Setting Optimal Inventory Policy For Mold Spare Components In A Medical Device Production Facility

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

Abstract

Inadequate inventory management policies utilized by the maintenance facility of a manufacturing plant result in the lack of spare components needed to carry out essential repairs on molds used in injection molding operations, thereby reducing the plant's effective production capacity. Thus, molds need to be run for longer periods to produce the same quantities of finished products, exposing them to a higher rate of wear and tear, ultimately incurring higher maintenance costs, utility costs and repair costs. This research creates a framework for properly categorizing the spare components based on their characteristics and applying relevant inventory models to each category to derive the inventory control parameters of reorder quantity, safety stock level and reorder point. Spare component inventory will be categorized by usage rates and their criticality to mold repairs while critical inventory parameters of safety stock, reorder point and reorder quantity are set to ensure a 97.5% service level while reducing total inventory costs by 9.1% or by $38.7K per year.

Keywords: Inventory management, spare components, inventory modelling, inventory categorization, Analytical Hierarchy Process

Thesis Supervisor: Stephen C. Graves

Title: Abraham J. Siegel Professor of Management Science

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1 Introduction

CB is a medical technology company engaged principally in the development, manufacture and sale of a broad range of medical supplies, devices, laboratory equipment and diagnostic products. CB serves healthcare institutions, life science researchers, clinical laboratories, industry and the general public. CB has three worldwide business segments – CB Medical, CB Diagnostics and CB Biosciences. CB products are marketed in the United States and internationally through independent distribution channels and directly to end-users by CB and independent sales representatives. CB employs approximately 28,000 people in approximately 50 countries throughout the world with worldwide revenues, based on fiscal year 2008, of $7.2 billion which is a marked increase of approximately 13% from the previous year.

CB Tuas plant manufactures cannula, needle, and syringe products. These products are first shipped to the various CB's distribution centers (DC), which then supply the products to their respective clients. The plant is organized into value streams (VS). There are currently 7 VS, each producing a different product family. The 7 VS are Product S, Product N, Product I, Flashback, Product U, Cannula and Tubing. Each VS is managed by a Value Stream Leader (VSL) and operates independently with its own equipment and workforce.

The core manufacturing process in CB Tuas is plastic injection molding. Out of the 7 VS mentioned, 5 of which are involved in manufacturing through injection molding which are Product S, Product N, Product E, Flashback and Product U value streams. The CB Tool Room supports the operations by providing periodic maintenance and repair to the molds. The tasks undertaken by the Tool Room help to ensure the molds are in good operational condition for good production runs within the plant. Hence, Tool Room plays a critical service for CB Tuas. The Tool Room supports the repair and maintenance of a wide range of molds. Figure 1.1 shows the proportion of molds dedicated to their respective VS which are under the care of the Tool Room.

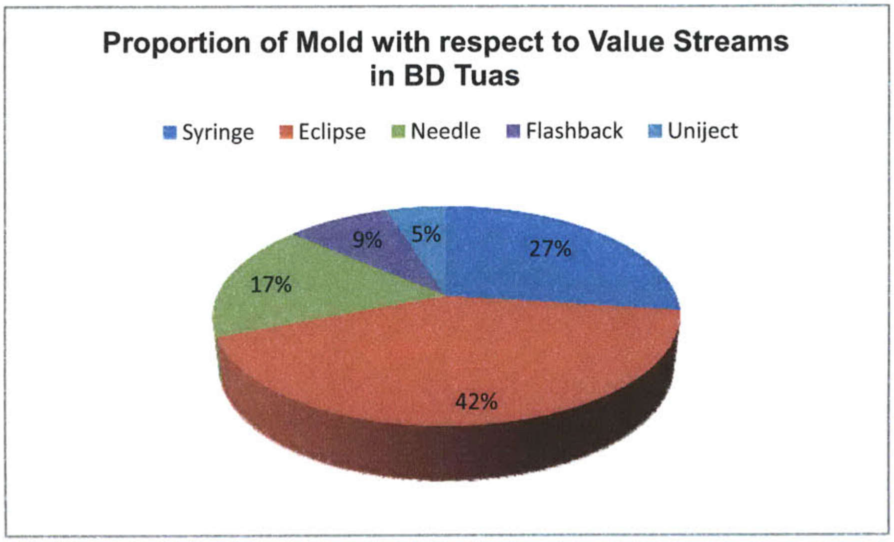

Figure 1.1: Overview of mold proportion by VS

The molds in each VS vary in size and shape since the products they produce come in various geometries and they serve different functional purposes. However, these products are still made from the same manufacturing process of injection molding. The following section provides an overview of the components and processes which constitutes injection molding.

1.1 Injection Molding Production Process

The medical devices made by CB comprise of plastic components which are injection molded. The process involves plasticizing or melting plastic pellets and injecting them into a metal mold via small openings called gates. The melted plastic is then formed into a specific geometry in the cavity of the mold. Upon cooling and solidification, the final part is formed.

The mold consists of the male and female mold halves and is an assembly of over 100 parts. These parts may or may not directly contribute to the geometrical formation of the final parts. Personnel in CB refer to the components of the mold that require more frequent replacement as a result of wear-and-tear due to their contact with hot or moving parts in the mold as "spares". For example, an insert in the cavity would be considered as a spare but a screw on the mold block exterior would not be considered as one even though they are all components of the mold. Figure 1.2 shows the cross-section of a mold.

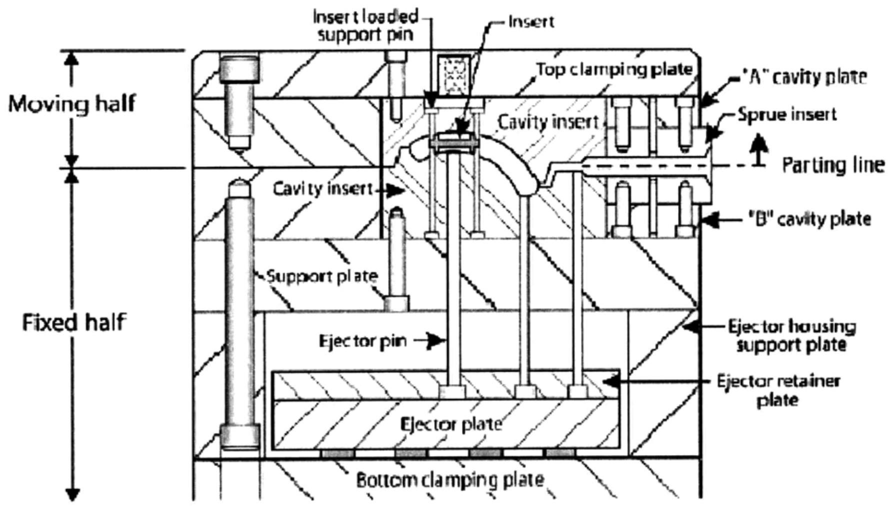

Figure 1.2: A schematic of a mold cross-section [1]

The male portion is referred to as the core whereas the female portion is called the cavity. The mold may consist of a single cavity connected to flow channels or runners which direct the flow of the melted plastic to the respective cavity. The fixed (stationary) half would consist of the ejector system. This enables the parts to be separated from the mold at the end of the solidification process. The moving half of the mold is connected to a hydraulic toggle of the injection machine which will retract to accommodate for part ejection. To support high production outputs, it is typical for injection molds to have multiple cavities. In CB, the injection molds can have as low as 4 cavities or as high as 96 cavities per mold. The complex geometry of CB products place stringent requirements on the mold and its cavities with some part dimensions in the mold controlled to five-thousandths of an inch. The molds are mounted on an injection molding machine.

Figure 1.3 below shows a schematic of an injection molding machine and Figure 1.4 depicts the injection molding process.

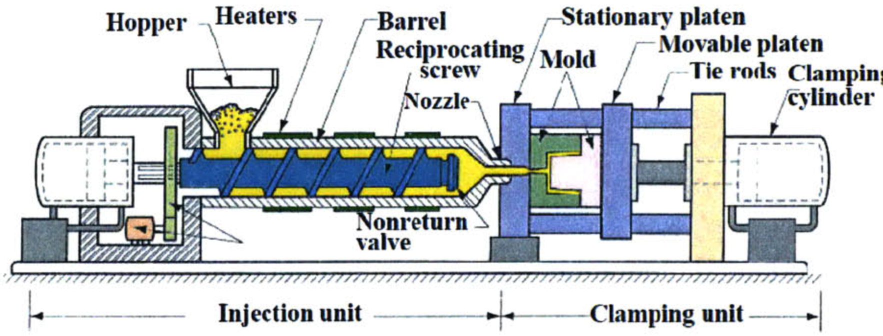

Figure 1.3: An injection molding machine

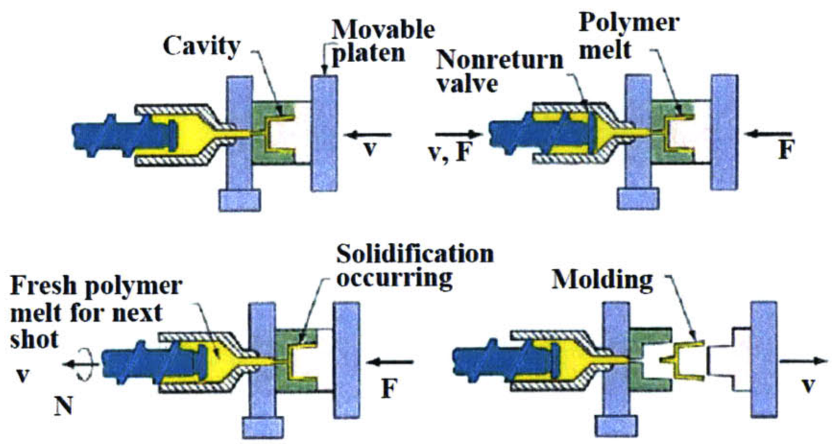

Figure 1.4: An injection molding cycle [2]

From the machines, operators can input the necessary parameters that govern the molding process. There are three basic operations to consider:

1. <u>Raising and holding the melt temperature to a pre-determined level to necessitate flow</u>

The raw plastic usually comes in pellet form. The pellets are heated in the injection heating chamber until it reaches a state of suitable viscosity. Heater bands and a reciprocating screw helps to push the melt through to the gates ensuring the melt is flowing at a required pressure and viscosity.

2. <u>Solidifying the melt in the mold</u>

The molten plastic from the injection cylinder of the injection molding machine is transferred to the various cavities of the mold where it finally conforms to the contour of the desired shape (core). The male and female parts of the mold are kept in intimate contact for a determined period of cooling time during this process of shape-forming. Just like many other parameters in injection molding, cooling time is experimentally determined depending on the complexity and geometry of the part and the type of plastic used. The venting system within the mold is crucial to obtain good quality plastic products.

3. Plastic part ejection

The part is then ejected after being confined under pressure and it would have frozen completely into the desired shape.

The above operations can determine process productivity since the speed of manufacturing the plastic products hinges on the speed at which the plastic can be heated to the molding temperature, how fast the molten plastic can be injected and the length of time for cooling to take place. Not all the parts that make up the products are injection molded. Only the plastic parts are injection molded and then assembled to other non-plastic component to form up the final product. The following section highlights the portions of Product S, Product N, Product E, Flashback and Product U which are injection molded and how defects in the plastic parts can affect the downstream production.

1.2 CB Product Types

Product S is a medical device used to inject fluid into or withdraw fluid from the body. Figure 1.5 shows an example of a syringe manufactured at CB. Product S typically consists of the barrel, plunger and stopper.

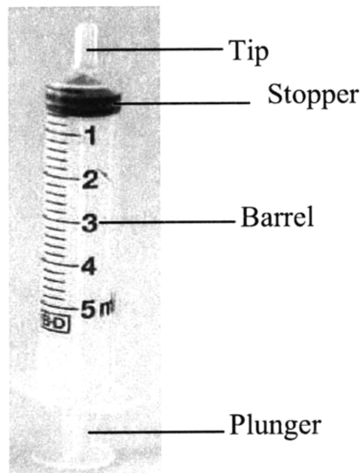

Figure 1.5: Parts of Product S

The barrel comes with different types of tips namely LL, LS and Ec tip. Figure 1.6 shows the assortments of Product S tips.

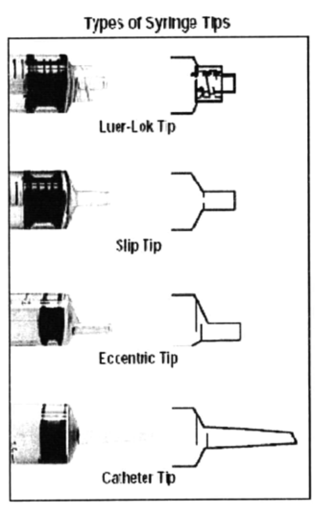

Figure 1.6: The various types of CB hypodermic Product S tip

All parts of Product S except the stopper is injection molded. The Tool Room supports the manufacturing operation of these parts by doing repair and maintenance on 22 molds with 7 molds responsible for plunger and the remaining tasked to produce the barrel. Of the 15 barrel molds, 3 are dedicated for 1cc LL production and 1 mold is reserved for 1cc LS production.

A CB Product N, as shown by Figure 1.7, consists of a polystyrene needle hub and a stainless steel cannula. Both the hub and the shield are injection molded.

Figure 1.7: CB Product N configuration

Tool Room supports Product N manufacturing operations by doing repair and maintenance on 6 hub molds and 6 shield molds.

A CB Product E, as shown by Figure 1.8, comprises of the needle with a safety shield that serves to cover the sharp Cannula after use.

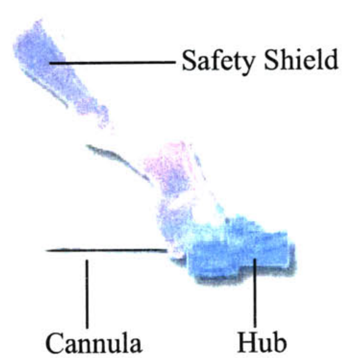

Figure 1.8: CB Product E configuration

The safety shield and hub are injection molded. Tool Room supports Product E manufacturing operations by performing repairs and maintenance on 1 needle shield molds, 2 safety shield molds, 22 hub molds and 10 LS hub molds.

A CB Product U, as shown in Figure 1.9, is a pre-filled injection device targeted to provide a cost-effective way to deliver vaccines and other drugs safely to people in pre-specified dosage.

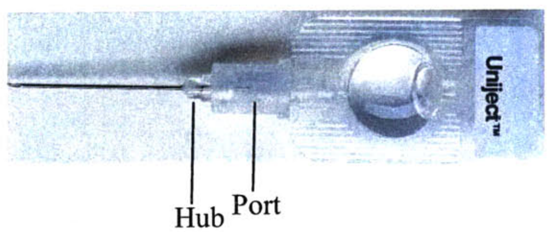

Figure 1.9: CB Product U configuration

The CB Product U comprises of the shield, port, hub and seat. These are injection molded plastic parts. The Tool Room supports the manufacturing operation of these parts by doing repair and maintenance on the 4 distinct molds.

Figure 1.10 shows a CB Product F product. It comprises of a luer and a shield which is injection molded.

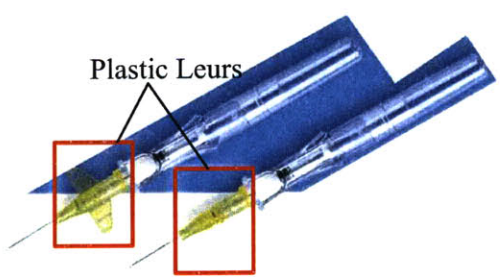

Figure 1.10: CB Product F products used in CB Catheters

The Tool Room supports the manufacturing operation of these parts by doing repair and maintenance on 3 male luer and 2 shield molds. Table 1.1 summarizes the molds available in CB Tuas and the type of products that they are responsible for.

