company’s manufacturing facility in Tuas, Singapore. BD’s Eclipse Safety Needle production line is facing increasing pressure to reduce its high WIP and long cycle times. With the forecast of increasing demand, the current production control practice will sooner or later push the shop floor space to a limit. We divided the overall system into three manageable subsystems and analyzed different strategies for each. This paper documents the approaches to schedule 30 molding machines. These machines are located at the first stage of the production line. Although the total production rate of the 30 machines is higher than the downstream machines, the production rate of each product type is much slower because of machine constraints. This project groups the 30 machines into three groups, and proposes different strategies to reduce the total WIP level and cycle time.

Thesis Supervisor: Stephen C. Graves
Title: Abraham J. Siegel Professor of Management, Sloan School of Management
ACKNOWLEDGEMENT

First and foremost, we wish to express our deepest appreciation to our thesis supervisor, Professor Stephen C. Graves from the Sloan School of Management in MIT, for his consistent guidance and encouragement throughout the project. We will always feel inspired by his enthusiasm, dedication to excellence, and careful attention to details.

We would also like to thank Associate Professor Sivakumar Appa Iyer from the School of Mechanical and Aerospace Engineering in NTU as an advisor of this project. Professor Siva helped us with exploring scheduling policies and simulation tools for this project.

Kind thanks also goes to Becton, Dickinson and Company for sponsoring this work. Specifically we want to thank Mr. Tan Kok Hui, our corporate supervisor, for giving us valuable feedback and suggestions. Many thanks go to all the staffs in the Eclipse safety needle production line in BD Tuas plant, for their strong support in the project.

I would also like to thank the other two team members of this project, Kai Meng and Yi Qian. This project could not be possible without their teamwork.

Finally, I would like to thank my wife, Suh In, for the support and love she had given me throughout this project.
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1 INTRODUCTION

To produce the right parts, at the right time, at competitive costs is the key success factor in the modern manufacturing world. To achieve the competitive advantage, to improve the overall performance of manufacturing operations and to obtain time and cost saving, production cycle time and work in process (WIP) limiting control strategies have become essential.

The Eclipse Safety Needle production line in BD Medical’s Singapore manufacturing facility is facing increasing pressure to reduce its high WIP and long cycle times. With the forecast of increasing demand, the current WIP management and production scheduling practice will sooner or later push the shop floor space to a limit. Long cycle time will also delay the company’s response to product obsolescence and quality issues. Evidently, effective strategies for reducing cycle time and limiting WIP will be necessary for BD to strengthen its competitive position.

The challenge of the task lies in the complex setting of process flow and equipment capability. Multiple product types take different routes in a multi-station production line. The only shared resource among all product types is the bottleneck in the company; yet, this piece of equipment operates faster than any other single machine. Depending on the product-mix demand distribution, other machines may experience high utilization as well. At the multi-machine molding station, there are long changeover times to switch from one product type to another. Setting up machines to produce a particular product type at maximum possible rate can help to reduce cycle time and WIP, but it also results in more changeovers. Such tradeoffs between cycle time and changeover cost further complicate the problem.

1.1 Background

1.1.1 BD Medical and BD Tuas Plant

Becton, Dickinson and Company (BD) is a global medical technology company that is focused on improving drug therapy, enhancing the diagnosis of infectious diseases and advancing drug discovery. BD manufactures and sells medical supplies, devices, laboratory instruments, antibodies, reagents and diagnostic products. It serves healthcare institutions, life science researchers, clinical laboratories, industry and the general public.

BD Tuas plant manufactures cannula, needle, and syringe products; it supplies these products to BD’s distribution centers (DC), which then supply the worldwide market. The plant is organized in value streams. There are 7 value streams (VS) producing 7 different product families in the plant. Each VS operates independently with its own equipment and work force. This project focuses on the VS that produces safety needles. This VS is internally referred to as Eclipse Value Stream.
1.1.2 The Team Project

Sponsored by Singapore-MIT-Alliance program and the company, this internship project serves as the basis for the theses for MIT's Master of Engineering degree in Manufacturing. A team approach is adopted, in which a group of 3 students identify and analyze the problem jointly; then each of the three students focuses on solving a sub-problem on an individual basis.

The team identified three sub-problems and provided an analysis and possible solutions for each. Details of the project are documented in the three theses. Titles of the three theses are listed below. Proposed strategies for the Needle Assembly machine (AN) and downstream packaging machines are discussed in Thesis 1 and Thesis 2. Scheduling of hub molding machines is extensively studied and documented in Thesis 3. Inventory management and production scheduling for Needle Shield (NS) and Safety Shield (SS) molding machines is presented in Thesis 1.

Thesis 1: Reduce Cycle Time and Work In Process in a Medical Device Factory: The Problem and a Proposed Solution


Thesis 3: Reduce Cycle Time and Work In Process in a Medical Device Factory: Scheduling of Needle Hub Molding Machines

1.2 Thesis Overview

In Chapter 2 we will provide background information of the company's operations and the cycle time and WIP problem in the Eclipse safety needle production line. In Chapter 3 we analyze the root cause of the problem and present an overall solution. In Chapter 4 we analyze issues related to the scheduling of the needle hub molding machines and present a solution.
2 ECLIPSE SAFETY NEEDLE PRODUCTION LINE

In this chapter, we will provide background information of the company’s operations and the cycle time and WIP problem in the Eclipse safety needle production line.

2.1 The Product

2.1.1 Eclipse Safety Needle

A needle product is a hypodermic needle connected to a syringe for hypodermic injection. It is detachable from the syringes. A conventional needle consists of a plastic needle hub, a metal cannula, and a plastic needle shield for the cannula. The needle hub is used to attach the needle to a syringe. The cannula is fixed on the needle hub by epoxy. The needle shield is a safety cover for the cannula for protection both before and after injection.

Eclipse safety needle (Figure 1) is a new product introduced by BD Medical in 2005. Different from conventional needles, the safety needle has an extra safety shield installed on its needle hub. The safety shield is designed to shield and lock the needle cannula after injection. The major reason to have the safety shield is to protect end users, like nurses, from being injured with the use of the needle (Figure 2).

Figure 1 A Luer-Slip Safety Needle with Syringe

Figure 2 How to Use an Eclipse Safety Needle
2.1.2 Four Major Product Types

In the Eclipse product family there are four major types of safety needle products, which differ in packaging and needle hub design. They are

1) **Luer-Lok Needle in Individual Blister Package (LL-PN):** LL-PN products are packaged individually in blister packages. They are shipped to 3 DCs in North America, from where the products are distributed to retailers nationwide. Luer-Lok refers to a needle hub design. In a Luer-Lok design, the needle hub connects to a syringe by screw threads. The Luer-Lok design is mainly used in the North America market.

2) **Luer-Slip Needle in Individual Blister Package (LS-PN):** The same as LL-PN, LS-PN products are also packaged individually in blister packages. They are shipped to a DC in Europe and then distributed to retailers in the European countries. Similar to Luer-Lok, Luer-Slip refers to another type of needle hub design. In a Luer-Slip design, the needle hub connects to a syringe by snap fit (Figure 1). Different from Luer-Lok needles, a Luer-Slip needle has a metal clip inside its needle hub, which makes a "click" sound when a syringe is correctly attached. The Luer-Slip needles are mainly used in the European market.

3) **Luer-Lok Needle in Bulk Package (Bulk):** Bulk needles are packed in units of a few thousand in large plastic bags inside paper cartons. They are shipped to 3 DCs in North America, and then to other BD plants or pharmaceutical companies for secondary processes. Currently, the Tuas plant only produces Luer-Lok needles in bulk package.

4) **Luer-Lok Needle with Syringe in Combo Package (Combo):** A combo product is a Luer-Lok needle packaged together with a syringe in a single blister package. They are shipped to the 3 DCs in North America.

2.1.3 28 SKUs

Each of the four product families has a few SKUs. The SKUs differ in cannula gauge size and length. A difference in cannula gauge size also results in a difference in needle hub size. Hubs of different gauge sizes are molded in different colors for easy differentiation. Safety shields and needle shields are the same for all the SKUs. Table 1 shows the 28 SKUs. The product name contains information about cannula gauge size and length. Take PSN 22×1 as an example, PSN represents Needle in Individual Blister Package, 22 is the cannula/needle hub gauge size and is internally referred to as 22G, with an external diameter of 0.8 mm; and 1 is 1 inch, the cannula length.
### 2.2 Demand and Customers

#### 2.2.1 Demand Distribution

Because the Eclipse products have been introduced to the North America market for less than 3 years and to the European market for about 1 year, there is very high demand fluctuation. BD expects the demand to increase rapidly, especially in the European market. Demand of different products types and SKUs are not evenly distributed.

In FY 2006, LL-PN contributes over 50% of the total units sold to the DCs, followed by LS-PN and Combo with about 20% each. Bulk constitutes less than 4% of the total units sold. For each major product type, demand usually concentrates in a few SKUs. For instance, SKUs with gauge size 18G, 21G, 23G, and 25G have higher demand than others in LL-PN.