Table 1.1: Summary of the molds and the related products they produce

Product S

S/N	Product: Volume	Product: Part	Mold
1	1 cc	Barrel	*L6 (LS-Tip)*
2			L23 (LL-Tip)
3			L75 (LL-Tip)
4			L78 (LL-Tip)
5		Plunger	L81
6			L13
7	3 cc	Barrel	L40
8			L7
9			L81
10		Plunger	L41
11			L21
12	5 cc	Barrel	L9
13			L10
14		Plunger	L15
15	10 cc	Barrel	L11
16			L12
17			L42
18		Plunger	L16
19	20 cc	Barrel	L27
20		Plunger	L26
21	50 cc	Barrel	L29
22		Plunger	L28

Product E

S/N	Product	Mold
23	Needle Shield	L43
24	Safety Shield	L44
25	Safety Shield	L45
26	Hub	L50
27		L51
28		L52
29		L53
30		L54
31		L55
32		L56
33		L57
34		L58
35		L59
36		L60
37		L61
38		L62
39		L63
40		L64
41		L65
42		L66
43		L67
44		L68
45		L69

Product F

S/N	Product	Mold
46	Hub	L70
47		L71
48	LS Hub	LS1
49		LS2
50		LS3
51		LS4
52		LS5
53		LS6
54		LS7
55		LS8
56		LS9
57		LS10

Product F

S/N	Product	Mold
58	Male Luer	F1
59		F2
60		F3
61	IV Shield	F6
62	NP Shield	F7

Product N

S/N	Product	Mold
63	Short Shield	L1
64		L19
65		L77
66		L79
67	Regular Shield	L2
68		L20
69	Hub	L3
70		L4
71		L5
72		L73
73		L82
74		L34
75	IIP	L24
76		L25

Product U

S/N	Product	Mold
77	Shield	L30
78	Port	L31
79	Hub	L32
80	Seat	L33

1.3 The Role of Injection Molding on Production Flow

In a company that manufactures medical equipment, quality is paramount in ensuring that each of these products is able to deliver its respective function. These injection molded parts are put through stringent quality controls. Part feature tolerances can be as low as in microns. As shown by Figure 1.11, the production flow overview, molding operations form the top of the flow followed by printing, assembly and packaging.

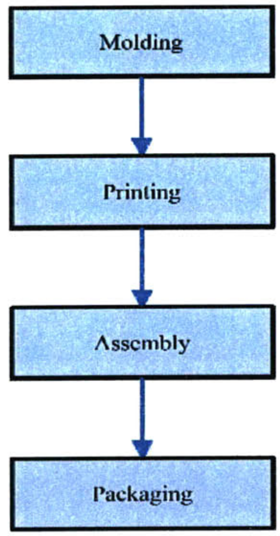

Figure 1.11: Overview of production flow in CB Tuas

Printing is responsible for measuring labels and lines on the device components. Assembly is tasked to put together the components, plastic and non-plastic, that make up a device to form a functional product. Packaging refers to packing the products into individual blister packs and/or cartons to prepare for shipment out of CB Tuas. The sterilization process would take place before the product is packaged.

Inspection occurs during molding and after printing. Inspections done during the molding process ensure that product parts are not defective. Quality checks at the molding operations are performed bi-hourly on the current batch run of parts. Inspections performed after printing ensures that measuring labels are consistent and visible. Flaws that occur in the molded parts during molding operation will mean that the downstream operations cannot proceed until the proper troubleshooting on the molds and/or molding process is carried out. Consequently, the shipment of products to customers might be delayed. Since molding operations sits at the start of the production flow, it becomes a critical factor in ensuring if CB meets the targeted customer service level or not. Hence, the support that Tool Room provides to the molding operation becomes equally as important too.

1.4 CB Tool Room Department

The Tool Room department is responsible for ensuring that the molds used in the injection molding machines are capable of supporting production demand. Operations carried out by the Tool Room include:

- Repair molds and mold cavities to ensure good quality parts are produced
- Conduct periodic maintenance on molds
- Setup changeover in molds for different product production
- Investigation of defects in molds and conduct Root Cause Analysis
- Purchasing of spares and other mold-related parts
- Quality control of incoming parts
- Inventory management of spares and mold-related parts
- Record keeping of the above activities

The primary task of the Tool Room is to repair molds and mold cavities, the overall process flow can be seen in Figure 1.12 below:

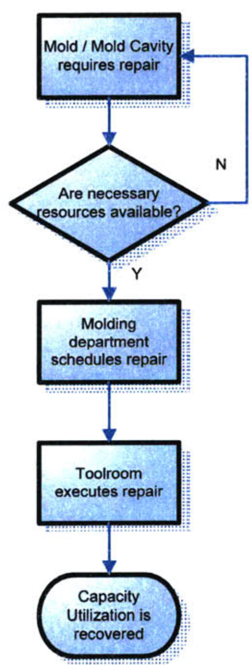

Figure 1.12: Simplified repair process flow

The necessary resources in this case are the spares availability, labor, and time. This is why the inventory of spares is being managed by the Tool Room as well, as they are expected to ensure that the necessary spares are kept for any repair operation to be carried out.

1.4.1 Tool Room organization and CB value streams

As described in the previous sections, CB organizes the product families into value streams which are managed separately from each other; each value stream will have its own set of molding machines which are dedicated for that VS. Thus the molding process is not governed as a Molding department each value stream will manage their respective molding processes individually instead.

Thus, the Tool Room organizes itself to support the value streams in a similar manner. For larger value streams such as the Product N and Product S department, two Technical Specialists (TS) are assigned to execute any repair operations required. Product E is a smaller value stream with lower production volumes, so there is one TS assigned to support it. Product U and Product F are the smallest value streams of all so there is one TS overseeing both value stream repair operations.

To perform the other functions of Tool Room, there is one TS overseeing the scheduled preventive maintenance programs for the molds. These programs are organized by time, so molds are maintained every quarterly, six-monthly, or annually. There is one more TS who is in-charge of purchasing spares at the request of the other TS in the Tool Room, and check the quality of incoming spares. The TS working in the Tool Room is commonly referred to the Tool Room TS (TTS) whereas the TS working in the production area is called the Molding TS (MTS).

1.4.2 Tool Room Vision and our project

The Tool Room vision states "*To work as a team and provide better mold turnover time while meeting targeted Capacity Utilization with CB's quality requirements to satisfy our customers.*"

Capacity Utilization (CU) refers to the percentage of the cavities per mold that are able to produce good parts. This is also a key performance indicator of Tool Room operations. Our project is thus to focus on helping Tool Room improve its operations so as to achieve this vision. The ultimate goal is to achieve close to 100% CU recovery every time. This is the service level that the senior management hopes to achieve in the long run.

1.5 Mold Repair Work Function

The primary function of CB Tool Room is to carry out mold repair work to support the molding production operations. In order to carry out the work, the Tool Room has to work closely together with the molding function in order to understand the problems they encounter. The Tool Room also carries out analysis of the defective parts that do not meet the quality requirements and diagnose the problem and then carry out the necessary work on the molds to correct them. This requires a significant level of technical skill and experience.

1.6 Purchasing and Inventory Management Function

One of the key functions of the Tool Room is to manage spare component inventory. Inventory levels need to be optimized such that a high service level is achieved in providing spare components for maintenance activities. This complements the goal of the Tool Room to meet its proposed service level of close to 100% in terms of CU recovery.

Traditionally, spare components that are used for the repair, maintenance and setup changeover activities are managed by the individual TS. Each TS has the responsibility to carry out all these activities on the molds from their value stream. This includes ensuring that they keep enough quantities of the spare components on-hand for their needs and purchasing these parts whenever they need to replenish the inventory. They have to ensure that the cost of the purchases each month does not exceed the given budget for such spare components.

1.6.1 Purchasing Process

The task of purchasing spare components is assigned to one TS in the Tool Room who oversees other non-technical tasks within the department. Each TS who needs to purchase spare components would submit an order verbally to the purchaser. The purchaser would then communicate directly with the vendor to inform them of the item to be purchased, the order quantity, the requested delivery lead time and other custom requirements for that particular spare component. Following this, the purchaser will raise a Purchase Requisition (PR) through the SAP system that would be sent to the Purchasing department. Once this is vetted by Purchasing, the PR would be converted to a Purchase Order (PO) that is sent to the appointed vendor. The vendor will deliver the spare component to the warehouse when it is manufactured. Once the part is received by the warehouse, they will inform the Tool Room of the availability of the spare component. The warehouse is located on the same premises but at a different location, and is considered a department by itself, responsible for storing inventory. The purchasing process is completed when the order is delivered to the warehouse. The purchaser will draw out the spare component from the warehouse when it is required by the TS for either the repair, maintenance or setup changeover activities. Once the component is drawn from the warehouse, it is considered as used in the system and the quantity is deducted from the on-hand inventory level. The system is setup in this manner so as to provide traceability of inventory levels and also the usage of spare components. The TSs are not allowed to keep any inventory of spare components within the Tool Room but only to draw out the spare components when they need it. The TS are responsible for monitoring the inventory levels of each spare component and ensuring that they have enough on-hand to meet requirements.

Variations to the whole procurement process flow occur on certain occasions. Firstly, if the vendor faces unexpected delays in fabricating the spare component on time, he would either apply for an extension to the lead time required for delivery or deliver it late. Secondly, whenever a new spare component is bought, it needs to undergo a quality control inspection to ensure that the dimensions of the spare component conform to requirements. The component might be rejected because it did not meet the specifications and the total lead time to deliver a finished part would be extended.

The SAP software is utilized as an inventory management program by CB. During purchasing activities, the program is used to create a PR form. Each individual spare component is assigned an SAP number which acts as an identifier of that component from the particular mold that it is used in. This identifier, together with the unique PR and PO numbers for a particular order, are used by the system to track the purchasing history of the spare component in SAP.

The tracking of the spare component would allow the user to generate reports regarding order patterns of the spare component inventory. They would be able to monitor via the reports when the particular component was purchased by month, the quantity that was purchased and the total cost of the spare component purchased.

The SAP software also contains values for the safety stock and reorder quantity. Based on past purchasing and usage history, the system utilizes this information to recommend safety stock levels, reorder quantities as well as other metrics that are related to inventory. These recommendations are provided to the user and the decision lies with the user whether to use the recommended parameters. In addition, the SAP system is able to send an alert to the purchaser to recommend making an order when the inventory level of any spare component drops to the safety stock level or below.

2 Problem Statement

The aim of the tool room is to restore any defective mold to 100% capacity utilization (CU). This would ensure that each mold can produce the maximum yield when it is run on the production press. The problem that the tool room faces is that many of the molds do not run on 100% CU. Defects which occur due to mechanical wear occur very frequently, lowering the CU of the mold. Due to the inability to restore molds to 100% CU, each mold is set a respective targeted capacity utilization. The targeted CU currently serves as a benchmark for all production for that mold. Molds running below 100% CU are more likely to require longer production runs to meet the desired work-in-process (WIP) level or demand. Inevitably, such molds wear out more quickly. Since there are no replicates of molds for each part or component, a quicker wear rate means more disruptions to production.

Molds running below their targeted CU will be removed from production for inspection and repairs. During this process, spare components that make up the mold might be replaced with new ones if they are found to be unrepairable. Ideally, the Tool Room TS should be able to return the molds back to production in an as-good-as-new condition with all cavities running flawlessly. However, they are often not able to return the molds to 100% CU even after performing their repair work. The inability to return a mold for production with full CU has implications downstream of the production line. It takes longer to produce a certain volume of the end product to fulfill a customer order, thus increasing the lead time taken for CB to fulfill customer demand for that particular product. Lengthier production runs will lower CB's service level which could lower customer satisfaction. Therefore, the implications of not meeting 100% CU are potentially felt all the way downstream to the customer.

Three key areas have been determined to contribute to the overall problem of the tool room's inability to meet the 100% CU aim for its molds. These have been identified as (1) inefficiencies inherent in the current CU recovery process, (2) the lack of on-hand spare components to carry out repairs and (3) the lack of data on defect characteristics in the molds which could be used to identify underlying trends.

2.1 Inefficiencies in CU Recovery Process

The effects of inefficiencies inherent in the CU recovery process can be easily seen. They cause the inability of the current system to meet the target of 100% CU recovery. Finger pointing and fire-fighting are the norm between the Molding and Tool Room departments. However, the constraints faced by the current process are not as easily identifiable. The Tool Room personnel (Tooling) have been involved in tackling problems which are symptoms of the inefficiencies. As yet, no one has attempted to take a more in-depth look at the underlying causes which are the source of those symptoms. To some extent, the CU recovery process needs to be re-engineered to eliminate or reduce those inefficiencies, or "waste". The whole process can be broken down into separate parts that could be looked into in more detail.

2.1.1 Mold Recovery Preparation

Every morning, the TSs spend more than an hour in a meeting discussing the molds which need to be taken offline from their presses in order to be repaired to full CU. In this meeting, the issues that are discussed include:

- Determining what the exact problem is with the mold and how best to fix the problem
- The amount of lead time needed to carry out the CU recovery process
- The schedule of repairs to be undertaken for the various defective molds

This discussion is excessive and unnecessary, consuming a lot of time which could be spent on the CU recovery process itself. Waste is present as there are currently no specific standard procedures that are utilized in preparation of the CU recovery activities. The various stakeholders arbitrarily try to determine the best way to solve the problems encountered based on past experience and their subjective opinions. These stakeholders include the Tooling TS, the Molding TS and the Molding engineer who are in charge of the production line.

This problem can be attributed to the lack of a system of accountability and transparency in this preparation process. There is no way to identify repetitive problems and to make a quick decision based on past data. Despite the existence of software, such as Apriso and SAP that is meant to aid the stakeholders in the decision process of commencing mold recovery activities, these aids are not sufficiently utilized. Therefore, there is much scope for improvement in terms of decreasing the time taken to complete these preparations for repair activities. This would help to decrease the turnaround time for a mold that is not online. The lack of accountability is evident as the molds are used in the Molding department, which is where the defects and issues occur, yet the current system allocates the responsibility of ensuring the molds are at high CU levels to the Tool Room. This creates friction between the departments when problems occur.

2.1.2 Mold Recovery

While the CU recovery process is underway in the Tool Room, the TS also have to be continuously involved in expediting activities to ensure that the molds are repaired within the required lead time. There are two reasons why this occurs. Firstly, the schedule of repairs is often interrupted by more critical molds that have a higher priority. These molds are considered more essential for production activities by the molding engineer or production engineer, who overrides the decisions made between the Molding and Tooling technical specialists during daily meetings in the morning before the start of the morning shift, called Shift Start Ups (SSU). Often at times, this causes the Tooling TS to be overwhelmed with too many molds to recover at the same time. This creates a log jam of jobs that the TS would struggle to repair in the expected amount of time due to the sudden increase in workload. Expediting the repair of more critical molds thus causes a disruption in the repair schedule of the defective molds that are in process with the TS. This eventually leads to more delays in the overall CU recovery process for each product value stream.

This situation is compounded by the practice of blocking cavities within the molds when a problem occurs during production and not carrying out the recovery process for the problematic cavities sooner, thereby allowing the mold with blocked cavities to continue operating on the production press. As a result, when these molds have reached the point when their recovery must occur, this time coincides with the breakdown of other molds.

The common responses to these situations are to increase overtime hours in the Tool Room, which increases the Tool Room's operating costs. Such situations increase the resentment among Tool Room members who feel that the Molding department is simply pushing all the work and blame to them.

Secondly, expediting occurs because on many occasions, the TS do not have the necessary spare components that are needed to carry out the CU recovery work. They either discover that they do not have enough of that particular component in the inventory or that the part is out of specification when it is needed.

2.1.3 Post Mold Recovery activities

Until today, the Tool Room uses paper-based forms to record information. These handwritten forms are poorly maintained, are not standardized across value streams, and are filed away into cabinets and kept for storage. The open ended nature of handwritten forms results in a naming convention left to the whim of the person making the entry, barely legible handwriting which further aggravates the poor quality of the information. Initiatives by various individuals in both the Molding and Tool Room have been made, such as creating their own spreadsheets to record the information they feel is important to them. While they should be applauded for their proactive efforts, this is inefficient as there is no sharing of such information among the individuals.

2.1.4 Current Solutions

An attempt has been made to improve the process of CU recovery. The Tool Room manager has incorporated a system that rewards the TS who are able to maintain the molds, for which they are responsible above a certain capacity level. This encourages them to actively seek solutions to maximize the percentage of working cavities after each CU recovery process. They have an incentive to take more responsibility for the repair activities carried out and to manage the process better. The Tool Room engineer has also started keeping records of the defects which occur in the molds. This is an attempt to determine the root cause of the defects to the mold which could allow the TS to carry out repairs more effectively and reduce the mean time to failure of the molds. Further recommended solutions are provided by Lin [3].

2.2 Inventory oversight for Spare Components

The lack of spare components to carry out necessary repairs is a significant problem for the Tool Room. The lack of on-hand spare inventory prevents the TS from carrying out a 100% recovery for any defective mold. This results in the mold having to be used in production at less than 100% CU. A corresponding concern for the Tool Room is also the failure to meet the cost constraints imposed on it. With regards to spare component inventory, the Tool Room is provided with a monthly budget to purchase spare components. However, the purchases by each value stream on the spare component inventory frequently exceed the allocated funds deemed sufficient to meet the demands of the Tool Room.

Both of the above-mentioned problems occur primarily due to the lack of proper management practices for the spare component inventory of the Tool Room. This is characterized by two main issues.

1. <u>Inadequate Safety Stock Levels</u>

Lack of sufficient spare inventory on hand occurs because safety stock levels of the spare components used by the Tool Room have not been adequately set or are non-existent. As a result, the TS, who manages the inventory of spare components, bases the amount that they should have on-hand on an arbitrary estimate of usage over a period of a few months at a time. This could create bias in stock keeping where the TS underestimates the optimal level of inventory of the spare components to keep. Due to a lack of proper records of previous usage of the spare components, there is no basis to determine the proper level of safety stock is.

2. <u>Inconsistent Reorder Quantities</u>

Excessive ordering of certain spare components also takes place. This is due to the lack of proper evaluation of past usage data. Ordering of spare components is largely dependent on the opinion of the respective TS of the perceived future demand for the spare component in repairs. Thus, there is human error involved in the estimates of reorder quantities, resulting in inconsistent replenishment of spare components. As each value stream has a limited budget for the purchase of spare components, using this budget for rarely used components might prevent the purchase of other components which are just as critical and which are ordered on a more consistent basis. This also creates a lack of spare components on hand when emergency repairs need to be carried out.

Having insufficient inventory of spare components results in partial CU recovery of defective molds. This hinders the service level of the Tool Room. Not having enough inventory is also a serious problem due to the fact that certain components have known lead times which can last up to several weeks. If the TS requires a large number of the spare components within this period, he could run out of critical spare components. Furthermore, there could be unforeseen delays such as supplier production delays or the Tool Room having to reject the spare components because they are out of specification. Long lead times are due to some of the suppliers being located overseas and having to ship components to the Tuas manufacturing plant in Singapore.

Although metrics such as safety stock and reorder quantities can be determined by SAP, this was not done even with the SAP system in place. The cause of this lies with the improper use of the system by the Tool Room personnel. Historical data was not readily available for determining those inventory parameters due to the lack of proper records of previous spare component usage. The TS resorted to recording the repair records manually using hardcopies. Such records were usually poorly filled with non-standard terms used by each individual TS. Frequently, there would also be missing records of spare component usage due to time constraints on the TS and human apathy.

Even when the usage of spare components was recorded on hardcopies, the transfer of this information to the SAP system was not meticulously done. Therefore, this led to the further loss of such information, not to mention the additional workload created by recording information both on hardcopies and in the SAP software.

In addition, the system is not adequately configured. Currently, only a low percentage of the spare components have been assigned an SAP number. This translates to approximately 15% of all spare components. This means that 85% of all the other spare component inventory is not tracked properly by the system as they have not been assigned an SAP number. Historical records of usage and purchases of such parts are inconsistent due to the lack of standardization of names used. Furthermore, for the spare components which have been assigned SAP numbers, information about the vendors and the pricing are currently inaccurate due to recent changes made as a result of ongoing vendor evaluations.

The personnel also do not adhere strictly to the recommended practice of drawing spare components from the warehouse only when they require it for repairs or maintenance activities. Due to the added inconvenience of having to physically walk to the warehouse whenever a spare component is needed, each TS also holds on to a quantity of each spare component to provide easy access to it. The actions of the TS in doing so also hinders the traceability of spare component inventory levels as the spare components drawn from the warehouse are considered expended within the SAP system.

As a result, much of the information on inventory levels displayed in SAP can be considered unreliable. Historical data on mold repairs can also be considered inaccurate and does not give a true picture of actual spare component usage.

2.2.1 Current Solutions

The Tool Room has recently tried to improve the tracking of spare component inventory and tackling the problems causing stock outs to occur. The TSs have recently been trained in the use of the SAP software to track the actions taken during the CU recovery process and the spare components that have been used for the repairs. They are being monitored in their use of the relevant forms that have to be filled whenever a repair activity is carried out. By closely monitoring the usage of spare components in SAP, the system can provide the necessary data needed to evaluate the appropriate inventory parameters such as safety stock and reorder quantities in future.

CB has also created a department named the Tool Crib to be wholly responsible for managing the spare component inventory. This is meant to provide more accountability regarding the usage of the inventory and more visibility regarding inventory levels of various components.

The creation of the Tool Crib is an important step as the TS will no longer have to dedicate time to managing inventory of spare components. They will be able to focus on carrying out the CU recovery process. This will allow for increased traceability of the spare components due to the implementation of a uniform system to procure and withdraw spare components from the on-hand inventory.

The Tool Room has commenced the handing over of its inventory to the Tool Crib and it will take a period of time for the system to be used for handling the spare component inventory.

2.3 Lack of Analysis of Defects

Lastly, there was no proper process for defect tracking within the molds. The current practice is that the TS records the repair activities into a form provided for them. Although the defects were recorded, these were usually disparate records done by various parties which created redundant work. Furthermore, these records were done for the sake of having them without being properly compiled and evaluated. Even if these records were used to obtain a defect trend across the various molds and within specific molds, analysis was usually rudimentary. These results could potentially be utilized to come up with a root cause analysis to reduce the frequency of breakdowns. In addition, the frequency of defects occurrences can be utilized to identify the appropriate time for conducting regular maintenance.

2.3.1 Overview into Defect Investigations

The morning SSU provides the information to the TTS and the engineer for the problem(s) sustained by the molds. Samples of the defective products are consolidated by the production technician (PT) and MTS and these will be handed over to the engineers for a close-up observation. Through the defects detected from the molded products, engineers and TTS might be able to identify the root cause to these defects. In analysing these defects, the experience of the engineer and TTS will prove to be crucial since the defects can be caused by the machine, mold components, operator-handling and molding process. There are instances when the engineer has to look into all four defect-causing agents before proposing a feasible root cause. Investigations into the defects that occur can range from a day to a week, or in some cases, it might even be longer.

Defect-types that have been identified are entered into the Monthly Mold Report form by the TTS who perform the mold repair. A particular defect-type can be called differently by different TTS. This lack-of-standardization issue seems to appear in the naming of mold components as well as defect-types. TTS performing the repairs tend to omit key information such as the length of repair time done for the respective defect-types. Even if repair times are entered into the form, they may appear to be ambiguous, for example, seemingly trivial repairs take longer than expected.

2.3.2 Current Solution

The TTS make a conscientious effort to update the Mold Monthly Report form. Dates of the repairs done are entered accurately. At the present, Tool Room engineers will input the information from the Mold Monthly Report form into Microsoft® Excel spreadsheets. With the aid of a PivotTable function in the spreadsheets, engineers will be able to identify trends of defect occurrences. However, that is the only analysis that the engineers do with the data in the spreadsheets. In addition, there is no attempt as yet to standardize the names of defect-types and there is no enforcement on the TTS to provide accurate repair times.

Analysing the trend(s) in defect occurrences and reliability of the molds can be an area of study to better manage the repair activities in the Tool Room. This is further discussed by Mohd Fauzi [4].

2.4 Project Objective and Scope

Our team aims to assist with the current efforts of the Tool Room in improving on their operations. The project will be split into 3 components targeting 3 different aspects of operations.

One component involves looking at using the SAP and Apriso information technology systems to implement a process to manage the information flow for mold repair operations. Improving the information management process will increase visibility to the states of the molds and their performances, enhance real time decision making, and reduce time wasted on unnecessary efforts in duplicated work to transfer data from hardcopy to softcopy.

Recommendations will be made to improve Tool Room work processes by utilizing this system to extract performance measures that will measure the productivity of the Tool Room. This part of the project will be handled by Lin [3].

To assist with the setting up of the Tool Crib, another component will focus on improving the management of spare parts that are under the responsibility of the Tool Room. The task is two-fold. Firstly, the spare components will be categorized according to common characteristics such that the appropriate inventory management tools can be applied to each category of spare components. This is currently lacking in the planned system for the Tool Crib. Secondly, proper analysis will be carried out to define the optimal inventory level of these spare components by deriving initial safety stock levels and reorder quantities to be used by the Tool Crib. The aim is to reduce costs from stocking excessive inventory and improving the service level of meeting demand for spare components needed to carry out CU recovery. Indirectly, the service level in terms of percentage of CU recovery by the Tool Room will also be improved. This part of the project will be further elaborated on in subsequent sections of this paper.

The last component will look at the top few occurring mold defects that are unique to a pilot of 1cc Product S molds, L23 and L78, and a 3cc Product S mold, L7. These top few occurring types of defects will be classified as priority defect-types. The damage to the associated mold components will be determined from the mold product defects. There are many factors causing defects to occur on the molded parts. These factors can be process, operator-handling skills, injection molding machine and environment and the parts condition of the mold. However, this part of the project will focus on the effect of defective mold components on product defects. Obtaining the trend(s) in top defect occurrences allows the prediction of the length of time a mold can run before the same defect occurs again. From this, the following will be derived:

- With the defects-to-components list mapped out, we can then proceed with designing and recommending tasks that handle replacement of necessary spare parts.
- Understand the reliability of the molds based on past failure times data.
- Plan the preventive maintenance (PM) interval based on the available task list.

This part of the project will be handled by Mohd Fauzi [4].

3 Literature Review

The following part of the thesis delves into the proposed framework that should be set up with the objective of improving inventory management of spare components of the molds by the Tool Room. The aim is to establish proper inventory policy which will allow the Tool Room to meet its required service level in terms of meeting demand of spare components for repair, and also the percentage of CU recovered for the molds.

3.1 Inventory Management in Production Planning

Inventory Management as a science has been practiced for many decades. Companies devote attention to their inventory because it is a strategic asset that allows a company to achieve various goals. One function of inventory is to act as a buffer against uncertainty. Uncertainty is present in the form of demand of the finished product sold to customers, it is present in the supply of parts that are needed to produce the finished product and it is also present in the movement of goods between different points in the supply chain.

There is always a trade-off between holding more inventory to meet uncertainty and the cost of doing so. The cost takes the form of holding costs in storing the inventory, cost of obsolescence if the inventory becomes obsolete, cost of capital as there is an opportunity cost involved in locking up capital used to procure inventory and the unit cost of buying the inventory. In order to manage the trade-off and optimize inventory levels, inventory models have been developed to determine how much inventory should be held in various scenarios.

In maintenance planning, spare component inventory has to be kept to ensure that repair and maintenance activities can be readily carried out. This occurs whenever there are defects in the production tools or they are scheduled for maintenance. Spare component inventory can be used to ensure a high service level for the maintenance staff who are responsible for keeping equipment in operating condition. This is crucial as proven in a survey by Ikhwan and Burney [5], who found that 34% of the companies they surveyed in Saudi Arabia had stated that their most severe problem was delays in obtaining spare components. Spare component inventory levels are a function of how equipment is used and maintained and such information is important.

Managing spare inventory has its unique characteristics quite unlike inventory of finished goods or Work-in-Progress (WIP) inventory. This section reviews the literature that exists on spare component inventory management and selects the relevant theory that can be applied to the existing problem faced in this study.

3.2 Inventory Policies for Spare Components

Previous work explores inventory management practice thoroughly. Silver [6] describes in detail models that are used to cater to a wide range of scenarios for inventory management in production planning. These models are broadly useful although they do not specifically address the needs of spare component inventories. More relevance in inventory modelling for spare components is found in the literature review of Nahmias [7]. Policies to manage spare component inventories are described and analytical models are provided which address optimal inventory levels of spare components. However, this literature is dated, last being updated in 1981, and an article by Kennedy et al [8] delves into more recent literature which covers a broad spectrum of topics dealing with the management of spare component inventories. Kennedy et al also classifies literature that deals with different specific maintenance policies targeting age-based replacement, multi-echelon problems, problems involving obsolescence, repairable spare components and other special applications. Brief descriptions about literature dealing with these scenarios are given, however, no quantitative details are provided about specific models.

Among the recent literature outlining management policies for spare components in the article by Kennedy et al, Gajpal et al [9] outlines a useful method of categorizing spare components that complements the use of reliable partitioning methods such as ABC analysis and VED (Vital, Essential, Desirable) analysis. They address the need to properly group spare components according to common characteristics of criticality before applying models to optimize inventory. The criticality of a spare component is defined as the functional necessity of the part in production and maintenance operations. It is a very important factor to be taken into account with specifying service levels. This dovetails nicely with the classification of inventory to differentiate the way different categories of spare components are managed to allocate resources appropriately in order to derive the most benefit.

Gajpal et al quantifies the criticality of the spare components by utilizing the Analytic Hierarchy Process (AHP) which is a multi-criteria decision making tool developed by Saaty [10]. The model is based on structuring the problem into a hierarchy of 3 or more levels. The criteria are compared pair-wise based on their relative importance to the overall objective while the decision alternatives are compared pair-wise with respect to each criterion. Weights are then assigned to the decision alternatives based on the algorithm defined by Saaty [10].

On the other hand, Luxhoj and Rizzo [11] propose an alternative to grouping spare component inventory which allows for the determination of demand for the spare components based on the categorization. This method would be useful in deriving appropriate inventory parameters if we can derive good forecasts of demands for particular categories of spare component inventory and using them in the right models. However, the derivation proposed by Luxhoj and Rizzo requires the inclusion of failure characteristics such as Mean Time Between Failure (MTBF) and Mean Time To Failure (MTTF). The existing inventory management system in the company does not provide such statistics. Therefore, this categorization method is inappropriate in this case.