A more detailed illustration of the demand distribution is shown in Table 2. We summarize the distribution based on the total units sold to the DCs in FY 2006. Due to confidentiality concerns, the real demand quantity is not disclosed. Nevertheless, to provide information on the demand fluctuation, we calculate the coefficient of variation $c.v. = \frac{\text{Mean}}{\text{standard deviation}}$ based on the monthly demand of each SKU. The 4th column summarizes the demand percentage of each SKU in its major product type; and the 5th

<table>
<thead>
<tr>
<th>Package</th>
<th>Product</th>
<th>Hub Type</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luer-Lock</td>
<td>PSN 18 x 1 /2</td>
<td>LL Pink</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 21 x 1 TW</td>
<td>LL Green</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 21 x 1/2 TW</td>
<td>LL Green</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 22 x 1</td>
<td>LL Black</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 23 x 1</td>
<td>LL Light Blue</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 25 x 1</td>
<td>LL Orange</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 25 x 1 /2</td>
<td>LL Orange</td>
<td>High Runner</td>
</tr>
<tr>
<td>Luer Slip</td>
<td>PSN 20 x 1 (Luer-Slip)</td>
<td>LS Yellow</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 21 x 1 (Luer-Slip)</td>
<td>LS Yellow</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 21 x 1/2 TW (Luer-Slip)</td>
<td>LS Light Blue</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 23 x 1 (Luer-Slip)</td>
<td>LS Light Blue</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 25 x 5/8 (Luer-Slip)</td>
<td>LS Orange</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>PSN 27 x 1/2 (Luer-Slip)</td>
<td>LS Grey</td>
<td>High Runner</td>
</tr>
<tr>
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<td>PSN 30 x 1/2 (Luer-Slip)</td>
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<td>Bulk</td>
<td>Bulk Needle 22 x 1 1/2</td>
<td>LL Black</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>Bulk Needle 22 x 1 TW (ABG)</td>
<td>LL Black</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>Bulk Needle 23 x 1 MTW (ABG)</td>
<td>LL Light Blue</td>
<td>High Runner</td>
</tr>
<tr>
<td>Combo</td>
<td>21 x 1 1/2 TW 3 ml Combo</td>
<td>LL Green</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>21 x 1 TW 3 ml Combo</td>
<td>LL Green</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>22 x 1 1/2 3 ml Combo</td>
<td>LL Black</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>22 x 1 3 ml Combo</td>
<td>LL Black</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>23 x 1 3 ml Combo</td>
<td>LL Light Blue</td>
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<td>25 x 1 3 ml Combo</td>
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<tr>
<td></td>
<td>25 x 5/8 1 ml Combo</td>
<td>LL Orange</td>
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<tr>
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<td>27 x 1/2 1 ml Combo</td>
<td>LL Grey</td>
<td>High Runner</td>
</tr>
<tr>
<td></td>
<td>30 x 1 1/2 1 ml Combo</td>
<td>LL Yellow</td>
<td>High Runner</td>
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</table>

Table 1 Available SKUs of the Eclipse Safety Needle Production Line

---

15
column indicates the demand percentage of each product type in all the safety needle products in FY 2006.

<table>
<thead>
<tr>
<th>Major Types</th>
<th>SKUs (Gauge x Length)</th>
<th>c.v.</th>
<th>SKU/Type</th>
<th>Type/Total</th>
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<tr>
<td>LL-PN</td>
<td>PSN 25 x 1</td>
<td>0.76</td>
<td>14.2%</td>
<td></td>
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<tr>
<td></td>
<td>PSN 23 x 1</td>
<td>0.65</td>
<td>17.5%</td>
<td></td>
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<tr>
<td></td>
<td>PSN 22 x 1/2</td>
<td>1.01</td>
<td>9.4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PSN 21 x 1 TW</td>
<td>0.77</td>
<td>11.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PSN 21 x 1/2 TW</td>
<td>1.21</td>
<td>7.9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PSN 18 x 1/2</td>
<td>0.50</td>
<td>31.9%</td>
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</tr>
<tr>
<td></td>
<td>PSN 25 x 1/2</td>
<td>0.76</td>
<td>5.8%</td>
<td></td>
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<tr>
<td></td>
<td>PSN 22 x 1</td>
<td>2.39</td>
<td>1.5%</td>
<td></td>
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<tr>
<td>LS-PN</td>
<td>PSN 25 x 5/8 (Luer-Slip)</td>
<td>0.74</td>
<td>32.1%</td>
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<td></td>
<td>PSN 27 x 1/2 (Luer-Slip)</td>
<td>0.72</td>
<td>6.8%</td>
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<td>PSN 30 x 1/2 (Luer-Slip)</td>
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<td>0.90</td>
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<td>16.1%</td>
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<td></td>
<td>1 ml 27 x 1/2 Combo</td>
<td>0.40</td>
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<tr>
<td></td>
<td>1 ml 30 x 1/2 Combo</td>
<td>0.56</td>
<td>2.8%</td>
<td></td>
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<tr>
<td></td>
<td>3 ml 21 x 1 TW Combo</td>
<td>0.00</td>
<td>1.9%</td>
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</tr>
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<td></td>
<td>3 ml 25 x 5/8 Combo</td>
<td>0.54</td>
<td>19.9%</td>
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<td>0.57</td>
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<td>0.52</td>
<td>26.6%</td>
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<td>1.00</td>
<td>1.9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 ml 25 x 1 Combo</td>
<td>0.73</td>
<td>3.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 ml 22 x 1 Combo</td>
<td>0.00</td>
<td>1.9%</td>
<td></td>
</tr>
<tr>
<td>Bulk</td>
<td>Bulk Needle 22 x 1 1/2</td>
<td>0.33</td>
<td>28.9%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bulk Needle 23 x 1 MTW (ABG)</td>
<td>0.09</td>
<td>27.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bulk Needle 22 x 1 TW (ABG)</td>
<td>0.35</td>
<td>43.4%</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Demand Distribution

2.2.2 Customers and Orders

Although products from the Eclipse line are consumed by both end users and industrial customers, the production line's direct customers are the 3 DCs in North America and the 1 DC in Europe, who then provide supply to regional customers.

In the beginning of a fiscal year, the Tuas plant receives an order forecast from the 4 DCs, which contains information about the monthly order quantity for each SKU in the next 12 months. The DCs can update their forecast subject to a 45-day frozen window rule imposed by the company, in which they could only change the forecast at least 45 days in advance of an order. In other words, the forecast becomes a firm order when its shipment date is less than 45 days away. The plant can start to produce an order once it becomes firm. The forecast is updated mostly via email between the DCs and plant planner.

The time unit for order quantity commitment from the DCs is a month, which means there is not a more specific due date on an order. With the 45-day frozen window, orders for the next month are usually confirmed on the 15th of the current month. For example, if there is an order for a particular SKU in May, it is confirmed on April 15th. Its deadline will be the end of May and it could be shipped any time in May. There is no planned finished goods inventory in BD as production is to order and orders are shipped once they are ready to go. This is true for all SKUs.
As a conclusion, the order for next month from each of the four DCs is confirmed on the middle of the current month. The orders for next month must be shipped by the end of the next month at the latest.

2.3 The Eclipse Value Stream

2.3.1 Process Flow of the Eclipse Production Line

Figure 3 shows the process flow of the Eclipse line, with the clean room boundary marked in black lines. The scope of this project is limited to the processes inside the clean room.

Figure 3 The Eclipse Production Line Process Flow (Modified based on BD Internal Source)

2.3.1.1 Processes inside Clean Room

The processes inside the clean room can be divided into three stages: molding, assembly and packaging. There are four groups of 33 injection molding machines in the molding stage, two machines in the needle assembly stage, and three machines in the packaging stage.

2.3.1.1.1 Molding Stage

This process produces plastic parts by injection molding; these parts are used in the assembly stage. There are four types of plastic parts being molded: Needle Shield (1 machine), Safety Shield (2 machines), Luer-Lok Hub (20 machines), and Luer-Slip Hub (10 machines). Luer-Lok and Luer-Slip hub molding machines produce 13 different types of needle hubs. Each machine can produce a few types of hubs by changing its mold
inserts. The changeover typically takes 2 hours. There is only one type of needle shield and safety shield, so there is no changeover for the shield molding machines.

The production at the molding stage follows a monthly production plan. For hub molding, production capacity of a specific hub type is constrained by the number of available machines and mold inserts. Moreover, a mold insert can only run on a limited number of machines on which it has been validated. For example, there are 10 Luer-Slip Hub molding machines, but there are only 5 mold inserts for 20G hubs. These inserts can only run on 5 validated machines out of the 10. Thus, we are constrained to have at most five machines producing 20G hubs at any point of the time.

2.3.1.1.2 Assembly Stage

Needle Assembly (AN) Machine

Needle assembly is performed by a complex assembly machine, which assembles the cannula, needle hub, and needle shield together into an assembled needle. The detailed steps involved in this stage are:

a) Insert cannula into the needle hub.
b) Apply epoxy between the cannula and hub.
c) Rotate the cannula position in the hub.
d) Heat the epoxy to create bond
e) Put on needle shield.

All products produced in the Eclipse line are processed through this station. As a consequence, BD perceives the AN machine as the bottleneck of the whole process flow. It is highly utilized in order to meet monthly demand. Its utilization can go as high as over 90% when demand is high. A changeover is required between assemblies of different SKUs. A typical changeover takes 30 minutes on average.

Snap Clip Assembly (AN SC) Machine

Only Luer-Slip products require this process step. It is done by a single machine, which takes assembled needles from AN and inserts a metal clip into the needle hub. A changeover is required between assemblies of different SKUs. A typical changeover takes 30 minutes on average.

2.3.1.1.3 Packaging Stage

Packaged Needle Assembly (PN) Machine

The PN machine first attaches a safety shield to the needle hub. It then seals the needle in a single blister package, and finally packages the blister packages in cartons. All three steps are performed by a single machine. Both LL-PN and LS-PN products have to route through this machine.
**Bulk Needle Packaging Machine**

Only one type of product, Bulk needles, uses this machine, which packages needles in bulk form. Because the bulk product has very low demand (less than 4% of the total demand in FY 2006), this machine runs only a few shifts per month.

**Combo Packaging Machine**

This machine is very similar to the PN machine. An assembled Luer-Lok needle from AN is assembled with a safety shield, then packaged together with a syringe into a blister package, and finally packed in cartons. Syringes are manufactured and supplied by another value stream in the same plant.

2.3.1.2 Processes outside Clean Room

After being packaged in cartons, products are moved out from the clean room. Processes outside the clean room include sterilization, out gassing, shrink wrap, and shipment to customers. The total processing time of these operations takes 15 days on average. As a consequence, products need to complete all operations in the clean room 15 days before their shipment date.

**2.3.2 The Eclipse Value Stream Production Planning Team**

Coordinated by a Value Stream leader, the production planning team consists of a production planner, shift supervisors, technicians and material handling personnel working on the shop floor. Major decisions on scheduling and production control are made by the planner.

**2.4 Current Practice**

**2.4.1 Planning**

The production plan is generated monthly for each individual machine by a planner using Excel spreadsheets. Based on the current WIP level and demand, the planner sets the production quantity, start date and finish date for each part for each machine monthly. After these production plans are generated, they are released to the production floor. The production plans of the Eclipse line are also passed to other value streams who supply syringes and cannula, so that syringes and cannula would be delivered according to the plans.

As AN is perceived as the bottleneck, the current planning strives to minimize the changeover on AN by producing large batches. Typically the production batch size of each SKU is chosen to be the order quantity for an entire month, which can go up to 5 million pieces for high demand SKUs. The transfer batch size is always the same as the production batch size, which means any downstream production of one SKU would not start until its upstream process is finished. Moreover, the production plans build in a time buffer between successive operations; thus, according to the schedule, a production batch
from upstream will complete well before the scheduled start for its next downstream operation. This scheduled queuing time varies from a few days to a few weeks. For instance, the scheduled queuing time for hubs between molding stage and assembly stage is usually around 1 to 3 weeks. The scheduled queuing time for assembled needles between assembly stage and packaging stage is usually around a few days to 2 weeks.

Because of the long queuing time, there is a long cycle time for producing any of the product types. Due to the long cycle time, the current planning practice must rely heavily on the demand forecast. Figure 4 describes an example of the current planning practice. Planning for production in May is started on 15th Apr, when customer orders for May are confirmed. Because products require 15 days for processes outside clean room, orders in May have to be completed from packaging at the latest by 15th May. As a result, products produced at the packaging stage after 15th May are for demand in June, which is still based on forecast when the production plan for May is generated. For molding and assembly stages, production starts even earlier than packaging. From our analysis, 80% of assembly and 100% of molding are planned based on forecast due to the long cycle times. It is evident that shortening the cycle time is critical to enable production to be based entirely on firm orders.

![Figure 4 Current Planning Practice](image)

**2.4.2 Machine Capacity and Performance**

**2.4.2.1 Capacity**

Currently, demand is very close to the originally designed capacity of many machines in the line, especially for the AN machine and PN machine. Since only the data from the produced quantity of the final products in FY 2006 is available, we calculated the demand for each machine based on the produced quantity, the flow paths of those
products in the line, and the yield on each path, as shown in Equation 1. The quantity that machine A processes is equal to the quantity of the final products that are routed through this machine divided by the product of yield in the particular machine and downstream machines. Due to confidentiality concerns, the real demand quantity for each machine is not disclosed.

\[
Demand_{machineA} = \frac{Q_{Final \ Products \ Route \ Through \ MachineA}}{\Last \ Machine \ \prod_{i=\text{machineA}}^{\text{Last \ Machine}} Yield_i}
\]

Equation 1 Calculation of Demand of Each Machine

A shortfall could happen when the machine demand exceeds the machine capacity. There was no shortfall with the given demand data of FY 2006, because what we were given was the actual quantity produced in FY 2006.

Since all products visit the AN machine, as shown in Figure 3, this machine’s designed capacity is already very close to the demand. It has to be utilized more than 90% during peak times. It is perceived to be the bottleneck. Nevertheless, the second bottleneck, PN machine, has a high utilization close to AN.

2.4.2.2 Performance

The machines on the production line are quite sophisticated yet still very reliable. Regular preventive maintenance is carried out on all machines to minimize breakdowns and excessive depreciation. The yield rates of the machines are also very high. Most machines have a yield rate of over 98%, and only AN yields a little lower at around 92%.

BD recently implemented a software suite developed by Apriso Corporation to track machine performance. Available information from the system includes production quantity, quality (yield), machine up time, planned / unplanned downtime, etc. Because the Apriso system was introduced less than one year ago, the tracking of machine data is not fully automated. The machine up and downtime are automatically recorded for most machines, but not the molding machines. When machines undergo planned downtime, for instance preventive maintenance, the reasons of stopping have to be manually entered from a list. Similarly when machines experience unscheduled failure, the reasons also need to be manually entered. We found many discrepancies between the performance data recorded by Apriso and that described by the production floor. For example, the reasons for machine failure are sometimes captured into wrong categories. In spite of this, the data recorded for production quantity, quality, and overall production time is reasonably accurate for most machines.

Measurements of production variability, like MTTF and MTTR, are not directly available from Apriso. In theory it is possible to estimate these metrics from the scheduled production time, unscheduled downtime and downtime-count data in Apriso. However, we met many problems when trying to do so. First of all, the recording errors in the Apriso system can make big differences in MTTF and MTTR. For example, planned
Downtime is sometimes recorded as unplanned downtime in the system. Because the planned downtime can sometimes be very long, it could increase MTTR dramatically if it gets recorded as unplanned downtime. Moreover, the machine downtime-count data is inaccurate in most cases. For example, the waiting time for material from upstream operations is often falsely recorded as machine downtime. Such recording errors increase downtime drastically. As a conclusion, the exact measurements of production variability are not available for our project. Because the company regards the machines as very reliable, we expect there is little loss from ignoring variability in our analysis.

2.4.3 Cycle Time and WIP Level

The WIP that we discuss in this project includes molded hubs and shields before assembly, as well as assembled needles. The locations of WIP on the process flow are indicated in Figure 5. Four major product types are labeled with different color and the light blue ellipses represent the WIP locations.

![Eclipse Flow Paths Version 2](image)

**Figure 5 Representation of WIP Inventory on Flow Paths**

The Apriso system is able to accurately track the real-time WIP status, but it does not store historical data. Table 3 summarizes the actual WIP quantity and cost extracted from the Apriso system, based on daily observation over the month June 2007.
In the month of June, an extraordinary problem with raw material supply forced the Snap Clip Assembly (AN SC) machine to stop for a month. Contamination of metal clips from the only supplier caused AN SC to starve, affecting all the Luer-Slip products. Those assembled Luer-Slip needles with the stained metal clips have to be scrapped sooner or later. The other three types of products do not route through ANSC. Upstream of the ANSC, the bottleneck AN continued to process Luer-Slip products because the company believed that ANSC would be able to catch up quickly as soon as it returned to production. As a result by early July, the WIP produced by AN kept building up in the buffer space before ANSC. Because of this rare problem, the figures in Table 3 over-state the actual inventory level for assembled Luer-Slip needles. However, the table still provides good estimate of assembled Luer-Lok needles, as well as molded components.

The average WIP inventory amounts to ~13 million pieces for molded parts, and at least ~14 million pieces for assembled needles after discounting the inflated estimate for Luer-Slip. Compared to the demand in FY 2006, the inventory levels for molded parts and assembled needles are both more than their average monthly demand. A large WIP inventory leads to long cycle time in the product line. The recorded current cycle time is about 60 days for the processes within clean room. Given the 45 days’ order frozen window and the 15 days required for processes outside the clean room, the cycle time inside the clean room has to be within 30 days for the production to be fully based on firmed demand. Since the current cycle time inside the clean room far exceeds 30 days, the production is forced to be based on the demand forecast.

Reducing the cycle time may enable the production plan to be based on the firm orders. By reducing the cycle time, the factory also has the advantage of gaining flexibility [1]: The system will be more capable of very fast turnaround on individual orders, and the factory may more readily adapt to a changed order because the corresponding job may not have begun its processing. By reducing the WIP on the shop floor, the factory has the benefit of reducing inventory holding cost, faster detection of quality problems, hence less scrap or rework.

Table 3 Actual WIP Inventory Quantity and Cost

In the month of June, an extraordinary problem with raw material supply forced the Snap Clip Assembly (AN SC) machine to stop for a month. Contamination of metal clips from the only supplier caused AN SC to starve, affecting all the Luer-Slip products. Those assembled Luer-Slip needles with the stained metal clips have to be scrapped sooner or later. The other three types of products do not route through ANSC. Upstream of the ANSC, the bottleneck AN continued to process Luer-Slip products because the company believed that ANSC would be able to catch up quickly as soon as it returned to production. As a result by early July, the WIP produced by AN kept building up in the buffer space before ANSC. Because of this rare problem, the figures in Table 3 over-state the actual inventory level for assembled Luer-Slip needles. However, the table still provides good estimate of assembled Luer-Lok needles, as well as molded components.

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Table 3 Actual WIP Inventory Quantity and Cost

<table>
<thead>
<tr>
<th>Molded parts</th>
<th>Quantity (K)</th>
<th>Unit Inventory Cost ($)</th>
<th>Inventory Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luer Lock Hub</td>
<td>4,904</td>
<td>$0.013</td>
<td>$62,962</td>
</tr>
<tr>
<td>Luer Slip Hub</td>
<td>4,402</td>
<td>$0.018</td>
<td>$79,040</td>
</tr>
<tr>
<td>Needle Shield</td>
<td>2,003</td>
<td>$0.007</td>
<td>$14,508</td>
</tr>
<tr>
<td>Safety Shield</td>
<td>1,761</td>
<td>$0.008</td>
<td>$14,633</td>
</tr>
<tr>
<td>Total Molded</td>
<td>13,070</td>
<td></td>
<td>$171,144</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Assembled parts</th>
<th>Quantity (K)</th>
<th>Unit Inventory Cost ($)</th>
<th>Inventory Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety Needle - LL</td>
<td>8,892</td>
<td>$0.039</td>
<td>$342,765</td>
</tr>
<tr>
<td>Safety Needle - LS (before Snapclip)</td>
<td>6,316</td>
<td>$0.047</td>
<td>$294,323</td>
</tr>
<tr>
<td>Safety Needle - LS (after Snapclip)</td>
<td>4,725</td>
<td>$0.106</td>
<td>$499,108</td>
</tr>
<tr>
<td>Total Assembled</td>
<td>19,733</td>
<td></td>
<td>$1,136,196</td>
</tr>
</tbody>
</table>

* Figure based on average of daily figure from 1st June to 31st June, 2007
3 PROPOSED SOLUTIONS TO THE OVERALL SYSTEM

After understanding the current operation practice and measuring the WIP inventory level, in this chapter we will analyze the root causes to the high WIP and long cycle time problem, and discuss our approaches to the problem.