Moncrief [12] also prescribes a method of categorizing inventory that caters specifically to spare components. With experience managing such inventory from the 190 sites of 52 companies from a variety of industries including power, pulp and paper, chemical and petrochemical, refining and railroad, the author has determined that a spare component's usage rate is the most important factor in deciding the best inventory policy that is used to manage inventory levels. Of the items which are defined to be rarely used, Moncrief further proposes that they be subdivided into key and non-key items based on criteria decided on by the manager. This is similar to the method used by Gajpal et al in the categorization of spare components. Thus, it seems reasonable to combine the characteristics of both models proposed by Moncrief and Gajpal et al in the subsequent analysis of spare component inventory. Consequently, the derivation of appropriate models to provide key inventory parameters for each category of inventory will be done by studying the proposed inventory models in Silver [6] and Nahmias [7].

3.3 Inventory Optimization

With the appropriate categorization of spare components, applying the right inventory models to each category of spare components will allow for the determination of inventory levels that will provide the most benefit at the least cost. For inventory with frequent replenishment over a year, the demand could be forecast with reasonable accuracy. Spare components with such characteristics allow for inventory optimization by applying the Q,R Continuous Review model or Base Stock Periodic Review model which is available in much of the literature on inventory modelling. The exact type of model to be applied would just depend on the amount of resources that should be dedicated to managing inventory levels of the spare components.

More attention needs to be paid to managing spare components which experience low and infrequent demand over a year. It is difficult to forecast the demand for such components. Furthermore, holding large quantities of such inventory is not feasible as they usually have a high unit cost and would need to be stored for an indeterminate amount of time, thereby racking up other inventory costs such as holding costs and costs of obsolescence.

Dhakar et al [13] puts forward an (S-1, S) policy with three modes of replenishment: normal repair, emergency repair and expediting of outstanding orders. This model not only accounts for the characteristics of spare components which face infrequent and low demand, but also caters to a variety of lead time scenarios. However, it is not suitable for application in this case as there is inadequate data on the failure rate of the spare components. Furthermore, there is a high level of complexity in this model which requires simulation methods. Instead, with limited information available, a more preferable option is expounded by Moncrief, which is a risk-based decision support tool that determines the optimum stock level of rarely used spare components at minimum cost.

4 Methodology

The aim of this study is to introduce new inventory policy within the Tool Room and Tool Crib such that spare components used for repair and maintenance activities are managed more effectively in order to improve the service level of meeting spare component requirements and reduce inventory costs. This work done to accomplish this goal is divided into two main parts. The first part designs a new framework used to categorize the spare components and the second part involves the application of appropriate inventory models to derive the desired inventory parameters of safety stock, reorder point and reorder quantity necessary to control the inventory levels.

For this thesis, the analysis will be carried out on a subset of the total spare component inventory. The spare components that were considered for this study were taken from the molds used for the production of parts of the Product E product. These molds are represented by the labels L50 to L71 for the Product E LL Hub molds, L43 for the Product E Needle Shield mold and L44, L45 for the Product E Safety Shield mold. The Product E LS Hub molds were not considered as they were slated to be transferred to another manufacturing plant by the end of the year. This study is confined to the Product E product family as the total inventory of spare components handled by the Tool Room numbers in the hundreds. Therefore, carrying out the analysis on a representative subset of all spare components within the limited timeframe would be faster and more effective.

As the Tool Room did not have an existing list of components from each mold that were defined as spare components, this study began with the definition and selection of these components from the Bill of Material (BOM) of the molds. The complete BOMs are listed in Appendix A. Spare components for each mold i.e. L43 - L45, L50 – L71, were defined as parts which would undergo wear and tear over the lifetime of the mold, would fail and then require replacement after a period of time. These components were selected with the approval of the technical specialist responsible for purchasing spare components.

4.1 Categorization of Spare Components

Separating the spare components into different categories allows the Tool Crib to allocate the appropriate amount of resources needed to properly manage the inventory level of these components. It is inefficient to manage all inventories aggressively; instead, the Tool Room would obtain the most benefit by allocating the most amount of time to manage the spare components which fulfil criteria which are most important to the Tool Room. Furthermore, each category of spare components has different characteristics which require different stocking logic to obtain the most optimal solutions. Categorizing the spare components also provides quantifiable criteria that can be used as guidelines for future inventory classification.

The framework that is utilized for inventory categorization is illustrated by the Inventory Tree in Figure 4.1: Inventory Tree Diagram. Spare component's usage rates have traditionally been found to be the most important factor in determining which inventory management technique should be applied. Therefore, the spare components managed by the Tool Room were first divided and categorized by their usage rates. As shown in the Inventory Tree, this inventory characteristic has been used as the first tier criteria to differentiate the spare components. Information of past usage for the various components was used to group the components into "Commodities", "High Volume Items" and "Low Volume Items". Following that, a second tier categorization was used to separate the Low Volume Items into critical components and non-critical components. The analysis used to derive the framework for categorization is described in the following section.

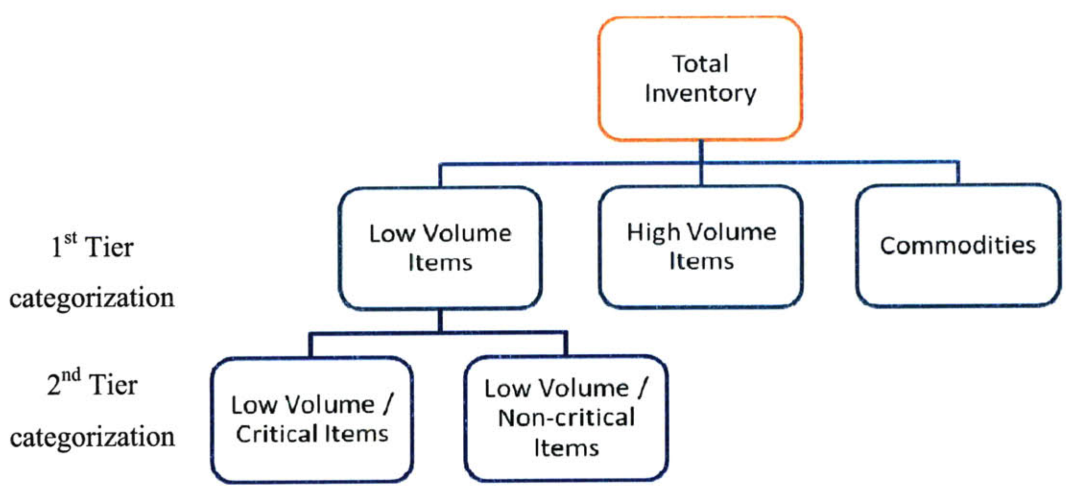

Figure 4.1: Inventory Tree Diagram

High Volume Spare Components

High volume components are ordered frequently and are relatively easier to forecast. This potentially allows the relative costs of stocking such inventory to be significantly reduced as their usage is more predictable. Items classified under this category have the following quantifiable characteristics:

- They are used at least once every month
- The price of the spare component exceeds $20 per unit
- Orders for the item can be for 20 or more pieces

Low Volume Spare Components

On the other hand, low volume components are used less frequently for repair and maintenance activities. It is not possible to predict future usage of these items with much accuracy. Keeping such components in inventory drives costs up due to the potential to go for long periods in storage. Such components frequently have the distinction of having a high unit cost and long replenishment times. Items classified under this category have the following quantifiable characteristics:

- They are used less than once every month
- The price of the component exceeds $20 per unit
- Orders for the item are always below 20 pieces

Although by definition these components might be rarely used, they are still required for the mold to function. For most of these components, the mold will not be able to be used if they are defective and there is none on hand to be used to carry out repairs. On the other hand, as mentioned previously, keeping these items in stock could be costly as they could be kept for long periods of time, possibly for a duration of several years, before they are required for repair activities. Many of these rarely used spare components are also expensive, costing up to a few thousand dollars per piece, which prohibits the Tool Room from holding on to a large quantity of them in stock. Therefore, these spare components require more attention to manage in terms of determining the optimum inventory level. An attempt is made within the framework proposed to balance these costs in determining inventory levels. In the second tier of differentiation, a set of criteria is used to categorize the criticality of the spare component. These criticality criteria differentiate the spare components not by the importance of their function, as all the components are in general required by the mold for it to be operated on the production line, but by other characteristics which affect the backorder costs of such components. Allocating more resources to manage the critical, low volume components would help to derive the most benefit in terms of reducing potential backorder costs and thereby also increasing the service level.

The criteria used to rank criticality of the spare components are as follows:

1. Replenishment Lead Time

   Replenishment lead time is a function of the complexity and value of the spare component. The greater the complexity and value, the longer the lead time required. This is also a function of the availability of the spare component. Availability in this case refers to whether the spare component is custom made and can only be procured from a particular vendor or whether it is a standard component that is readily available from many vendors. Lower availability results in a longer lead time due to the need to procure the component from a specific overseas vendor as compared to a variety of local vendors.

2. Commonality across molds

   The greater the number of molds which rely on a particular spare component to function, the more critical the component is considered to be.

3. The importance of the mold for production activities based on the frequency of usage per month.

This links the criticality of the spare component with the criticality of the mold. The frequency of usage is measured by the percent loading of the mold per month. This refers to the number of hours the mold is run on the press as compared to the total number of available hours in a month. Certain product families utilize a number of molds for the production of some of the parts. To factor the contribution of each mold (for a group of molds producing the same product) to the total production capacity, we calculate the total percent loading for that group of molds as per follows:

$$Total\ \%\ loading = \sum \left[\%\ loading\ of\ individual\ mold * \frac{Number\ of\ cavities\ in\ individual\ mold}{Total\ number\ of\ cavities\ for\ all\ molds} \right]$$

The percent loading of the molds from the various value streams is given in Appendix B.

To separate critical components from non-critical components, an Analytic Hierarchy Process (AHP) Model was utilized to provide a measure of criticality. This model is useful in quantifying the various criteria which contribute to the criticality of the spare component in a consistent manner. The hierarchy structure used for the analysis is shown in Figure 4.2.

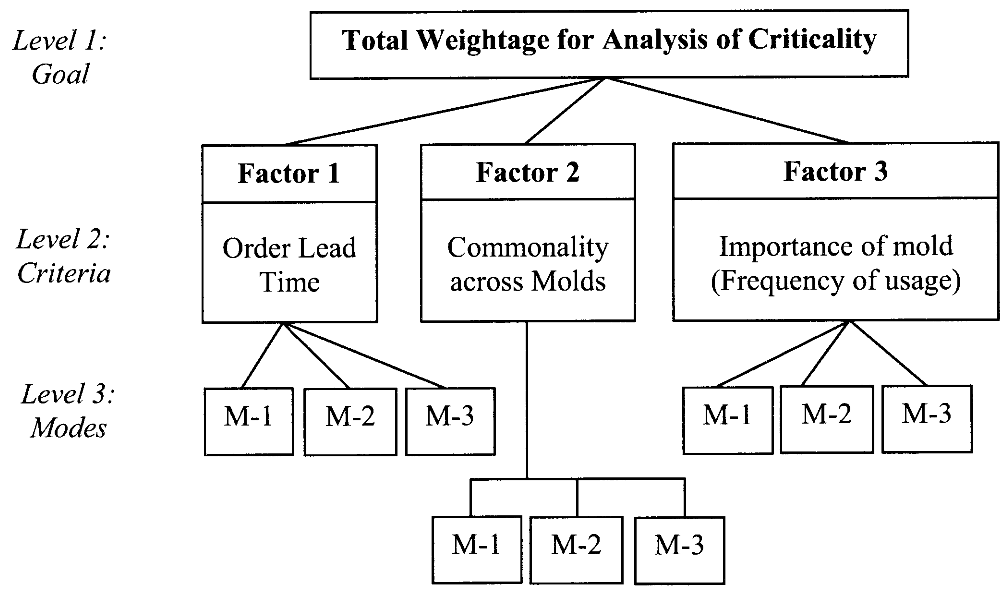

Figure 4.2: Hierarchy Structure for analysis - AHP Model

The focus at level 1 is the evaluation of the criticality of the spare components. At level 2, the criteria used to determine the criticality of the spare components are listed. Finally, at level 3, the alternative modes for each criterion are listed. The modes for the various criteria are given as follows:

1. Replenishment Lead Time

    a. Less than 1 week

        These components are easily sourced from local vendors and are standard components available from a variety of sources.

    b. Between 1 week and 7 weeks

These components are sourced from local vendors but require custom manufacturing.

c. More than 7 weeks

These components can only be sourced from overseas vendors, which are usually the original manufacturers of the molds. They require custom manufacturing.

2. Commonality across Molds

    a. Spare components are used across 1 to 2 molds

    b. Spare components are used across 3 to 5 molds

    c. Spare components are used across more than 5 molds

3. Importance of Mold based on Frequency of Usage

    a. The molds have an average monthly % loading of less than 40%

    b. The molds have an average monthly % loading of between 40% and 85%

    c. The molds have an average monthly % loading of 85% and more

The framework utilizes the knowledge of several "experts" who have experience handling inventory operations within the Tool Room to provide a quantitative system of decision making in categorizing inventory.

Commodities

Commodities are classified as items which are ordered in bulk. These are standard items which can be procured from a wide range of suppliers who supply manufacturers in other industries, thereby having short replenishment lead times. These items are also considered non-critical to operations as their function does not directly affect the performance of the mold in production activities. Therefore, such components require the least attention out of the different inventory categories because of their high availability, ease of procurement and relative low importance to the functioning of the mold. Items classified under this category have the following quantifiable characteristics:

- The components could be used for regularly scheduled preventive maintenance
- The price of the spare component is less than or equal to $20 per unit
- Orders for the item can be for 20 or more pieces

4.2 Inventory Modelling

Each type of inventory requires the application of a different inventory model to derive the inventory control parameters for safety stock, reorder point and reorder quantity. In order to calculate the values for these parameters, we first need to derive the inputs to be used for the models. The methodology used to derive future demand for the spare components and various inventory costs is described as follows:

Future Demand

We assume that the demand for spare components for the molds tends to be level over time. The life cycles of the molds are generally very long, exceeding 20 years. Therefore, it is reasonable to assume that future demand will not deviate very much from historical demand for spare components used to repair the molds. Future demand rate is calculated by compiling past usage data and deriving usage rates.

Inventory Costs

The unit variable costs are given from past purchasing data and by consultation with the purchasing and value stream TS. Broad approximations are given for the inventory costs in order to facilitate the creation of the framework for the inventory policy which is the main objective of this study.

The fixed ordering cost, A, is given by taking the average amount of time to process an order and using the corresponding labour cost, adjusted to include other transactional costs. The time taken to process the order is approximately 1 hour and includes the time needed to submit the Purchase Requisition (PR), follow up with the creation of the Purchase Order (PO) which is sent to the vendor, facilitating the order throughout the replenishment lead time of the spare component and the collection of the part from the vendor which includes checks for the quality of the part. The labour cost for the purchasing TS is S$13.64 per hour and this figure is rounded to S$15 to include transactional costs which are the overhead costs of the company. The cost of obsolescence is not included as the life cycle of the mold is relatively long, thereby making the probability of obsolescence for the spare components low. The inventory carrying cost is set at a conservative rate of 0.2. This follows the recommended value given by Brown [14] who asserts that this value is used by most organizations. The inventory model used for each category of inventory is described in the following section.