3.1 Root Causes to the high WIP and long Cycle Time Problem

3.1.1 Unnecessary Early Start in a Push-Pull and Pure Push System

From the current planning practice (Section 2.4.1), we observe that the current practice is actually a mixture of push-pull and pure push approaches. In a pure push system, production is planned based on forecast. In a push-pull system, the upstream production is scheduled based on forecast, which is push, and the downstream production is based on demand, which is pull.

In the current practice, upstream machines, like the molding machines, produce completely based on forecast. It is a very typical push approach. The planning of the downstream machines, which are the assembly and packaging machines, is more complicated. For packaging machines, they produce based on demand in the first half of a month and based on forecast in the second half. As a result, they change from pull to push in the middle of each month. The situation for assembly machines is similar, but they transform from pull to push earlier (See Section 2.4). When we look at the production line as a whole, it is a push-pull system in the first half of a month and a pure push system in the second half. When it is a push-pull system, a push-pull boundary exists between molding and assembly at first, and then quickly moves to between assembly and packaging. As a result, a large amount of WIP is built up at the push-pull boundary, before and after the assembly, especially between assembly and packaging.

The major problem with this mixture of push-pull and pure push is that it does not work well with a make-to-order system, which the Eclipse line is designed to be. A push-pull approach could be used in a make-to-order system, but a pure push system is definitely not. However, how could the current practice survive with a pure push system? The secrets are the relatively accurate forecast and the planner’s ability to communicate with customers frequently to further reduce forecast errors.

Even though the current practice seems to work well with meeting demand, it can increase cycle time and WIP. There are two reasons.

First of all, push starts production too early in either pure push or push-pull scenarios. The current practice simply starts pushing production of molded parts about one and half months earlier than demand, which directly increases cycle time and WIP.

Secondly, because the production line is supposed to be make-to-order, there is no finished goods inventory. If there is an error in forecast, like a cancellation of an order, the last stage (packaging stage), would not produce the cancelled order. The already
partially produced order from upstream would sit in the buffers as WIP and wait until the next order of the same SKU arrives.

### 3.1.2 Unsynchronized Production Flow

Under the current practice, a monthly production plan is generated for all stations before the month starts. The plan specifies the production quantity, start and end date for each batch of material on all machines in the month. It is equivalent to say that the time that each batch visits each machine on its route is pre-determined. Because it is difficult to predict the exact time when the batch will be ready from the upstream station, the plan usually gives a more conservative schedule by requiring the upstream to complete the batch earlier. This planning method causes a lack of synchronization of flow for each product type and introduces an extra delay between stations on top of the queuing time.

### 3.1.3 Rationales behind the Root Causes

In summary, the two root causes which explain the high WIP and cycle time are

1) Unnecessary early start of production in a push-pull and pure push system.
2) Unsynchronized production flow caused by the over-detailed production plans.

After we find the root causes of our problem, it is not hard for us to understand the rationales behind them. First of all, because the AN machine is the bottleneck of the production line as a whole, the best interest of planning would naturally be to prevent starvation at the AN station. To prevent starvation, the plan requires molded parts to always be available in front of the AN machine. In order to do so, molding starts much earlier than assembly, the earlier the better AN is protected from starvation. However, a problem starts to develop when molding starts earlier and earlier. The make-to-order system gradually transforms from a pull system to push-pull system, or even pure push system. Because of the nature of push, products are manufactured based on forecast. In the case when the partially finished products do not have actual demand, they have to stay in the shop floor because there is no finished goods inventory. As a result, the last stage of the line has to be scheduled after the orders become firm. This is exactly what happens in the current practice. The last stage operates on pull according to its production plan and the other stages push material to the downstream. In the end, overly detailed production plans introduce extra delays to the production flow and further increase cycle time and WIP.

### 3.2 Our Approaches to Reduce Cycle Time and WIP

After understanding the root causes, our basic approaches to the problem became very clear.

First of all, we need to eliminate the unnecessary early start. Our goal is to gradually transform the system back to a pure pull system, in this case make-to-order manufacturing. However, if the cycle time can not be reduced to the quoted lead time to
customers, a push-pull system is still necessary. Our goal would then be to move the push-pull boundary as far upstream as possible.

Then, we also need to achieve better synchronization of the production flow for each product family. Downstream machines could use FIFO policy instead of detailed production plans, if a pure pull system is used. If a push-pull system is required, only the most upstream machines and the machines right after the boundary have to be scheduled. Other machines can still use FIFO. Extra delays would be automatically eliminated with FIFO.

![Diagram](image)

**Figure 6 An Example of the Proposed Planning Cycle**

These two basic approaches require some changes of the current planning cycle. The current planning cycle is from the beginning of a month to the end of it. To transform the system to a demand-based make-to-order system, we change the cycle to be from 16th of every month to 15th of the following month, which is just the first 30 days of the order frozen window. It is important to note that, in our new planning cycle, we just want to produce the orders which are confirmed on the 15th of that month. It means planning for each cycle is done just one day before the cycle starts based on actual demand.

Figure 6 shows an example of our proposed planning cycle. On 15th April, demand for May is confirmed. We release the production plans for the period from 16th Apr to 15th May on that day, based only on actual demand in May. During the production period, 16th Apr to 15th May, we run the machines to satisfy demand in May. An optimal outcome is that all products for May leave the clean room before 15th May, so that they can proceed to processes outside the clean room and be shipped before May 31. A new planning cycle for June then starts on 15th May.

There are two important questions to be addressed in the above example.
First of all, can the demand of May be satisfied, if we only start production on 16\textsuperscript{th} Apr? If the answer is yes, then what we have described is a make-to-order or pull system which meets demand. If the answer is no, we need to further adjust the pull system to be push-pull, which means upstream of the production line has to start before 16\textsuperscript{th} Apr.

Secondly, the current practice requires 10 days to do planning, is it possible to plan everything in just one day now? The answer might be yes. As we have already discussed, we propose to use FIFO when possible. No planning would be required when a machine produces based on FIFO. If the answer is no, our proposed solution would be hard to implement.

Now we can see that the two important questions are actually two requirements for our proposed solution. In the rest of our theses, we divide the problem into three parts and elaborate our solution in detailed steps. Meanwhile, we also show that the two requirements could actually be met by our solution.

The three parts are

1) Scheduling AN and downstream machines. In this part, we do not consider the molding machines other than to assume that molding will not starve the AN. Based on the proposed planning cycle, we analyze the machines downstream of molding in great details. Results are shown in both the first thesis and the second thesis.

2) Scheduling hub molding machines. With the findings in the first part, we then consider the whole line including the molding machines. These results are discussed in this thesis.

3) Scheduling safety shield and needle shield machines. We use a different approach for these two machines. This is discussed in the first thesis.
4 SCHEDULING THE HUB MOLDING MACHINES

As discussed earlier, we divided the team project into three parts. The hub molding machines are the last part studied in the project.

4.1 Hub Molding Stage

Needle hub molding is the first stage of the safety needle production. In this stage, needle hubs are produced from plastic resin and color concentrates by injection molding machines. The next stage after hub molding is needle assembly, in which hubs, needle shields, and cannulas are assembled together into assembled needles.

4.1.1 Products

Although there are about 30 SKUs in the safety needle product family, some SKUs use the same hub type. There are 13 types of hubs in total. They differ in design and gauge size. Hubs for Luer-Lok and Luer-Slip needles are different in design. For each design, there are a few gauge sizes. More specifically, there are 7 gauge sizes for Luer-Lok hubs and 6 sizes for Luer-Slip hubs. Each of the 13 types of hubs is produced in a different color, so that they can be easily differentiated.

4.1.2 Machines

Different from needle shield and safety shield, hubs are produced by a group of 30 small-capacity injection molding machines. The machines are managed in two groups. The first group of 20 machines is dedicated to Luer-Lok hubs, and the second group of 10 machines is dedicated to Luer-Slip hubs. Because of validation and other reasons, machines in one group can only produce the design to which it is dedicated. Within the two groups, machines can produce hubs with different gauge sizes by changing inserts.

Because one insert could only produce one gauge size, a changeover is required to produce a different gauge size. Changeover takes about 2 hours on average. Two main steps of changeover are cleaning and changing mold inserts. The steps are documented as standard operating procedures. Changeover time variation is very small.

4.1.3 Capacity

Because of different mold inserts design, the average production rates of the LL machines and LS machines are different. Each LL machine has an average capacity of 14,000 hubs per shift. Each LS machine has an average capacity of 10,000 hubs per shift. Higher capacity is achieved by running multiple machines in parallel.

For each gauge size, its maximum capacity is limited by the total number of inserts. For example, there are only 12 inserts for 18G LL hubs. Even if there are 20 LL machines, the maximum capacity is only the capacity of running 12 machines simultaneously. Because mold inserts used in hub molding are expensive, the number of inserts for each
gauge size is limited, and based on the demand. Table 4 shows the number of inserts for each hub type and the maximum capacity.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Schedule</th>
<th>Max mold inserts</th>
<th>Machine Compatibility</th>
<th>Max Production Rate (000/shift)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18G</td>
<td>High runner</td>
<td>12</td>
<td>any of the 20 machines</td>
<td>168</td>
</tr>
<tr>
<td>21G</td>
<td>High runner</td>
<td>12</td>
<td>any of the 20 machines</td>
<td>168</td>
</tr>
<tr>
<td>22G</td>
<td>Medium runner</td>
<td>7</td>
<td>any of the 20 machines</td>
<td>98</td>
</tr>
<tr>
<td>23G</td>
<td>High runner</td>
<td>12</td>
<td>any of the 20 machines</td>
<td>168</td>
</tr>
<tr>
<td>25G</td>
<td>High runner</td>
<td>12</td>
<td>any of the 20 machines</td>
<td>168</td>
</tr>
<tr>
<td>27G</td>
<td>Low runner</td>
<td>5</td>
<td>any of the 20 machines</td>
<td>70</td>
</tr>
<tr>
<td>30G</td>
<td>Low runner</td>
<td>6</td>
<td>any of the 20 machines</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 4 Capacity and Constraints of the Hub Molding Machines

4.1.4 Machine Compatibility

Machine compatibility refers to the compatibility between the molding machines and mold inserts. Because of natural variation on machines and inserts, an insert and machine pair has to be validated together before they can be paired for production. If an insert and machine pair passes validation, they are compatible and qualified for production.

Because the current validation process is costly and time consuming, some machines and inserts are still not compatible with each other. The compatibility issue exists in the Luer-Slip machine group. Table 4 shows compatible machines for each gauge size. For the Luer-Lok group, all mold inserts are compatible with any of the molding machines.

The compatibility issue creates an extra constraint in scheduling the LS machines. The company is working on the compatibility issue now, but we have to keep this constraint in our project.

4.2 Analyze the Problem

Demand of the safety needle products is described in 2.2. In the previous section, we described the capacity and constraints of the hub molding stage in detail. By translating the demand of safety needle products to the demand of hubs and comparing demand with capacity, we can understand the problem better.

4.2.1 Demand and its Distribution of Needle Hubs

We can calculate the demand of the needle hubs from the demand of final products. Because one hub type is usually shared by a few SKUs, its demand is the sum of the demand of a few SKUs. As hub molding is the first stage of the production line, we also need to consider downstream yield loss when calculating demand for the hubs. In our
calculation, we use the product monthly demand data of FY 2006 and average yield loss to estimate the demand of hubs in FY 2006.

Distribution of hub demand is also closely related to its direct consumer – the needle assembly machine. The assembly machine is the most highly loaded machine in the production line. Each needle has to go through this machine. In FY 2006, the monthly demand is close to its capacity. In order to fully utilize this machine to meet demand, the plant wants to minimize its idle time, including changeover. In current practice, changeover at this machine is minimized such that production batch size of a SKU is usually the same as its monthly demand. In other words, the assembly machine only produces each SKU once a month. We follow the same practice in our project. As a result of this practice, the monthly demand for a needle hub type occurs only when it is being assembled on the needle assembly machine. The period varies from one shift to a few shifts, depending on demand. In this period, demand of a hub type is just the average production rate of the assembly machine (250,000 per shift).

As a conclusion, monthly demand of the hubs is calculated from the monthly demand of final products with yield loss. For a particular hub type, its demand is concentrated into the few shifts when the hub type is being assembled on the needle assembly machine. Demand is zero for the rest of the month.

4.2.2 Machine Capacity and Hub Inventory

The total capacity of the 30 molding machines is 380,000 per shift (280,000 per shift for LL and 100,000 per shift for LS), which is much higher than the capacity of the assembly machine (250,000 per shift). However, the maximum capacity of each individual hub type is actually smaller than the capacity of the assembly machine (see Table 4). Thus, the production rate of a hub type is actually slower than its consumption during its assembly period.

Theoretically, this is not a problem. As long as we can have the total production rate of hubs be higher than the assembly rate, the assembly machine can always avoid starvation by getting a different hub type when stock of the current type is exhausted. It means that, if the total molding production rate is higher than the assembly rate, even if molding and needle assembly start at the same time, we can avoid starvation.

However, in the actual case, because the assembly machine only produces each SKU once a month, it does not produce another SKU until the current one is completed. If a hub type is depleted when its SKU batch is not completed, starvation would happen.

As a result, there must be enough stock of a hub type before its assembly starts. Otherwise, the assembly machine might be starved. The solution is to start hub molding much earlier than needle assembly. For example, hub molding of SKU B can be started while assembly machine is still working on SKU A. When SKU A is finished at the assembly machine, a stock of hubs for SKU B is already built.

When early start of hub molding is required, the question becomes how early it should start, or how many hubs should be stocked before assembly starts. As the average rates of
production (production rate of hub molding for each SKU) and demand (production rate of assembly) are known, we can consider the question as a simple Chase Problem. Production runs first in this problem. Demand starts a few shifts later and chases production. If demand catches up with production before the finish line, starvation happens. The total distance is the production batch size (monthly demand) of a SKU. The problem is formulated below, from where we can calculate the minimum early start time or inventory level for hubs.

For each SKU,

\[ t_{AN} = \frac{\text{ProductionBatchSize}}{\text{AssemblyProductionRate}} \]

\[ t_{HUB} = \frac{\text{ProductionBatchSize}}{\text{HubProductionRate}} \]

To prevent starvation of the assembly machine, we must have

\[ Time_{AN \text{ Start}} - Time_{HUB \text{ Start}} \geq t_{HUB} - t_{AN} \]

Or inventory of hubs before assembly is

\[ \text{Inventory} \geq (t_{HUB} - t_{AN}) \times \text{HubProductionRate} \]

Equation 2 Equations to Calculate Assembly Starvation

The simple equations show that the minimum early start time and inventory level of hubs are functions of production batch size, production rates of hubs, and production rate of assembly. As discussed earlier, the production batch size is always the same as the monthly demand and the production rate of assembly is always at its maximum. We only have the freedom to control hub production rate in this project.

A high production rate of hubs results in a small minimum inventory and early start time, which also means small cycle time and WIP. However, the highest production rate of each hub type is achieved by running the maximum possible machines in parallel. When the total number of machines is limited to 30, this means very frequent changeover of mold inserts on the machines is necessary. Frequent changeover could be a problem for the production floor. Currently, there are at most about 30 to 40 changeovers monthly. Any more changeovers would require extra labor force and changeover stations. We need to consider a tradeoff between changeover frequency and the minimum hub inventory (cycle time) in our analysis. We analyzed two extreme cases of the tradeoff.

To minimize changeovers, it is possible to dedicate a portion of the machines (more than half of the 30 machines, based on a detailed analysis with demand in the first 9 months of FY 2006) to some high demand hub types. For the first 9 months of FY 2006, some dedicated machines require no changeovers, and most other machines require only two or three changeovers. Appendix A shows the detailed hub type assignment of every machine in the 9 months. The average number of changeovers in a month is about 10 times.
However, the production rate of each hub type is low when machines are dedicated. We can use the simple equations discussed in this section to estimate how early hub production should start. For example, 4 LL machines are set up to produce hub type 18G in Oct. Production rate of 18G hubs is $4 \times 14k/\text{shift} = 64k/\text{shift}$. Using the equations, we find production of 18G hubs has to start at least 30 shifts (10 days) earlier than assembly. If we do the same calculation for every hub type in the 9 months, we find the required early start time is about 1 to 2 weeks for LL hubs and 2 to 3 weeks for LS hubs.

To minimize inventory of hubs, we can produce the hubs at their maximum production rates. We can use the same method in the previous paragraph to estimate early start time of hub production in this case. A quick estimate shows that for FY 2006, hub molding, at its maximum rate, only needs to be started about 5 shifts earlier than its assembly on average (about 9 shifts for LS and 3 shifts for LL). The resulting cycle time and inventory level would be much smaller compared to the previous case. However, about 90 changeovers are required every month, which would be much more than what the production floor can handle.

### 4.2.3 Variability of Production Rate

A very important issue is the variability of the machines. The simple starvation equations do not consider variability. When variation of molding and assembly are considered, the minimum inventory level has to be adjusted to compensate for it. Any disruption to the molding production, like machine breakdown, could increase the minimum inventory requirement.

To consider variability, we might use a few models to calculate the minimum inventory requirement. An inventory model, like periodic or continuous model, could be considered. The variability of molding could be modeled as variability in supply, like lead time variability, and variability of assembly could be modeled as variability in demand. We can also approximate the molding machines as one single machine and use a Two Machines with One Finite Buffer model to obtain an approximate solution. Variation of machines, like MTTR and MTTF, are considered in the model. The exact relationship between buffer size and overall production rate could be solved, if Markov processes are assumed.

In section 2.4.2, we have discussed the inaccuracy and unavailability of the machine variability measures in the current system. Based on the description by the machine operators, both molding machines and assembly machines are generally reliable. A one-shift-long Preventive Maintenance is carried out weekly. Machine problems could almost always be solved within one shift’s time.

As a result, we use the average production rate of machines, which is an average of the actual production rate in the last 9 months, in our calculation. Machine variations, like MTTF and MTTR, are not considered in our analysis. They could be considered in future work.
4.3 Current Practice

As discussed in 2.4.1, production plans for hub molding machines are generated monthly. Hub molding starts about 1 month to 1 week earlier than assembly on average. The production quantity is entirely based on forecast. Because the forecast is generally accurate, this seldom gives problems. The production rate of each hub type is generally about 50% or more of its maximum rate. Hubs produced in the first half of a month are usually assembled in the same month, and those produced in the second half of the month are usually assembled sometime in the following month.

The current inventory level for hubs is quite high. For LL hubs, the average level in June is about 50% of its average monthly demand in FY 2006. The peak level is about the same as its average monthly demand. For LS hubs, the average inventory level is about 150% of its average monthly demand. The peak can be as high as twice of its average monthly demand. The net amount LL and LS hubs are about the same, as their demand is different.

There might be three reasons for the relative inventory level (inventory/demand) of the LS hubs being higher than that of the LL hubs. Firstly, LL molding is faster than LS molding. They don’t have to be started as early as LS molding. Secondly, LL molding doesn’t have the compatibility issue (see 4.1). It is much easier to plan the LL machines. Lastly, demand of the LL hubs is more than twice that of the LS hubs. The planner usually focuses on reducing the relative inventory level of the LL hubs in order to reduce the net inventory.

4.4 A Proposed Solution

We have already discussed that hub production of each type has to start earlier than its assembly to prevent starvation. Starvation is usually not acceptable, because production might not be able to meet demand if it happens. However, early start of hub production unavoidably increases cycle time and hub inventory. In our proposed solution, we are trying to reduce early start of hub production. If it is reduced, both the cycle time and WIP level could be reduced.