4.2.1 High Volume Items

The inventory model that is applied to this class of inventory is the continuous review (s, Q) order point, order quantity model. The reorder quantity is fixed and is determined by the Economic Order Quantity (EOQ).

$$Reorder\ Quantity\ (EOQ), Q = \sqrt{\frac{2AD}{Ic}}$$

Where, A = Order fixed cost (S$)

D = Demand rate over time (units/year)

I = Carrying cost of inventory (Cost per S$/year)

c = Unit variable cost (S$/unit)

The reorder point is calculated from the average demand over the replenishment lead time and the safety stock needed to cater to fluctuations in demand over the replenishment lead time.

$$Reorder\ Point, s = \hat{x}_L + SS$$

$$SS = k\sigma\ ;\ \hat{x}_L = \hat{\mu}L\ ;\ k = z\sqrt{L}$$

Where, $\hat{x}_L$ = Forecasted average demand over replenishment lead time

SS = Safety stock

σ = Standard deviation of demand per month

L = Replenishment lead time (months)

$\hat{\mu}$ = Average demand per month

z = safety factor, set to correspond to the number of standard deviations for a standard normal variable required to meet a service level target.

We make the following assumptions in using this model:

- For high volume items, the demand is independent between time periods and is normally distributed
- The replenishment lead times are determinate
- The average demand rate is constant over time

This model is chosen as it closely resembles the inventory system to be used in the company. The setting up of the Tool Crib will allow for continuous monitoring of the inventory levels with high visibility. The order quantity also has to be large enough such that the inventory position after an order is made will exceed the reorder point. This would take into account a scenario when the quantity used for a major repair operation is large enough such that the reorder quantity would not bring the inventory position to be greater than the reorder point. This would be a rare occurrence, in which case, a multiple of the reorder quantity is ordered.

We prefer for the order quantity to be fixed. As the company uses the SAP system to make purchases of inventory, information about the vendor needs to be set before purchases can be made. The limitation of the system is that changes to this information are not easily made, which would occur when variable order quantities cause a change in per unit variable cost for different orders. Furthermore, this model creates less complexity as the order quantities are fixed, with less likelihood of error.

4.2.2 Low Volume Items

The continuous review (s, Q) order point, order quantity inventory model is applied to this category of inventory as well. As the items in this category face low demand over the replenishment lead time, a Poisson distribution is used to represent the demand rather than the normal distribution.

The reorder quantity is obtained from the demand of the item as a function of its unit cost. We derive this from the following procedure:

Given the total inventory cost function,

$$C_{inv} = \frac{QIc}{2} + \frac{AD}{Q}$$

Where, A = Order fixed cost (S$)

D = Demand rate over time (units/year)

I = Carrying cost of inventory (Cost per S$/year)

c = Unit variable cost (S$/unit)

Q = Reorder quantity (units)

We are indifferent between ordering two quantities, e.g. $Q_1 = 1$ and $Q_2 = 2$ when the following is true:

$$\frac{Q_1 Ic}{2} + \frac{AD}{Q_1} = \frac{Q_2 Ic}{2} + \frac{AD}{Q_2}$$

Where, A = Order fixed cost (S$)

D = Demand rate over time (units/year)

I = Carrying cost of inventory (Cost per S$/year)

c = Unit variable cost (S$/unit)

Q_1, Q_2 = Reorder quantity levels (units)

Thus we can obtain the range of values for D as a function of the unit cost for each reorder quantity which minimizes the total inventory cost of the spare component. Given A = 15 and I = 0.20:

E.g. With $Q_1 = 1$ and $Q_2 = 2$,

$$D = \frac{0.20c}{15} = 0.0133c$$

This indicates that values of D less than 0.0133c should have reorder quantity Q = 1; for greater values of D, we would prefer Q =2 rather than Q = 1. Table 4.1 lists the reorder quantities for each range of values of the cost of the component, obtained from the previous equation. The appropriate amount is selected from the listed values.

For low order quantities, this method of deriving the reorder quantity is simple to implement. As the demand for these items is characterized by the Poisson distribution, this method of deriving the reorder quantity is suited to the discrete nature of the distribution. Furthermore, the cost penalty from not using the exact EOQ values is not significant. Since we are looking at increments of 1 of the reorder quantity, these slight deviations in reorder quantity for low volume items from the exact EOQ value would not have a large effect on the inventory cost. From historical demand data of these low volume items, the usage for any one repair activity does not exceed 10 at any point in time. Therefore, we can use the given relationship above to derive the different reorder quantities to be used for such items.

Table 4.1: Reorder Quantity for Low Volume Items

Reorder Quantity, Q	Requirement
1	$D < 0.0133c$
2	$0.0133c \leq D < 0.0400c$
3	$0.0400c \leq D < 0.0800c$
4	$0.0800c \leq D < 0.1333c$
5	$0.1333c \leq D < 0.2000c$
6	$0.2000c \leq D < 0.2800c$
7	$0.2800c \leq D < 0.3733c$
8	$0.3733c \leq D < 0.4800c$
9	$0.4800c \leq D < 0.6000c$
10	$0.6000c \leq D < 0.7333c$

The reorder point is derived from the fixed backorder cost for each spare component. We utilise backorder costs rather than service levels to determine the reorder point in this case due to the fact that low volume items will often not be used for long periods of time; hence, defining a service level over a period of time is less meaningful. Rather, we are more concerned with the potential backorder costs, especially with low volume, critical. For low volume, non-critical items, the fixed backorder cost will be set proportionately lower relative to that of low volume, critical items.

This model utilises the expected costs associated with adopting the reorder point, s, to determine the appropriate reorder point. In this case, the costs associated with the reorder point are the backorder cost of not having the inventory on-hand when it is required and the inventory holding cost if the demand over the lead time does not exceed the reorder point. Therefore, we derive the required reorder point for each spare component in this category by comparing those associated costs for different reorder points. This is shown below:

$$EC_{inv>}(s) = Ic\sum_{x_l}^{s}(s - x_l)p_x(x_l) + \frac{D}{Q}Bp_{x>}(s)$$

Where, s = Reorder point

D = Demand rate over time (units/year)

I = Carrying cost of inventory (Cost per S$/year)

c = Unit variable cost (S$/unit)

Q = Reorder quantity (units)

B = Fixed backorder cost (S$)

x_l = Demand over replenishment lead time (units)

$p_x(x)$ = Probability that demand is equivalent to x

$p_{x>}(x)$ = Probability that demand is greater than x

We are indifferent between two adjacent reorder points, s and (s+1), when we derive the following relationship from the expected total inventory cost:

$$EC_{inv>}(s) = EC_{inv>}(s + 1)$$

$$\frac{p_x(s+1|\hat{x}_L)}{p_{x\leq}(s|\hat{x}_L)} = \frac{QIc}{DB}$$

Where, $\hat{x}_L$ = Forecasted average demand over replenishment lead time

$p_x(s + 1|\hat{x}_L)$ = Probability that a Poisson variable with mean $\hat{x}_L$ takes on the value s + 1

$p_{x\leq}(s|\hat{x}_L)$ = Probability that a Poisson variable with mean $\hat{x}_L$ takes on the value less than or equal to s

The fixed backorder cost is calculated by finding the value of the lost production of the finished product over the replenishment lead time of the spare component that is required for repairing the mold. This value is derived by multiplying the selling price of the finished product and the total quantity of the finished product that would be produced over the replenishment lead time of the spare component. This backorder cost thus depends on the replenishment lead time of each spare component.

The finished product for each mold is combined during the assembly process to produce the final Product E product. Therefore, we simplify the calculation of the backorder cost by assuming that the finished product of any of the Product E molds takes on the selling price of Product E. This is acceptable as the lack of any of the finished products from any mold would starve the assembly line used to assemble Product E. Furthermore, each finished product from each mold does not by itself have a selling price in the market.

Therefore, for the purposes of calculating the backorder cost, Product E has a selling price of S$130 for a batch of 1000.

Using pre-determined values of s and $\hat{x}_L$, the corresponding value of $\frac{QIc}{DB}$ was calculated. For each value of s, a range of values for $\hat{x}_L$ were used to derive a curve which provides the boundary values of $\frac{QIc}{DB}$ that differentiates between the use of adjacent values of the reorder point. These are referred to as indifference curves for the reorder point which are shown in Figure 4.3 below.

Thereafter, the reorder point is ascertained by using the parameters for each particular spare component to calculate the value of $\frac{QIc}{DB}$ and the corresponding replenishment lead time demand. The segment within which the point of intersection lies determines what the appropriate value of the reorder point should be. The graph shown in Figure 4.3 below shows the relevant reorder points for a range of values of $\hat{x}_L$ calculated from demand per year of 0.25 to 10 units and a replenishment lead time of 2 to 8 weeks.

As mentioned previously, for the low volume items, we are more concerned with potential backorder costs rather than a targeted service level in determining the reorder point. Setting a service level would be less meaningful as these components are rarely used.

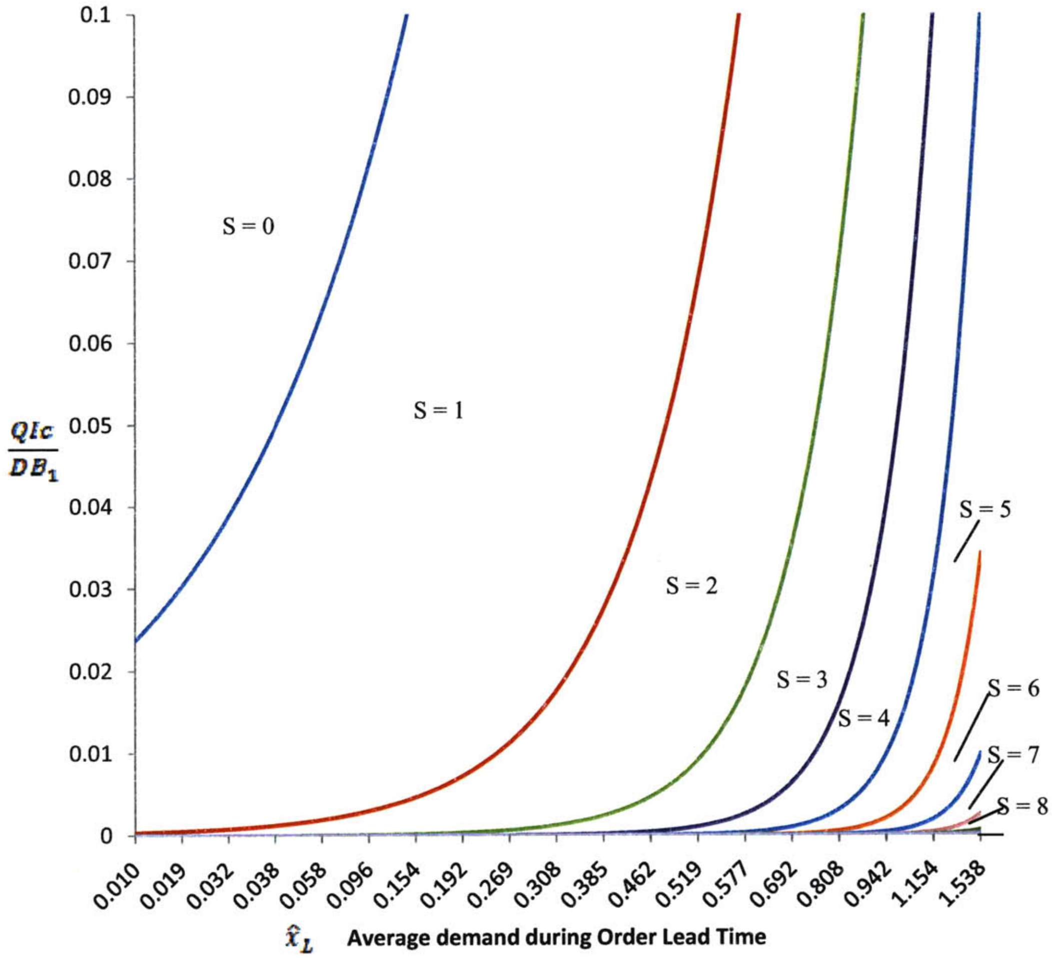

Figure 4.3: Indifference curves for the Reorder Point

We will utilise the model outlined above to set the inventory parameters for low volume items. Under the proposed inventory categorization framework, we will need to differentiate between low volume items which are considered critical and those not considered critical. For low volume, non-critical items, the backorder cost is calculated in a similar manner. However, this value of the backorder cost for such items will be reduced to a fraction of the cost to reflect the relatively lower importance of these items. We have also established through the use of the criticality criteria that these items are less critical in terms of their potential backorder cost in the event of a stockout. The fraction for the backorder cost that is proposed is 0.13. This fraction is similar to the criticality weighting used to classify low volume items as non-critical as compared to low volume items which are critical

We make the following assumptions in using this model:

- For low volume items, the demand is independent between time periods and has a Poisson distribution
- The replenishment lead times are determinate
- There is complete backordering of demand when out of stock
- The average demand rate is constant over time

This model is chosen because it is applicable to very slow moving and expensive inventory. It is often applied to inventory which corresponds to "A" items in inventory classification as shown by Silver [6]. The spare components which face low demand for use in repair activities adopt similar characteristics.

4.2.3 Commodities

The inventory model that is applied to this class of inventory is the continuous review (s, Q) order point, order quantity model. In comparison to the model used for high volume inventory, different methods are used to derive the reorder quantity and reorder point.

The reorder quantity is obtained from a modified version of the EOQ, which refers to the use of time supplies. Time supplies are equivalent to the quantity of spare components that are used over the corresponding period of time for repairs based on historical usage data. This order quantity is derived first by multiplying the value of the spare component and its demand over a period of time, then comparing this value to the range of values corresponding to the appropriate time supply. The time supplies we use are 6, 12 and 24 months. Based on past data, these items are only replenished a maximum of twice a year, therefore, the smallest time frame used should be 6 months.

We now describe the procedure for determining the reorder quantity. Given the total inventory cost function which is similar to that shown for the low volume items,

$$C_{inv} = \frac{QIc}{2} + \frac{AD}{Q}$$

Where, A = Order fixed cost (S$)

D = Demand rate over time (units/year)

I = Carrying cost of inventory (Cost per S$/year)

c = Unit variable cost (S$/unit)

Q = Reorder quantity (units)

We substitute time supplies in place of the reorder quantity in this case:

$$T = \frac{12Q}{D}$$

where, T_i = Time supply (months)

We are indifferent between ordering two time supplies worth of inventory, e.g. $T_1 = 6$ and $T_2 = 12$, when the following is true:

$$\frac{DT_1Ic}{24} + \frac{12A}{T_1} = \frac{DT_2Ic}{24} + \frac{12A}{T_2}$$

This is simplified to the following:

$$Dc_{indifference} = \frac{288A}{T_1T_2I}$$

a. *6, 12 months*:

$$Dc_{indifference} = \frac{288 * 15}{6 * 12 * 0.2} = \$300$$

b. *12, 24 months*:

$$Dc_{indifference} = \frac{288 * 15}{12 * 24 * 0.2} = \$75$$

The relevant time supplies for each spare component in this category is given in Table 4.2 as a function of the Demand rate (D) and the Unit variable cost (c).

Table 4.2: Suggested Reorder Time Supplies for Commodities

Annual Dollar Usage, Dc (S$/yr)	Time Supplies for Reorder Quantity
$300 \leq Dc$	6
$75 \leq Dc < 300$	12
$Dc < 75$	24

We use this method as it is simple to implement in the work environment. The user just needs to refer to the relevant range of values of Dv for each item to determine the reorder quantity. Furthermore, time supplies are used for commodities due to several reasons. Usage rates for such items, such as screws and O-rings, are not recorded as it requires too much effort for items which are easily and inexpensively obtained in bulk amounts. Therefore, it is preferable to aggregate the demand over a significant length of time. As the usage and purchase of such items is done in bulk amounts, using time supplies will also allow for the infrequent replenishment of these items. As the unit cost of such items is less than a dollar, the inventory holding cost is quite insignificant and we seek to minimize the ordering cost as much as possible.