One important point to note is that the early start is for each hub type. We must also keep in mind that the overall molding production rate is still higher than that of the assembly. As a result, if the constraint of production batch size at assembly stage (see 4.2.2) could be taken care of, the molding process as a whole does not have to start much earlier than assembly.

Meanwhile, we also need to keep the monthly changeover of molding machines at an acceptable level. It should not be more frequent than that from the current practice.

The current practice takes about 10 days to generate the monthly production plan. We also try to propose a simple solution, so that planning could be more efficient.
Finally, we must make sure that production could meet demand with our proposed solution. The monthly demand must be produced within a 30 day lead time inside the clean room.

4.4.1 Create Three Groups of Molding Machines

The first step of our solution is to group the molding machines into three groups. The reason to create groups is to make scheduling easier. After grouping, we can let the three groups run simultaneously and feed the assembly machine one at a time. It is a simple and clear structure to take advantage of the fact that overall molding capacity is bigger than assembly capacity. Each hub type is only produced from one group, so that a big scheduling problem becomes three smaller problems with less complexity. The scheduling is simplified.

The three groups are one LS group and two LL groups, with each group having 10 machines.

The LS and LL machines are in different groups, which is the current practice. Because the demand and production of LL and LS hubs are not related, we can consider different strategies for LL and LS hub production. The motivation to do so is that the scheduling of LS machines is more complicated than that of LL machines, due to the compatibility issue (see 4.1). We have more flexibility with scheduling LL machines.

To split the 20 LL machines into two groups is to simplify the problem. Table 5 shows the details of the two groups. Hub types are allocated to the two groups in such a way that demand is split evenly. The total monthly demand of final products is divided almost equally to the two groups. Furthermore, demand of the two major product types, Combo and LL-PN, is also divided almost equally to the two groups.

<table>
<thead>
<tr>
<th>Guage</th>
<th>Inserts</th>
<th>SKU</th>
<th>Total Demand</th>
<th>Ratio of Combo Products</th>
<th>Ratio of LL-PN Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>18G</td>
<td>10</td>
<td>PSN 18 x 1 1/2</td>
<td>47%</td>
<td>45%</td>
<td>53%</td>
</tr>
<tr>
<td>25G</td>
<td>10</td>
<td>PSN 25 x 1</td>
<td>PSN 25 x 1 1/2</td>
<td>1 ml 25 x 5/8 Combo</td>
<td>3 ml 25 x 5/8 Combo</td>
</tr>
<tr>
<td>27G</td>
<td>5</td>
<td>1 ml 27 x 1/2 Combo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30G</td>
<td>6</td>
<td>1 ml 30 x 1/2 Combo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21G</td>
<td>10</td>
<td>PSN 21 x 1 TW</td>
<td>53%</td>
<td>55%</td>
<td>47%</td>
</tr>
<tr>
<td>22G</td>
<td>7</td>
<td>PSN 22 x 1</td>
<td>PSN 22 x 1 1/2</td>
<td>3 ml 22 x 1 Combo</td>
<td>3 ml 22 x 1 1/2 Combo</td>
</tr>
<tr>
<td>23G</td>
<td>10</td>
<td>PSN 23 x 1</td>
<td>3 ml 23 x 1 Combo</td>
<td>Bulk Needle 23 x 1 MTW (ABG)</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 Two Groups of the LL Molding Machines
Because there are only 10 machines in each subgroup, the maximum possible production rate of each hub type would be the rate of running 10 machines in parallel. As a result, the hub types with 12 inserts could only run at a maximum of 10 inserts in parallel. This is a drawback of our grouping scheme.

Next, we discuss the strategy we use for each group.

### 4.4.2 Strategy for the LS Group

For LS machines, we suggest the machine dedication approach discussed in section 4.2.2. 4 out of the 10 machines could be dedicated to 3 hub types in FY 2006. No changeover is required for the entire year. For the other machines, they produce different hub types from month to month according to demand. Most of them only need one changeover per month. Our calculation (based on the simple equations in 4.2.2) shows that with this approach, LS hub production needs to start about 2 to 3 weeks earlier than assembly.

There are several reasons to use the machine dedication approach.

Firstly, demand of the LS hubs is much lower than that of the LL hubs. If we start its production about 2 to 3 weeks earlier than assembly, average inventory level of the LS hubs would be approximately equals to its average monthly demand, which is acceptable and similar to the current WIP level. The same approach would not be acceptable for the LL hubs, because its monthly demand is much higher.

Secondly, the LS machines are constrained by the compatibility issue, which makes it very difficult to schedule. Tremendous efforts spent on optimizing the LS machine schedules might not be rewarded by great savings on cycle time and WIP. In the dedication approach, because most machines only produce one hub type every month, it is very easy to schedule the machines.

Thirdly, we have an accurate forecast to allow us to produce LS hubs 2 to 3 weeks in advance. In fact, current practice is also based on this forecast.

The difference between our approach and the current practice is the emphasis on machine dedication. The emphasis could reduce the complexity of planning and minimize the number of changeovers. The inventory level and cycle time for the LS hubs are expected to remain the same with our approach.

### 4.4.3 Strategy for the Two LL Groups

The basic strategy for the LL groups is to shorten their early start time as much as possible to reduce cycle time and inventory. How short the early start time could be depends on if it would result in starvation and if the starvation would lead to unmet monthly demand.

In 4.4.2, we talked about the strategy for the LS group. Following our strategy, the LS hubs are always in stock when their assembly starts. We can take advantage of this property when exploring the strategy for LL machines. As the LS hubs are always ready,
we use the LS hubs to feed the assembly machine at the start of the month, so that the two LL groups can afford more time to build up inventory.

In the following sections, we discuss the early start time for the two LL groups in detail.

4.4.4 Details of the Proposed Solution

Although we present this as a solution for the hub molding machines, it incorporates scheduling policies for the entire production line. There are two reasons to do so.

Firstly, to reduce cycle time and WIP, it is optimal for the assembly machine to be fed by the three hub molding groups in a cyclic fashion. A scheduling policy for the assembly machine is then required.

Secondly, we need to simulate the entire line to evaluate our scheduling policy against performance measures like the total cycle time, WIP level, and if production meets demand. The policies for the whole line are required in our simulation.

The basics of the proposed solution follow the overall solution discussed in 3.2. The planning and production cycle follows the overall solution. In detail, the assembly machine starts production on the beginning of a production cycle (16th of a month). We have shown that monthly demand could be met if assembly starts on that day.1 The LS hub molding group starts about 2-3 weeks earlier than assembly based on the forecast. The LL hub molding groups start only a few, or even zero, shifts earlier than assembly (details will be discussed later). Figure 7 shows the proposed solution graphically. We will talk about scheduling policies for assembly and molding machines in detail in the next section.

1 Details are presented in the second thesis of the project.
4.4.4.1 Scheduling Policy for the Assembly Machine

The scheduling policy for assembly is a monthly production sequence derived from the average monthly demand of FY 2006. Table 6 shows the production sequence. For each month, the assembly machine produces SKUs according to the release order in the first column. We use the same sequence for all the months in FY 2006. The production quantity is decided by the demand of that month.

![Table 6 The Proposed Production Sequence for the Assembly Machine](image)

We follow four guidelines to derive the production sequence.

Firstly, the assembly machine gets hubs from the three molding groups in a cyclic fashion. The time duration that the assembly machine stays in an LL group before switching to another is about the same, so that the early start time of the two LL groups can be balanced.

Secondly, assembly starts with LS-PN SKUs. The reason has been discussed in section 4.4.3.
Thirdly, the four major product types, LS-PN, LL-PN, COMBO, and BULK, are mixed in the release order. The reason to do so is to improve cycle time and WIP level in downstream machines.²

Lastly, the release order allows each molding group to produce a hub type only once in a month. Details will be discussed in the next section.

4.4.4.2 Scheduling Policy for Hub Molding Machines

4.4.4.2.1 The LS Group

As we discussed earlier in 4.4.2, LS hub molding starts about 2 to 3 weeks earlier than assembly machine. LS Hubs are all in stock when the assembly machine starts production. All SKUs are produced concurrently from dedicated machines. We created a spreadsheet to help in making machine allocation decisions. After the input of an allocation plan and demand data, the spreadsheet displays graphically if a month’s demand could be met with the allocation plan. If not, rearrangement can be made and tested. A screenshot of the spreadsheet is shown in Figure 8.

![Figure 8 A Screenshot of the LS Hub Molding Planning Tool](image)

To use the spreadsheet, we first input monthly demand data of LS products into the demand input cells located on the left bottom corner of the spreadsheet. We then adjust the capacity allocation of the non-dedicated machines in the yellow input cells below each machine. (The machines with grey cells are dedicated to a hub type.) For example, if machine LS2 is planned to produce the hub type 21G for half a month and 27G for the other half, we put 50% in the yellow cell for 21G under LS2 and 50% in the yellow cell for 27G under LS2. After allocating machine capacity to the gauge sizes, the spreadsheet calculates utilization for the gauge sizes using the following equation.

² Details of assembly and downstream machines are discussed in the first and second theses of the project.
Utilization = \frac{Demand}{Allocated Machine Capacity}

Equation 3 Calculation of Utilization in the Spreadsheet for the LS Hub Molding Machines

For example, if demand of 20G is 486k and one machine is allocated to it, the total allocated capacity is 10k/shift*60shift=600k (the normal operation time for the hub molding machines in a month is 60 shifts), the utilization is 486k/600k=81%. If utilization is higher than 100%, we need to allocate more capacity to the gauge size. It can be done by borrowing capacity from gauge sizes with low utilization. For example, if 20G has capacity more than 100% and 25G has extra capacity, we can make LS6, LS7, or LS9 give some capacity to 20G.

4.4.4.2.2 The LL Groups

For the two groups of LL machines, each group will produce a type hub at its maximum rate and will start only a few shifts before assembly. Their production schedules are closely related to the schedule of the assembly machine. Based on the schedule for assembly discussed in 4.4.4.1, the two groups produce according to the sequence in Table 7.

<table>
<thead>
<tr>
<th>LL1 Production Sequence</th>
<th>25G</th>
<th>18G</th>
<th>27G</th>
<th>30G</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL2 Production Sequence</td>
<td>22G</td>
<td>23G</td>
<td>21G</td>
<td></td>
</tr>
</tbody>
</table>

Table 7 The Proposed Production Sequences for the Two LL Hub Molding Groups

The remaining question now is how much earlier the LL groups should start production with the production sequences above. As we discussed in 4.4.3, we desire to meet demand as well as to minimize the early start to keep the cycle time small. A simulation model discussed in section 4.5 helps us to determine if monthly demand could be met with a given early start time.

4.5 Simulation

We simulated the proposed solution using SIMUL8 10.0 package. SIMUL8 is a powerful analytic tool for Discrete Event Simulation, which allows visual models to be easily created by drawing objects and results to be displayed interactively on the screen. The model is shown in Figure 9.
In Figure 9, the workstation labels named 'AN', 'AN SC', 'COMBO', 'Bulk' and 'PN' represent the assembly and downstream machines. The two workstations labeled "LL_Hub1" and "LL_Hub2" represent the two LL hub molding groups. The red triangles on the left, "LL Hub Order" and "LS Hub Order" are material release controls for LL and LS hub production. LL hub production is carried out at the two workstations, but LS hub production is not simulated. "LS Hub Order" directly releases hubs into the "LS Hub Inventory". This is explained in assumption 1 below. Scrapped parts from each machine are put into two bins named 'Scrap' and 'Scrap 2'. The cylindrical containers are buffers for WIP. The red triangles on the right named 'Combo Needle', 'Bulk Needle' and 'PN Needle' represent end products from the clean room. The small human figures with names "VM" are dummy controller to control material release to hub molding machines.

4.5.1 Assumptions

The following assumptions are made in our model.

1) The LS molding group is not modeled and LS hubs are always available for production. Because the strategy for LS hub molding is to start it early and have inventory always available before assembly, we make this assumption in our model. The reason to have this assumption is to simplify our model. As a result, the model does not determine the cycle time and WIP level of LS hubs.

2) The two LL groups are modeled as two single machines. This is another assumption to simplify our model. Each of the two single machines represents a LL group. The production rate of an SKU is modeled to be the maximum possible rate in its group. Changeover is a bit more complicated and is approximated with the following assumptions.

(a) We assume all the 10 machines in a group need changeover every time a hub type is produced.
(b) When it is time for changeover, we assume the 10 machines stop their current production at about the same time and wait for changeover.
(c) We assume changeovers of 2 machines can be carried out in parallel.
(d) We assume a machine starts production immediately after its changeover.

Based on these assumptions, we make the following approximations for changeover. When a group is going to produce a different hub type, the 10 machines in the group stop at around the same time. Then, we first do changeovers for 2 machines. These two machines start production immediately after changeover. As a result, they are idle for 1 changeover time, which is 2 hours. After that, another 2 machines (3rd and 4th machines) are changed over and then start production. These 2 machines are idle for 2 changeover times. For the next 2 machines (5th and 6th machines), they would idle for 3 changeover times. The 7th and 8th machines would idle for 4 changeover times, and the 9th and 10th machines would idle for 5 changeover times. The average idle time for the 10 machines would be \((1+2+3+4+5)/5=3\) changeover times each. As a result, we assume the changeover time for the two single machines in the model is 3*2=6 hours.

3) The processing time at each machine is the average time to process 10,000 pieces, and it follows an exponential distribution. Because the average time to process a single part in any machine is very small, it is easier for us to set the time for 10,000 parts. 10,000 pieces is also 1 storage unit for WIP in the line.

4) Average historical processing rate is used and production variation is not explicitly considered. This has been discussed in 4.2.3.

5) Based on the machine data from the past 9 months, we assume that AN and downstream machines have a normally distributed changeover time with mean of 30 minutes and standard deviation of 10 minutes.

6) Each machine has a constant yield rate which is approximated by the average yield observed in the past 9 months.

7) Transfer batch size used in the simulation is 10k. We choose 10k because it is easier to implement in simulation and there is no batch control required in the model. We have already shown that a batch size of 200k performs similar to 10k. We could choose 200k as the transfer batch size in actual implementation.

4.5.2 Objectives

There are two objectives for the simulation.

Firstly, we want to see if our proposed solution could meet the monthly demand. We run the simulation model with demand of the first 9 months of FY 2006, which is the actual quantity produced by the plant. We must satisfy it completely to match the current practice.

Secondly, we want to observe the cycle time and WIP level from the simulation. We expect a big improvement.
4.5.3 Simulation and Results

We simulate one month at a time. We start each month with an empty shop floor. The reason to have an empty floor is related to our proposed solution. In section 3.2, we have discussed that the proposed solution produces next month’s demand starting from a 30-day production cycle on the 16th of the current month. If demand can be satisfied, production should finish by the end of the 30-day production cycle, and there should be no jobs left inside clean room. As a result, the simulation of our proposed solution starts with an empty floor.

In the simulation, we store the monthly production quantity and sequence for hubs in the material release controls, “LL Hub Order” and “LS Hub Order”. The material release controls release jobs to the downstream workstation or inventory buffer when the simulation starts. The LL hub workstations, “LL_Hub1” and “LL_Hub2”, produce according to the production quantity and sequence released from “LL Hub Order”. The “LS Hub Inventory” stores parts released from “LS Hub Order”. When the simulation starts, the “AN” machine starts production immediately according to the proposed schedule. If a hub type is not available for production, the AN machine starves. The machines after the “AN” machine start production when their upstream buffers are not empty. Their production is based on FIFO.

Three scenarios are simulated.

Scenario 1: LL hub molding starts at the same time as the assembly machine

In this scenario, the two LL groups start on 16th of a month, which is the beginning of a production cycle. Results of this scenario are shown in Table 8. We can see that it takes more than 30 days to satisfy monthly demand in two out of the 9 months. The two months are February and May, highlighted in orange in the table. This happens because demand of the two months is high and starvation of the assembly machine reduces its utilization. To reduce starvation, we let the molding machines start a few shifts earlier than the assembly machine. The next scenario shows a scenario in which demand could be met.

<table>
<thead>
<tr>
<th>LL Hub Molding Starts at the Same Time as Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle Time (days)</td>
</tr>
<tr>
<td>Oct Nov Dec Jan Feb Mar Apr May Jun</td>
</tr>
<tr>
<td>COMBO</td>
</tr>
<tr>
<td>BULK</td>
</tr>
<tr>
<td>LL-PN</td>
</tr>
<tr>
<td>LS-PN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Demand Complete Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 23 30 24 31 23 30 30 29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LL Hub Inventory (000's)</th>
<th>Average</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct Nov Dec Jan Feb Mar Apr May Jun</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>164</td>
<td>341</td>
</tr>
<tr>
<td>213</td>
<td>289</td>
<td>673</td>
</tr>
<tr>
<td>940</td>
<td>1,550</td>
<td>1,160</td>
</tr>
</tbody>
</table>

Table 8 Simulation Results for LL Hub Molding Starts at the Same Time as Assembly
Scenario 2: LL Hub starts 12 shifts earlier than assembly machine

In this scenario, LL hub molding starts about 4 working days earlier than the assembly machine, which is around the 12th of a month. Results of this scenario are shown in Table 9. We can see that monthly demand is fulfilled within 30 days for all 9 months simulated. In the other parts of this project, we use 28 days as the normal operation time in a month. In this part, we need 30 days to satisfy demand in May and 29 days to satisfy demand in February. This is not a problem. In May, we can use overtime to satisfy demand. In February, although there are only 28 days, we can use the first day of the next month to complete shipments for February. The shipments on the first day of the next month would not be considered as late because they are shipped within 30 days from the first day of February production cycle. As a result, we can meet demand in this scenario.

<table>
<thead>
<tr>
<th>Cycle Time (days)</th>
<th>COMBO</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL-PN</td>
<td>6.5</td>
<td>8.4</td>
<td>9.9</td>
<td>9.2</td>
<td>13.5</td>
<td>13.6</td>
<td>13.4</td>
<td>12.0</td>
<td>15.9</td>
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<tr>
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<td>8.4</td>
<td>9.9</td>
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<td>13.6</td>
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<tr>
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<th>18</th>
<th>19</th>
<th>27</th>
<th>24</th>
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<th>23</th>
<th>27</th>
<th>30</th>
<th>25</th>
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<tbody>
<tr>
<td>LL Hub Inventory (000's)</td>
<td>Average</td>
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<td>1,076</td>
<td>2,904</td>
<td>3,291</td>
<td>4,156</td>
<td>2,610</td>
<td>2,825</td>
<td>4,022</td>
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<td>Max</td>
<td>4,273</td>
<td>3,570</td>
<td>4,520</td>
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<tr>
<td>LS Hub Inventory (000's)</td>
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<td>112</td>
<td>295</td>
<td>284</td>
<td>785</td>
<td>832</td>
<td>693</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>410</td>
<td>1,050</td>
<td>2,130</td>
<td>3,360</td>
<td>5,660</td>
<td>4,130</td>
<td>2,940</td>
<td>3,690</td>
</tr>
<tr>
<td>Needle Inventory (000's)</td>
<td>Average</td>
<td>352</td>
<td>382</td>
<td>736</td>
<td>820</td>
<td>2,249</td>
<td>912</td>
<td>934</td>
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</tr>
<tr>
<td></td>
<td>Max</td>
<td>1,250</td>
<td>1,200</td>
<td>1,160</td>
<td>1,470</td>
<td>3,560</td>
<td>2,220</td>
<td>1,510</td>
<td>2,860</td>
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</table>

Table 9 Simulation Results for LL Hub Molding Starts 12 Shifts Earlier than Assembly

Scenario 3: LL Hub starts 18 shifts earlier than assembly machine

In this scenario, LL hub molding starts about 6 working days earlier than the assembly machine. Results of this scenario are shown in Table 10. We can see that completion date of monthly demand is the same as they are in scenario 2, but the cycle time and WIP level increase.