The reorder point for items which are of relatively low importance is usually derived from a specified time between stockout occasions (TBS). This methodology of calculating the safety factor is recommended by Silver [6] for such items. However, with respect to the management of the commodities category of inventory, we can adapt the use of time supplies to determine the reorder point. This is coupled with the use of the two-bin system which is described later in this section. The use of time supplies can be justified in several ways. A significant amount needs to be kept at any point in time as the usage of these items at any one time occurs in bulk quantities. A large reorder point should alleviate the need to devote much attention to managing the inventory of such items. Using the equivalent time supply as the reorder quantity would simplify the implementation of inventory policy for commodity items as well, given that the size of each bin of items is similar for the two-bin system to be put in place.

This model is chosen as it describes a simple system suitable for managing low value inventory of relatively low importance. The reorder quantity is derived easily from the usage rate over a period of time while the use of time between stockouts for deriving the reorder point is straightforward and easily understood by management. In addition, this model is recommended for use in conjunction with the two-bin system of managing these spare components. On-hand inventory is separated equally into two "bins". Demand is satisfied from one bin until the inventory of spare components is depleted, whereupon the reserve bin is opened and a replenishment order is placed. Once the order arrives, this is used to refill the reserve bin which is then sealed again. Subsequent demand is fulfilled using the remaining inventory from the open bin.

4.3 Data Extraction

We have noted that previous historical data on the usage of the spare components is inaccurate. However, among the various value streams, the available data for spare components of Product E molds can be considered as the most complete and reliable, with past data being recorded in the most structured manner, in spite of the lack of proper usage of the SAP system. These data were in a large part extracted from MS Excel spreadsheets which were used for the recording of information, separate from the SAP system.

4.3.1 Inventory Categorization

For the first tier categorization, past usage data for the spare components was needed. This information was extracted from softcopies of the mold history records kept in MS Excel format. Usage data for the past 4 years from 2006 to the present time, mid-2009, was consolidated. A duration of 4 years was used as certain spare components are rarely used and might only be utilized once every few years. If a component was not used in 4 years, we assume that it is not needed by the Tool Room.

In addition, purchasing data was needed to establish the price and the minimum order quantity for each spare component. This information was extracted from a combination of sources. The primary source used was the SAP system which the company uses to track purchases of spare components. This gave the latest prices for each spare component as well as the record of quantities quoted in each purchase order. In certain cases, the information lacked clarity due to the non-standardized format of previous entries. The corresponding order would then be clarified with the TS who is in charge of the spare component, as well as through cross-referencing with the personal softcopy records of the purchasing TS in MS Excel format.

For the second tier categorization, data on replenishment lead time was obtained from the aforementioned purchasing data. To determine the percent loading for the molds used to produce the various parts, the data was obtained by softcopy directly from the molding engineer in charge of the machine press.

4.3.2 Inventory Modelling

In order for the analysis to be carried out using the selected models, information on the demand of spare components as well as cost characteristics of the inventory were also utilized. In addition, information about the replenishment lead time of each spare component was also necessary. These were obtained as described earlier in the section from historical usage and purchasing data.

Information regarding relevant inventory costs was not readily available. Unit variable costs were obtained from past purchasing data. However, other inventory costs such as inventory carrying cost, cost of obsolescence, as well as other transactional costs which are included in the fixed ordering cost were not tracked by the company. Therefore, assumptions were made for the calculation of the inventory parameters.

5 Results and Discussion

5.1 Inventory Categorization

5.1.1 AHP framework

In the inventory tree framework, the second tier categorization involves the separation of the non-critical, low volume items from the critical, low volume items. The AHP framework provides a quantifiable method of differentiating these spare components through the use of several relevant criteria. This section describes the results of the categorization based on the survey results drawn from personnel involved in the management of spare components of the mold.

Each criterion which affects criticality of the spare component was compared to each other. Information for this was drawn from Khor, the technical specialist responsible for purchasing spare components for the Tool Room, Thomas, the Tool Room engineer who is in charge of the Product E molds, and Alex, the technical specialist responsible for setting up the Tool Crib.

The survey results are summarized in the matrix illustrated in Figure 5.1 below. This matrix is referred to as Matrix A. The ratings from the scale used are given in Appendix C. The importance of each criteria relative to the goal stated in level 1 of the AHP model is quantified through the derivation of "Composite Weights". These are shown in Figure 5.1 as well.

	Order Lead Time	Multiplicity across Molds	Importance of Mold	**Composite Weights**
Order Lead Time	1	8	5	0.733
Multiplicity Across Molds	0.125	1	0.250	0.068
Importance of Mold	0.2	4	1	0.199

λ = 3.094 C.R = 0.081048
C.I = 0.04701 *(Consistency Ratio)*

Figure 5.1: Matrix illustrating comparison of criticality criteria

The weights are given as a 1x3 matrix referred to as Matrix w. Matrix w is given as a function of Matrix A according to the following relationship, where λ is the Eigenvalue of Matrix A and *I* is the Identity matrix. The derivation of the Eigenvalue is given in Appendix D.

$$\left(\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} - \lambda I\right)\begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = 0$$

In the AHP method, due to the fact that ratings used in the comparison are subjective, matrix A cannot be consistently perfect, i.e. for all i, j and k, $a_{ij} = a_{ik}/a_{jk}$. Therefore, this framework requires the calculation of the Consistency Ratio (CR) to determine if the level of consistency in the resultant matrix formed is acceptable. High levels of inconsistency could occur due to significant differences in judgments of personnel interviewed. This is indicated by CR > 0.1. This would mean that the ratings have to be reassessed to create a more consistent matrix A. The metric CR is calculated from the Consistency Index (CI) which itself is derived from n, the number of criterion and λ, the Eigenvalue. Both CR and CI are calculated as follows:

$$C.I = \frac{\lambda - n}{n - 1}$$

$$C.R = \frac{C.I}{Random\ Index\ of\ size\ n}$$

The random index of a matrix of size n = 3 is 0.58.

In this study, the composite weights are calculated using the Row Geometric Mean method of approximation which is used to derive the Eigenvalue. All calculations for this matrix and subsequent matrix analysis are fully illustrated in Appendix E.

In addition, the modes of each individual criterion were compared to each other to determine their relative importance as well. The matrices obtained from this analysis are given in Figure 5.2, Figure 5.3 and Figure 5.4. The corresponding modes for each criteria were given in the Methodology chapter. Again, the composite weights for each mode is derived in a similar manner as described previously:

1. Replenishment lead time

	a.	b.	c.	Composite Weights
a.	1	0.25	0.111	0.061
b.	4	1	0.167	0.176
c.	9	6	1	0.763

λ	=	3.108	C.R	=	0.0930
C.I	=	0.0539	*(Consistency Ratio)*		

Figure 5.2: Matrix illustrating comparison of replenishment lead time modes

2. Commonality across Molds

	a.	b.	c.	Composite Weights
a.	1	0.5	0.25	0.136
b.	2	1	0.333333	0.238
c.	4	3	1	0.625

λ	=	3.018	C.R	=	0.0157713
C.I	=	0.00915	*(Consistency Ratio)*		

Figure 5.3: Matrix illustrating comparison of commonality modes

3. Importance of Mold based on Frequency of Usage

	a.	b.	c.	Composite Weights
a.	1	0.14286	0.111111	0.057
b.	7	1	0.5	0.346
c.	9	2	1	0.597

λ	=	3.022	C.R	=	0.0187327
C.I	=	0.01086	*(Consistency Ratio)*		

Figure 5.4: Matrix illustrating comparison of mold usage modes

Given the composite weights from each mode, these are multiplied with the composite weights of the corresponding criteria used to measure criticality to obtain global weights for each mode. This is shown in Table 5.1 below:

Table 5.1: Global Weights of Modes

Criticality Criteria	Global Weights (Modes)		
	A	B	C
Replenishment lead time	0.0448	0.1293	0.5593
Commonality across Molds	0.0092	0.0161	0.0422
Importance of Mold (Frequency of Usage)	0.0114	0.0688	0.1188

The quantitative system of categorizing the spare components in this 2nd tier categorization is thus derived from obtaining the global weights of each mode and assigning them to each spare component based on their inventory characteristics. For each criteria used to determine the criticality of the low volume item, the relevant mode is assigned to the item.

For example, given a spare component named "Gate Insert" from the Product E Hub LL mold. We determine for each criticality criteria, which mode applies to this spare component:

Replenishment Lead Time: 4 weeks

Commonality across Molds: 21 molds

Importance of Mold: 80.83% (Refer to Appendix B)

After obtaining the global weights of a mode from each criticality criteria, these are summed up to obtain the criticality weight of the low volume item.

Following on from the example given above:

Sum of Global Weights: 0.1293 + 0.0422 + 0.0688 = 0.2403

If we let x be the criticality weight of each item, the criticality of the item can be decided by comparing it to the range of values of weights set by management for critical components and non-critical components as shown in Table 5.2 below:

Table 5.2: Criticality Categorization

	Weight Range
Critical component	$0.1298 < x \leq 1$
Non-critical component	$0 \leq x \leq 0.1298$

The spare components which are deemed as low volume items can thus be broken down further into critical and non-critical components according to the classification by the range of values of criticality weight that is assigned to each class. Once the low volume items are properly separated into critical and non-critical items, the appropriate inventory models will be used to derive proper inventory parameters of reorder quantity and reorder point for each of those items.

5.1.2 Inventory Categorization Discussion

To evaluate the effectiveness of the inventory categorization methods, we look at the results of grouping the spare components using the derived framework.

In the AHP analysis, the CR ratio for each of the matrices is below 0.1, which indicates a high level of consistency and no need to refine the comparisons made between the various modes and criteria. This is the threshold value before the ratings have to be re-evaluated again. Therefore, we can be assured that quantitatively, the framework supports the intuition behind the classification of criticality of spare components.

A comparison is also drawn between the breakdown for each category of spare components as a proportion of total inventory and the expected breakdown of such inventory in existing literature. According to Moncrief [10], the distribution of items across separate classes of inventory should be close to 10% group A, 20% group B and 70% group C, in order of the relative importance of the inventory and how much resources and attention should be dedicated to managing them.

In the inventory categorization framework proposed in this study, the breakdown of each inventory category as a proportion of total inventory is given below in Figure 5.5 according to which category of spare components that they fall into. Each category is differentiated by the relative amount of resources and attention that should be committed to the management of the inventory of spare components.

The categories of commodities, high volume items and low volume items are derived according to their usage rates, price points and order quantities which were elaborated on in the previous chapter on Methodology. Low volume, critical items and low volume, non-critical items are differentiated according to the AHP framework that was described previously.

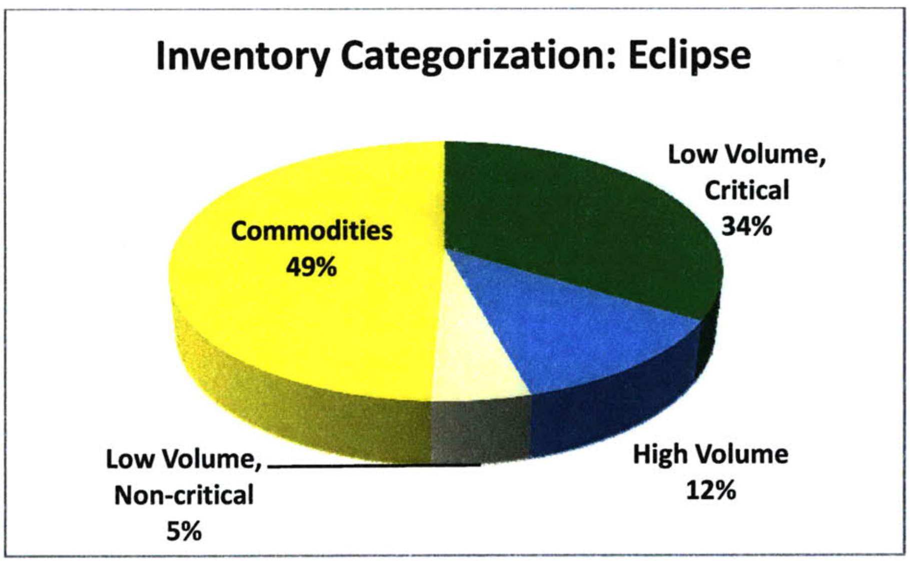

Figure 5.5: Breakdown of inventory as a percentage of total spare components used in Product E molds

Comparing the two methods of categorizing spare component inventory, the framework applied in this study has several significant differences.

Four categories are used as compared to the standard 3 categories. However, classifying the inventory in this way makes more sense for the company. Each category of spare component inventory requires a different level of treatment in terms of the effort required to properly manage the inventory of spare components.

The classification defined by the framework applied to the company has the percentage of low volume, critical inventory being higher than the percentage of high volume inventory.

We can justify this by the fact that the management of low volume items which are considered critical require the most attention to manage, as they are comprised of a significant proportion of total inventory value. Therefore, dedicating resources to managing this class of inventory properly would reduce costs to a significant extent. High volume items are considered less important relatively as most of these components are comparatively inexpensive, costing less than $100 per component on average. However, they are used in large volumes each year and have an accumulatively high cost to the Tool Room, thereby requiring more attention to manage than the low volume, non-critical inventory and commodities. Commodities are numerous and make up only a very minor part of total dollar investment, thus justifying the use of a simple order rule and monitoring system to manage. In addition, low volume, non-critical inventory will not have as great an impact on the service level and backorder costs of the Tool Room. Therefore, they also do not require as much resources and attention to manage.

Silver [6] also reiterates these objectives in classifying inventory and goes on further to mention that the "number of categories appropriate for a particular company depends on its circumstances and the degree to which it wishes to differentiate the amount of effort allocated to various groupings of inventory."

To account for differences in proportion of total inventory items between the default framework and the framework applied in this case, it can be suggested that there is a slight possibility that past purchasing and usage data has not been accurately captured, both of which could affect the classification of the spare components. Inaccuracies could be present regarding the lead time for ordering the components as the proper purchasing process was previously not strictly adhered to, causing some discrepancies in recording when the order is received by the Tool Room. However, the data used is assumed to be by and large complete, especially considering that the Product E molds and processes are the best managed and monitored by the Tool Room.

An alternative and more plausible explanation for the smaller proportion of spare components which fall under high volume inventory category could be the nature of the molds used for production. In general, the number of moving parts which would experience high wear and tear in the mold could be a small proportion of the total parts considered as spare components in the Bill of Material. Other components which require replacement over time are generally not replaced as often as once a month or more. Therefore, the percentage of low volume, critical inventory is higher in the case of spare components used in molds.

5.2 Inventory Modelling

In the following section, we determine the inventory parameters of reorder quantity, safety stock level and reorder point for each category of inventory.

5.2.1 High Volume Items

The mean and standard deviation of demand are calculated from the collected usage data. Using these, the inventory parameters of safety stock, reorder quantity and reorder point are derived as follows in Table 5.3:

Table 5.3: Inventory Parameters for High Volume Items

Mold Number	Spare Component	Reorder Quantity, Q (EOQ)	Safety Stock, SS	Reorder Point, s
L43/L44/L45	Gate Pin	21	27	35
L43/L44/L45	Melt Flow Bush	20	27	33
L44/L45	Local Core Insert M106	17	29	61
L44/L45	Cavity Insert 103	12	11	19
L44/L45	Main Cavity Insert M101	1	3	4
Hub LL	Gate Insert	2	5	7
Hub LL	Core Insert (Ø13 X 38.570)	6	8	11
Hub LL	Slide Insert 219 (Small Insert)	7	9	12
Hub LL	Pins Epoxy Gauge 18	11	16	27
Hub LL	Pins Epoxy Gauge 21	13	11	14
Hub LL	Pins Epoxy Gauge 22	12	7	10
Hub LL	Pins Epoxy Gauge 23	14	11	14
Hub LL	Pins Epoxy Gauge 25	15	9	13
Hub LL	Pins Epoxy Gauge 27	13	8	11
Hub LL	Bush Carbide Gauge 18	13	21	34
Hub LL	Bush Carbide Gauge 21	12	22	34
Hub LL	Bush Carbide Gauge 22	11	14	24
Hub LL	Bush Carbide Gauge 23	13	22	35
Hub LL	Bush Carbide Gauge 25	12	15	28
Hub LL	Bush Carbide Gauge 27	12	18	30

Hub LL	Sleeve Carbide Gauge 21	12	22	34
Hub LL	Sleeve Carbide Gauge 22	11	14	24
Hub LL	Sleeve Carbide Gauge 23	13	22	35
Hub LL	Sleeve Carbide Gauge 25	12	15	28
Hub LL	Sleeve Carbide Gauge 27	12	18	30

The safety stock level is obtained by setting the required service level at 97.5%. Therefore, the defined safety factor z = 1.96 based on a normal distribution of demand. This is a reasonable setting given that these high volume items are considered critical to the mold. The high service level is what the Tool Room aims to achieve in the long run as well.

5.2.2 High Volume Items Discussion

From the results, we can see that for some items, the reorder point set is higher than the amount that is currently kept based on the experience of the TS. This is possibly due to the fact that the TS would estimate the amount needed to keep in inventory based on the average usage. In order to obtain the desired service level though, the variance of demand and length of the replenishment lead time have to be taken into account as well. The reorder quantities are correspondingly lower compared to current expectations. This is shown in Table 5.4 below:

Table 5.4: Selected Comparison of Inventory Parameters of High Volume Items

		Without Inventory Model		*With Inventory Model*	
Mold Number	**Spare Component**	**Reorder Quantity, Q#**	**Reorder Point, s***	**Reorder Quantity, Q**	**Reorder Point, s**
L43/L44/L45	Gate Pin	30	20	21	35
L43/L44/L45	Melt Flow Bush	30	20	20	33
L44/L45	Local Core Insert M106	20	12	17	61
L44/L45	Cavity Insert 103	30	10	12	19
L44/L45	Main Cavity Insert M101	10	10	1	4

*Reorder Point: Sub-optimal figures highlighted in red
#Reorder Quantity: Sub-optimal figures highlighted in red

A list providing a comparison of the inventory parameters for all high volume items before and after the application of the inventory model is given in Appendix F. For all other items in this category, the reorder point set for the high volume items with the use of the applied inventory model is generally lower than the amount that is currently adhered to based on the experience of the TS. The current high levels of inventory kept by the TS for each of these items are not desirable as it would increase inventory costs. Furthermore, the reorder quantities are also much higher than the parameters specified by the inventory model.

With the proper amount of inventory kept in the Tool Room to cope with lead time demand, it is thus not necessary to order relatively large amounts.

It is necessary to note that given the small value of Q and the possibility of batch demands, when the inventory position drops below the reorder point and triggers an order, the order may need to be comprised of a multiple of the reorder quantity so that the resulting inventory position exceeds the reorder point.

5.2.3 Low Volume Items

Past usage data of these items is used to derive the reorder quantity of these items. The value of $\frac{QIc}{DB}$ is calculated for each component and plotted against the graph of indifference curves to determine the reorder point. These are shown in Table 5.5, Table 5.6 and Table 5.7 below:

Table 5.5: Inventory Parameters for Product E LL Mold Low Volume Items

Mold Number	Spare Component	Inventory Class	Reorder Quantity, Q	$\frac{QIc}{DB}$	Reorder Point
Hub LL	Sprue (Ø22.0 X 23.8)	Critical	2	7.662E-05	3
Hub LL	Runner Bushing	Critical	1	1.724E-03	2
Hub LL	Gate Pin (Ø9.6 X 69.40)	Critical	2	9.769E-05	3
Hub LL	Locating Ring (Ø60.0 X 12.0)	Critical	1	2.299E-03	1
Hub LL	Steel Chase (Ø17 X 13)	Critical	1	6.896E-04	1
Hub LL	Steel Chase (Ø18 X 14)	Critical	1	6.896E-04	1
Hub LL	Return Pin (Ø12 X 65)	Critical	1	4.597E-04	1
Hub LL	Ejector Pin (Ø3.5 X 100)	Critical	1	8.045E-04	1
Hub LL	Coil Heater (ID 19 X OD 24 X L 40)	Critical	1	3.975E-04	2
Hub LL	Cavity Support Pillar (M5/Ø7.8 X 17)	Critical	1	5.746E-04	1
Hub LL	Cavity Plate (158 X 130 X 15)	Critical	1	3.448E-03	1
Hub LL	Cavity Ejector Plate (148 X 40 X 7)	Critical	1	1.532E-03	2
Hub LL	Cavity Ejector Backplate (148 X 40 X	Critical	1	1.532E-03	2
Hub LL	Angular Cam (SQ10 X 50)	Critical	1	1.701E-02	1
Hub LL	Angular Cam Clamp (16 X 10 X 4)	Critical	1	1.149E-03	1

Hub LL	Cavity Return Pin (Ø6 X 25)	Critical	1	1.609E-04	2
Hub LL	Ball cage (765.06.150 - AGATHON)	Critical	1	4.597E-04	1
Hub LL	Cavity Guide Bush	Critical	1	1.532E-04	2
Hub LL	Cam Wear Plate (78 X 40.23 X 4)	Critical	1	2.069E-04	2
Hub LL	Stripper Bush (Ø11 X 10)	Critical	1	7.662E-04	2
Hub LL	Slide Guide Plate (56.5 X 10 X 6)	Critical	1	3.065E-04	2
Hub LL	Guide Rail (230 X 17.5 X 24.5)	Critical	1	9.194E-04	2
Hub LL	Core Holder Plate (Ø55 X 15)	Critical	1	1.149E-03	1
Hub LL	Stripper Bush Insert	Critical	1	1.724E-04	2
Hub LL	Slide Insert (7.477 X 4 X 3)	Critical	1	6.206E-03	1
Hub LL	Wear Plate Left (128 X 57.5 X 4)	Critical	1	5.057E-03	1
Hub LL	Wear Plate Right (128 X 57.5 X 4)	Critical	1	5.057E-03	1
Hub LL	Guide Bush (Z10/66/20)	Critical	3	6.975E-04	6
Hub LL	Guide Bush (Z10/66/18)	Critical	1	2.325E-04	2
Hub LL	Guide Pillar (Z00/36/20 X 115)	Critical	3	7.763E-04	6
Hub LL	Guide Pillar (Z00/36/18 X 115)	Critical	1	2.588E-04	2
Hub LL	Guide Bush (Z1100W/36 X 20)	Critical	3	1.210E-03	6
Hub LL	Guide Bush (Z1100W/36 X 18)	Critical	1	4.033E-04	2
Hub LL	Safety Needle Epoxy Pin G30	Critical	8	7.470E-04	2
Hub LL	Bush Carbide Gauge 30	Critical	8	1.287E-03	2
Hub LL	Sleeve Carbide Gauge 30	Critical	8	8.780E-04	2
Hub LL	Manifold	Critical	1	1.642E-03	3
Hub LL	Cartridge Heater	Critical	6	4.980E-05	5
Hub LL	Thermocouple (Ø1.5 X 150)	Critical	2	1.868E-04	2
Hub LL	Pin Core (Slider Insert Pin)	Critical	1	3.448E-04	1
Hub LL	Cavity Insert Gauge 18	Critical	1	5.304E-05	7
Hub LL	Cavity Insert	Critical	1	1.061E-04	4
Hub LL	Insert Slide	Critical	1	4.469E-04	5
Hub LL	Block Pressure	Critical	1	1.839E-04	2
Hub LL	Insert Holder Slide	Critical	1	2.873E-04	3

Table 5.6: Inventory Parameters for Product E L43 Mold Low Volume Items

Mold Number	Spare Component	Inventory Class	Reorder Quantity,	$\frac{QIc}{DB}$	Reorder Point
L43	Sprue Bush	Critical	1	4.024E-05	2
L43	HR Sleeve (Ø16.00 X 16.00)	Non-critical	8	1.300E-03	2
L43	Cal Rod Heater (230V/1000W)	Critical	1	4.949E-05	2
L43	Cartridge Heater (230V/600W)	Critical	5	3.184E-06	4
L43	Thermocouple Type J (Ø1.50 X 150)	Critical	3	3.678E-06	4
L43	Cavity Insert (Ø19.0 X 41.20)	Critical	1	3.772E-05	2
L43	Gate Insert (Ø20 X 5.311)	Critical	1	3.018E-04	2
L43	Cavity Insert Plate (150 X 150 X 47.00)	Non-critical	1	7.893E-03	1
L43	Wear Plate (51.0 X 57.0 X 8.00)	Non-critical	1	2.321E-03	1
L43	Leader Pin (Z03/66/32X175)	Non-critical	3	1.564E-03	3
L43	Leader Pin (Z03/66/30X175)	Non-critical	1	5.214E-04	1

L43	Leader Bushing (Z10W/136/32)	Non-critical	3	7.019E-03	3
L43	Leader Bushing (Z10W/136/30)	Non-critical	1	2.340E-03	1
L43	Leader Bushing (Z11W/46/32)	Non-critical	6	4.785E-03	6
L43	Leader Bushing (Z11W/46/30)	Non-critical	2	1.595E-03	2
L43	Thermocouple Connector (Han 40D)	Critical	1	3.018E-05	1
L43	Power Connector (Han 25D)	Critical	2	6.036E-05	1
L43	Sub-manifold	Critical	1	2.802E-03	2
L43	Main Manifold	Critical	1	1.509E-03	2
L43	Interlock Male (IV SHIELD)	Critical	4	8.802E-06	12
L43	Interlock Female (IV SHIELD)	Critical	4	2.263E-05	12
L43	Core Main (IV SHIELD)	Critical	1	2.641E-04	1
L43	Stripper A (IV SHIELD)	Critical	4	5.187E-06	5
L43	Stripper B (IV SHIELD)	Critical	2	6.602E-06	5

Table 5.7: Inventory Parameters for Product E L44/L45 Mold Low Volume Items

Mold Number	Spare Component	Inventory Class	Reorder Quantity,	$\frac{QIc}{DB}$	Reorder Point
L44/L45	Cal rod 230V/1250W (Ø8.2)	Critical	1	1.515E-04	2
L44/L45	Cartridge heater 230V/250W (Ø9.55 X 63.5)	Critical	6	1.597E-05	3
L44/L45	Thermocouple Type J (Ø1.5 X 120)	Critical	5	9.499E-05	2
L44/L45	Male Rectangular Inter lock (75 X 42 X 20)	Critical	4	7.482E-04	2
L44/L45	Female Rectangular Inter lock (75 X 28.5 X 20)	Critical	4	8.230E-04	2
L44/L45	Male Rectangular Inter lock (100 X 65 X 25)	Critical	4	1.291E-03	2
L44/L45	Female Rectangular Inter lock (100 X 45 X 25)	Critical	4	1.436E-03	2
L44/L45	Guide Pillar (Z00/96/32 X 95)	Critical	5	1.033E-04	2
L44/L45	Guide Bush (Z10/96/32)	Critical	7	1.500E-04	2
L44/L45	EJ. Guide Pillar (Leader Pin) GPH 25-	Non-critical	10	7.248E-03	1
L44/L45	EJ. Leader Bushings EGBB 25-20	Non-critical	7	6.396E-03	1
L44/L45	Sub-manifold	Critical	1	1.489E+00	2
L44/L45	Main Manifold	Critical	1	1.641E+01	2
L44/L45	Insert Core (PIVOT SHIELD) (503A)	Critical	2	1.689E-02	7
L44/L45	Core Local 503B	Critical	2	8.549E-03	9
L44/L45	Core Local 511 – Tail Insert	Critical	1	4.255E-01	1
L44/L45	Core Local 504 A&B	Critical	1	1.520E-02	3
L44/L45	Main Core Insert 501	Critical	1	7.346E-02	2

The above figures are derived based on the following decision rules:

- If there is no usage data available from the past 4 years to forecast future demand, the reorder quantity is set to be 1 with the demand set to be 1 every 4 years. This is the lowest possible demand given the data from the company.

The inventory parameters for the non-critical, low volume items are differentiated from the critical, low volume items; in particular their backorder costs are assumed to be 0.13 times of total backorder costs relative to the critical, low volume items.

5.2.4 Low Volume Items Discussion

The backorder cost is a key determinant of the reorder point of each spare component. It is reasonable to calculate this based on the cost of no production while the mold is waiting for the part to arrive in order to carry out repairs. This cost is based on the cost of lost sales due to the part not being produced for sale. The calculation is illustrated for the Product E Needle Shield mold given the replenishment lead time of 2 weeks for a spare component:

Average output per week for one mold: 4,078,298 parts

Cost per batch of 1000 Product E products: S$130

Backorder cost over 2 weeks: 2*(4,078,298/1000)*130 = $1,060,357

However, this methodology makes use of broad assumptions and discounts the effect of several other factors which might factor into a backorder cost. These include the cost of expediting the delivery of the spare component which might or might not be greater than the cost of no production over the replenishment lead time. Furthermore, the cost of lost sales might be greater if the customer does not place any subsequent order as a result of not receiving the finished products within their specified lead time. The cost of lost sales could also be lower if the selling price to the customer is discounted to reflect the lower service level. From a general point of view, the method used to calculate backorder cost in this study is suitable in providing a figure as a guideline to use in the framework introduced.

We might also be interested to determine the impact of changes in the backorder cost on the reorder point. This might indicate how much attention should be devoted to ensuring the accuracy of the backorder cost. We consider a range of values for each variable in the term $\frac{QIc}{DB}$, with the exception of I which is fixed, which characterize more than 95% of the items in this category. The figures are given in Table 5.8 below. This will give us the maximum and minimum possible value of $\frac{QIc}{DB}$ and $\hat{x}_L$. We will use these values to compare the sensitivity of the reorder point to the backorder cost:

Table 5.8: Min and Max value of variables in $\frac{QIc}{DB}$

Variable	**Min**	**Max**
Reorder quantity, Q	1	10
Unit variable cost, c	20	2000
Inventory carrying cost, I	0.2	
Demand rate (year), D	0.25	10
Replenishment lead time (months), L	0.5	2
Average lead time demand, $\hat{x}_L$.	0.009615	1.538462

For each different type of mold we assume a range of ±0.2 of average lost production to give us the relevant range of backorder costs. In Table 5.9 and Table 5.10 below, we list the range of backorder costs, and the corresponding values of the term $\frac{QIc}{DB}$ and the reorder point.