<table>
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<tr>
<th>Cycle Time (days)</th>
<th>COMBO</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
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<td>LL-PN</td>
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<td>10.9</td>
<td>8.3</td>
<td>12.9</td>
<td>8.3</td>
</tr>
<tr>
<td>Needle Inventory (000's)</td>
<td>Average</td>
<td>8.5</td>
<td>10.4</td>
<td>11.9</td>
<td>11.2</td>
<td>15.5</td>
<td>15.6</td>
<td>15.4</td>
<td>14.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Demand Complete Days</th>
<th>18</th>
<th>19</th>
<th>27</th>
<th>24</th>
<th>29</th>
<th>23</th>
<th>27</th>
<th>30</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL Hub Inventory (000's)</td>
<td>Average</td>
<td>1,480</td>
<td>1,442</td>
<td>3,739</td>
<td>3,875</td>
<td>4,720</td>
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<td>3,562</td>
<td>4,888</td>
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<td>8,450</td>
<td>5,640</td>
<td>6,480</td>
<td>7,940</td>
</tr>
<tr>
<td>LS Hub Inventory (000's)</td>
<td>Average</td>
<td>28</td>
<td>112</td>
<td>295</td>
<td>284</td>
<td>785</td>
<td>832</td>
<td>693</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>410</td>
<td>1,050</td>
<td>2,130</td>
<td>3,360</td>
<td>5,660</td>
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<td>2,940</td>
<td>3,690</td>
</tr>
<tr>
<td>Needle Inventory (000's)</td>
<td>Average</td>
<td>377</td>
<td>443</td>
<td>736</td>
<td>820</td>
<td>2,249</td>
<td>912</td>
<td>934</td>
<td>1,635</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>1,430</td>
<td>1,200</td>
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<td>1,470</td>
<td>3,560</td>
<td>2,220</td>
<td>1,510</td>
<td>2,860</td>
</tr>
</tbody>
</table>

Table 10 Simulation Results for LL Hub Molding Starts 18 Shifts Earlier than Assembly
4.5.4 Discussion of the Simulation Results

4.5.4.1 Meet Demand

From the simulation results, we see that our proposed solution could meet demand. In the second scenario, monthly demand could be satisfied within 30 days of production. As a result, all the produced products would have at least 15 days to go through processes after the clean room, which guarantees on time shipment.

By comparing the three scenarios, we find that the early start time of LL hub molding could affect production rate by starving the assembly machine. When demand is high, starvation could result in unmet demand or late deliveries (February and May in scenario 1). However, when the early start time is big enough, starvation of the assembly machine is avoided; increasing the early start time further need not shorten the production completion date. This happens in scenario 2 and 3. Further increasing the early start time from scenario 2 only increases the cycle time and WIP.

![Demand Completion Days]

Please Note:
Demand could NOT be met in Feb and May in the case of 0 Shifts.

**Figure 10 Comparison of the Demand Completion Days in the 3 Simulation Scenarios**

4.5.4.2 Reduce Cycle Time and WIP

It is obvious that the earlier LL hub molding starts, the longer is the cycle time and WIP. Results of the three simulation scenarios show the difference (see Figure 11 and Figure 12). The cycle time shown below is the time between when a product enters the system (enters the LL molding stage) and when it leaves the system (leaves the packaging stage).
We are also interested in comparing the simulation results with the current practice. There are a few comments required before we make this comparison.

First of all, there is no historical data of WIP level in the current practice. The only data we have is from a daily monitoring of the WIP level during June 2007 (see section 2.4.3). Because monthly demand was increasing in the past 9 months, it is not fair to compare the actual WIP level in June with a 9 month average from the simulation. As a result, we compare it with the simulation result for June only.
Secondly, we assume LS hubs are always available in our simulation. This is an assumption made based on our proposed solution (see 4.4.2). There is a small difference between simulation and the proposed solution. In simulation, we keep a required amount of LS hubs at the beginning and there is no replenishment of LS hubs throughout the production cycle. In the actual proposed solution, the same amount of hub inventory would be stored at the beginning, and the LS hub molding machine would produce hubs for the next month throughout the production cycle. As a result, the actual proposed solution would introduce more WIP than the simulation predicts. We have already discussed the cycle time and WIP level of LS hubs of our proposed solution in section 4.4.2. As a result, we would not compare cycle time and WIP of LS hubs in this section.

Thirdly, our simulation is on a monthly basis. When LL hub molding starts 12 or 18 shifts earlier than assembly, they actually start from a previous production cycle (or a month, as a production cycle is 30 days). As a result, it is more accurate to simulate for more than one production cycle continuously. But, because the early start time is relatively short, 4 or 6 days, we did not use a multiple month simulation model. However, there are two things to note. Firstly, at the beginning of our one month simulation, there is a warm-up period of 12 shifts (or 18 shifts) for the LL hub molding machines to build-up inventory of LL hubs. Secondly, in the actual case, the LL hub molding machines would start producing hubs for the next month in the last 12 shifts (or 18 shifts) of the current production cycle. We did not include that in our simulation. As a result, the simulated WIP level of LL hubs in the last 12 shifts (or 18 shifts) is slightly lower than the actual case.

Lastly, although demand of February and May could not be met in the first scenario, we can still compare the results of June in that scenario with actual data of June. The reason is that the first scenario can meet demand in June. As a result, in the following comparisons, we include the first scenario.

Now, we compare WIP level of LL hubs between the current practice and the three scenarios. We can see a ~50% reduction of LL hubs with our proposed solution (see Figure 13). The total reduction of WIP (excluding LS hubs) is even bigger, because of the huge reduction of WIP in downstream stages (discussed in the other two theses of this project). A comparison of cycle time is shown in Figure 14, which also shows a great improvement. The results are not surprising because we have effectively reduced the early start of production in our solution. Reduction of LL hub inventory level is achieved by reducing its early start time from about 3 weeks to 0-18 shifts. Reduction of cycle time is achieved by the reduction of early start time for both LL hub molding and assembly. (Details of reduction cycle time and WIP in the assembly and downstream machines are discussed in the first and the second theses.)
4.6 Conclusion

In this chapter, we presented a set of scheduling policies for the hub molding machines and the assembly machine. The policies work based on the overall solution discussed in 3.2. We have shown that the proposed solution could meet demand and also reduce cycle time and WIP. It could combine with the policies proposed in the other two theses of the project to reduce total cycle time and WIP of the production line.
The key in our solution is to start hub molding before assembly but not too far before. In our solution, LL hub molding starts only 4 days (12 shifts) before assembly and LS hub molding starts about 3 weeks before assembly. In the current practice, the average early start time is about 3 weeks or more, so our solution will reduce the cycle time and WIP level of LL hubs.

If we review the discussion of the root causes of the problem in 3.1, we can see that our proposed solution for hubs actually shifts a push-pull boundary of the current system to the very beginning of it. We minimize the early start of production at the same time.

The most critical aspect to minimize the early start is the set of production sequences for the molding and assembly machines, which allow us to feed the assembly machine from the three groups of hub molding machines in a cyclic fashion. By simulation we show that the same sequences work in all 9 months. This makes the planning procedure much easier. The only planning decision required each month is to adjust the production quantity according to the confirmed orders.

4.6.1 Implementation

The production sequences are based on the demand data of the past 9 months. Because safety needles are still new products, demand fluctuation could be high and demand is expected to grow rapidly. For actual implementation, although the overall solution could remain the same, we need to do the same analysis with future demand forecast to see if the production sequences are still suitable. They may need to be adjusted when the composition of SKUs in total demand changes largely.

The key factor to prevent starvation and meet demand is to start LL hub production earlier than assembly. We have already shown in the simulation model that demand could be met with LL hub production starts about 4 days earlier than assembly. In actual implementation stage, we would want to start with a larger early start time, 6 days for example, and reduce it to 4 days gradually.

4.6.2 Future Work

The current study does not consider production variability, like machine breakdowns, in detail. Machine variation can greatly affect the production rate sometimes. In future, we might want to consider it in our model. A short discussion in section 4.2.3 might give us some ideas of how to do it.

For the proposed solution in 4.4, there are still a few things that can be done.

Firstly, the same production sequence is proposed for all 9 months simulated. The sequence is derived from the average monthly demand of each SKU in that period. However, composition of monthly demand might sometimes be very different from the average value. For those months, another sequence might be preferred. We might want to develop a tool or a few guidelines to generate production sequences monthly.
Secondly, from the simulation results, we can see demand could be met with zero early start of LL hub molding in some months. In the other months, it could only be met with an early start of 12 shifts. As a result, we might want to adjust the early start time according to monthly demand in future.

Lastly, LS molding starts about 3 weeks in advance. One main reason to do so is the complexity of scheduling the LS machines. As the company is working on solving the compatibility issue with the LS machines, scheduling them would be less complicated in future. As a result, there would be new opportunities to improve the scheduling of these machines in future.
REFERENCES


### Appendix A: Production Assignment of the Hub Molding Machines to Minimize Changeovers

#### Remarks:

For the first month (Oct), assume every machine requires 1 changeover to start production.

Some machines are scheduled idle in some months. It is because demand could be met without running those machines in those months. We can run the idle machines to increase production rate of hubs, but we increase changeovers at the same time.

<table>
<thead>
<tr>
<th>Month</th>
<th>LS1</th>
<th>LS2</th>
<th>LS3</th>
<th>LS4</th>
<th>LS5</th>
<th>LS6</th>
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<td>-</td>
<td>-</td>
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#### LS Hub Molding Machines

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Average: 6.78

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<th>LS9</th>
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<th>Changeovers</th>
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Average: 2.67