For a minimum average lead time demand of 0.009615:

Table 5.9: Sensitivity analysis of B (min $\hat{x}_L$)

Terms	**LL Hub Mold**		**Needle Shield Mold**		**Safety Shield Mold**	
	Min	Max	Min	Max	Min	Max
B	$55,688	$334,129	$848,286	$5,089,716	$273,716	$1,642,299
$\frac{QIc}{DB}$	0.28731	1.1971E-06	0.01886	7.8590E-08	0.05845	2.4356E-07
s	0	2	1	2	1	2

For a maximum average lead time demand of 1.538462:

Table 5.10: Sensitivity analysis of B (max $\hat{x}_L$)

Terms	LL Hub Mold		Needle Shield Mold		Safety Shield Mold	
	Min	Max	Min	Max	Min	Max
B	\$55,688	\$334,129	\$848,286	\$5,089,716	\$273,716	\$1,642,299
$\frac{QIc}{DB}$	0.28731	1.1971E-06	0.01886	7.8590E-08	0.05845	2.4356E-07
s	3	9	6	9	5	9

As shown in the tables above, at a low value of average lead time demand, the reorder point does not change much as the value of the backorder cost changes. However, at a high value of average lead time demand, the reorder point changes significantly as the value of the backorder cost changes.

Lastly, when we compare the parameters proposed by the inventory model against the current practice, note that a majority of the components have reorder points and reorder quantities that are higher than the recommended levels provided by the inventory model. Otherwise, where the reorder point is not higher than the recommended parameter, it would be set to 0. The comparison is shown in Appendix G.

This indicates that the company can probably realise savings on inventory costs by implementing the parameters of reorder point and reorder quantity recommended by the inventory model. In those cases where the reorder point is set to 0, although inventory costs are reduced, once the part is needed for the repair of the mold, this would have adverse effects on the service level of the Tool Room in carrying out the repair.

5.2.5 Commodities

The demand for these items is inferred from the purchasing data due to the lack of records of the usage of such items. These are used to derive the reorder quantity and the reorder point which are similar to the equivalent time supply for each item. The parameters for each Product E mold are provided in Table 5.11, Table 5.12 and Table 5.13:

Table 5.11: Inventory Parameters for Product E LL Mold Commodities

Mold Number	Spare Component	Time Supply (s & Q)	Mold Number	Spare Component	Time Supply (s & Q)
Hub LL	Sleeve	4	Hub LL	Spring Washer	4
Hub LL	Spring Holder	2	Hub LL	M4x15 HT Allen Cap Screw	300
Hub LL	Retaining Ring	4	Hub LL	M5 x 40 HT Allen Cap Screw	100
Hub LL	Shoulder Bolts	2	Hub LL	M6 x 50 HT Allen Cap Screw	100
Hub LL	Spring (SWR 10.5 - 15)	2	Hub LL	M4 x 25 HT Allen Cap Screw	100
Hub LL	Spring (TF12 X 20)	4	Hub LL	M5 x 18 HT Allen Cap Screw	500
Hub LL	Spring (TF25 X 35)	4	Hub LL	M3 x 6 HT CSK Screw	100
Hub LL	Wire Clamp	5	Hub LL	M5 x 12 HT CSK Screw	100
Hub LL	Wire Connector	10	Hub LL	M4 x 8 HT CSK Screw	400
Hub LL	Cavity Insert Back Plate	4	Hub LL	M4 x 10 HT CSK Screw	400
Hub LL	Slide Stopper	4	Hub LL	M4 x 5 HT Set Screw	100
Hub LL	O-ring (Z98/5.8/1.5)	200	Hub LL	Dia 5 x 35 Shoulder Screw	30
Hub LL	Washer (Ø9.0 x 2.5)	2	Hub LL	Dia 5 x 40 Shoulder Screw	30
Hub LL	Washer (Ø17.5 x 3)	2	Hub LL	Viton O Ring (ID7 x 1.5)	400
Hub LL	Washer (Ø15.0 x 2.5)	2	Hub LL	Viton O Ring (ID10 x 1.5)	400
Hub LL	Washer (Ø34.6 x 3)	2	Hub LL	Set Screw (Ball Catch Stopper)	10
Hub LL	Washer (Ø9 x 2)	2	Hub LL	Ball Catch	50
			Hub LL	Stainless Steel Plug M8x1.5x6mm	10

Table 5.12: Inventory Parameters for Product E L43 Mold Commodities

Mold Number	Spare Component	Time Supply (s & Q)	Mold Number	Spare Component	Time Supply (s & Q)
L43	Brass Plug	140	L43	S.H.C Screw (M6 X 30)	2
L43	Dowel Pin (Ø16 X 80)	4	L43	S.H.C Screw (M6 X 20)	12
L43	Dowel Pin (Ø12 X 50)	8	L43	S.H.C Screw (M6 X 14)	8
L43	Dowel Pin (Ø12 X 40)	4	L43	S.H.C Screw (M5 X 16)	100
L43	Dowel Pin (Ø8 X 24)	120	L43	S.H.C Screw (M5 X 14)	10
L43	Dowel Pin (Ø8 X 22)	2	L43	S.H.C Screw (M5 X 12)	100
L43	Dowel Pin (Ø6 X 18)	32	L43	S.H.C Screw (M4 X 12)	8
L43	Flat Head Screw (M8 X 20)	150	L43	S.H.C Screw (M4 X 8)	600
L43	Flat Head Screw (M5 X 14)	24	L43	S.H.C Screw (M3 X 25)	600
L43	Shoulder Screw (Z38/16 X 30)	12	L43	S.H.C Screw (M3 X 12)	600
L43	S.H.C Screw (M8 X 20)	96	L43	S.H.C Screw (M3 X 5)	600
L43	S.H.C Screw (M16 X 60)	2	L43	S.H.C Screw (M10 X 35)	4
L43	S.H.C Screw (M16 X 110)	12	L43	S.H.C Screw (M12 X 170)	5
L43	S.H.C Screw (M12 X 60)	4	L43	M3 x 8 HT CSK Screw	600
L43	S.H.C Screw (M10 X 85)	12	L43	M3 x 10 HT CSK Screw	400
L43	S.H.C Screw (M8 X 80)	16	L43	O-Ring (Ø18 X 2.4)	20

L43	S.H.C Screw (M8 X 60)	12	L43	O-Ring (Ø14 X 2)	20
L43	S.H.C Screw (M8 X 40)	9	L43	O-Ring (Ø8 X 2)	200
L43	S.H.C Screw (M8 X 35)	8	L43	O-Ring (Ø6 X 2)	200
L43	S.H.C Screw (M8 X 30)	24	L43	Viton O Ring (ID7 X 1.5)	400
L43	S.H.C Screw (M8 X 25)	10	L43	Viton O Ring (ID8 X 1.5)	400
			L43	Viton O Ring (ID8.5 X 1.5)	100

Table 5.13: Inventory Parameters for Product E L44/L45 Mold Commodities

Mold Number	Spare Component	Time Supply (s & Q)	Mold Number	Spare Component	Time Supply (s & Q)
L44/L45	Shoulder Bolt (Z38/12 X 40)	60	L44/L45	SHCS (Z30 / 6 X 25)	4
L44/L45	Brass Plug (3/8" NPT)	16	L44/L45	SHCS (Z30 / 5 X 10)	8
L44/L45	SHCS (M16 X 140)	6	L44/L45	SHCS (Z30 / 5 X 16)	8
L44/L45	SHCS (M10 X 50)	4	L44/L45	CSK (Z33 / 6 X 20)	4
L44/L45	SHCS (M16 X 120)	8	L44/L45	CSK (Z33 / 8 X 30)	4
L44/L45	SHCS (M10 X 35)	8	L44/L45	SHCS (Z31/20 X 60)	2
L44/L45	SHCS (M16 X 50)	8	L44/L45	SHCS (Z30/10 X 25)	8
L44/L45	SHCS (Z30 / 8 X 50)	12	L44/L45	SHCS (Z30/10 X 70)	8
L44/L45	SHCS (Z30 / 10 X 35)	8	L44/L45	Dowel (Z26/10 X 40)	8
L44/L45	SHCS (Z30 / 10 X 30)	8	L44/L45	O' Ring (Z98/13.9/2.4)	140
L44/L45	SHCS (Z30 / 8 X 30)	24	L44/L45	"O" Ring (ID:Ø6.0, TH:Ø1.50)	300
L44/L45	SHCS (Z30 / 6 X 35)	360	L44/L45	Dowel Pin (Z25/6 X 14)	8
L44/L45	SHCS (Z30 / 8 X 50)	16	L44/L45	O-Ring (ID:Ø4.1, TH:Ø1.50)	700
L44/L45	SHCS (Z30 / 10 X 25)	16	L44/L45	Ejector Pin (Z41/3X 200)	60
L44/L45	SHCS (Z30 / 6 X 25)	2	L44/L45	Stepped Ejector Pin (Z44/1.2 X 160)	100
L44/L45	SHCS (Z30 / 8 X 50)	24	L44/L45	Stepped Ejector Pin (Z44/1.4 X 160)	60

The above quantities are determined based on the following decision rules:

- If past purchasing data in available in previous years, the product of the demand rate and the cost of the spare component is used to obtain the total value of the inventory over the period of 1 year (Dc). This is compared to the relevant time supply in table 4.2 in the Methodology chapter.
- If there is no purchasing data available, the quantity used is equivalent to the number of that particular component present in the mold. This quantity would be subject to

the minimum order quantity from the supplier, which was not specified in this study. The lack of purchasing data could be due to the inconsistent recording of such information previously or the lack of a need for replacement of that component.

5.2.6 Commodities Discussion

The management of commodities should be kept as simple and straightforward as possible. From the results shown, the recommended inventory policy seems to be able to accomplish this. Where purchasing data is available, the established time supplies indicate an appropriately large amount of inventory kept on-hand, depending on the cost of the item. This would alleviate the need to monitor the stock of inventory closely as there will be ample supplies available for use at anytime. Furthermore, the cost is not significant, thus holding on to large quantities will not result in a prohibitive cost to the company.

The current inventory policy in use involves arbitrarily setting the reorder quantity and reorder point according to the experience of the TS. In general, these items are only ordered when they are deemed to be needed in the near future, such as 2 to 4 weeks in advance. The reorder quantities also vary according to individual items and could either be much more or much less than the derived parameters with the recommended policy.

For approximately 60% of the commodity items, as past purchasing data is not available, the figures given are the minimum amounts needed on-hand at any point in time. However, as these quantities are odd amounts, the on-hand inventory would depend on the minimum order quantity from suppliers.

5.3 Cost Analysis of Inventory Policy

The benefits of implementing the recommended inventory policy are quantified in this section. The aim of this study is to assist the Tool Room department in improving on the service level of providing spare components for repair activities and reducing inventory costs from the derivation of optimal inventory levels which are generally lower than the levels set currently based on the experience of the end users.

It is difficult to quantify exactly the level of improvement on the current service levels as past usage data did not record instances when spare parts were not available during repair activities. Instead, cavities in the mold were blocked and it was left to operate at less than 100% capacity on the production line while the parts were procured. Through interviews with the end users involved in repair activities, it is verified that previous service levels were not satisfactory and nowhere above the 90% range. In aiming to reach a target 97.5% no stockout service level, the recommended inventory policy would be a visible improvement on current practices.

5.3.1 Reduction of Inventory Costs

We focus instead on the potential benefits of reducing inventory costs. This is done by deriving the projected inventory costs of using the recommended inventory policy and comparing it against the current estimated inventory costs over the period of 12 months.

Inventory costs are composed of three components. These are the ordering cost, the inventory carrying cost and the cost of procuring inventory. Together, these components make up the total inventory cost function. The relationship as a function of inventory variables is given below:

$$\textit{Ordering cost: } \frac{AD}{Q}$$

$$\textit{Inventory carrying cost: } \left(\frac{Q}{2} + s - \hat{x}_L\right)(Ic)$$

$$\textit{Procurement cost: } Dc$$

$$\textit{Total inventory cost function: } C_{inv} = \frac{AD}{Q} + \left(\frac{Q}{2} + s - \hat{x}_L\right)(Ic) + Dc$$

Where, A = Order fixed cost (S$)

D = Demand rate over time (units/year)

Q = Reorder quantity (units)

s = Reorder point (units)

I = Carrying cost of inventory (Cost per S$/year)

c = Unit variable cost (S$/unit)

$\hat{x}_L$ = Demand over lead time (units)

We do not include the cost calculation for commodities as the usage of these items was not recorded in historical data. However, the change in costs for these items is not significant compared to low volume and high volume items as their unit variable cost is relatively much lower.

The total inventory costs incurred by the company over one year currently stands at $423.6K. After implementing the inventory policy in this study, the estimated total inventory costs will be $384.9K. Therefore, the estimated eventual cost savings that the company would potentially enjoy is $38.7K. This is a 9.13% decrease in current total inventory costs. It should be noted that in the current inventory policy, certain items are not reordered. This would have a negative impact on service level even though inventory costs are reduced as these components are not ordered. Therefore, the cost savings should be considered in conjunction with the improvement in service level of at least 10%. Backorder costs of not having the spare component on-hand to carry out repairs were also not included in this calculation which could also be potentially very significant. The estimated backorder cost per week is S$34.8K for the Product E Hub LL molds, S$530.2K for the Product E Needle Shield mold and S$171.1K for the Product E Safety Shield mold. Many of the spare components have an replenishment lead time exceeding one week.

The cost savings calculated in this section only applies to the spare components used in the repair for the Product E molds. If the inventory policy proposed in this study is applied to the other value streams, the potential cost savings would be proportionally higher as well.

6 Recommendations and Future Work

6.1 Recommendations

6.1.1 Inventory Categorization

The management should utilize the frameworks provided in this study for the categorization of spare component inventory used by the Tool Room. These include the Inventory Tree framework that groups spare components according to usage rates and the Analytical Hierarchy Process (AHP) which provides a quantitative and consistent method of separating low volume items into critical components and non-critical components. These act as a reference for a more structured management of mold spare component inventory as compared to the current system which has a non-existent categorization process. In addition, the Tool Room should properly define the parts in their molds which are defined as spare components and draw up a BOM as well. This would aid in the inventory categorization process.

Following the application of these frameworks to the spare components for the Product E molds, the management should phase in the use of these frameworks for the spare components of molds from the other value streams as well. The categorization should similarly be based accordingly on the category characteristics for low volume items, which are split between critical and non-critical components, high volume items and commodities. Doing so will allow the management to determine which components are more important to them. I.e. represent a high proportion of total inventory value, and thus focus more attention on these components. In comparison to the current system, spare component inventory can thus be systematically managed and inventory levels optimized, resulting in lower costs and enabling the Tool Room to stay within its allocated budget.

6.1.2 Inventory Modelling

The inventory models introduced in this study should be applied to the relevant categories of spare components from the molds of the other value streams once the categorization frameworks have been applied. They will allow the management of the company to utilize a proper system to derive inventory parameters to improve the inventory management system. The current system relies on the intuition of each TS from the individual value streams. This has several drawbacks. Each decision made by the TS regarding how much inventory to buy and how much to keep in stock is arbitrary and prone to misjudgement. There will inevitably be bias in such decisions. For example, a surge in usage of a low volume item would create a stockout situation since the TS did not originally have much inventory in stock. Following such an incident, the TS would order a relatively large amount of that particular item. Since the item traditionally experiences low usage, the ordered parts would be considered excess inventory and will incur unnecessary costs.

Another drawback is that such knowledge would be accumulated after a long period of work. Not many TS in the Tool Room have more than 5 years of working experience, thus they are not able to make an accurate prediction of demand based on past working experience. Furthermore, once any of the TS leaves the company, new employees would not have such knowledge to rely on.

Therefore, the derived inventory reorder quantities and reorder points listed in the Results and Discussion section should be used by the Tool Room and the Tool Crib. They would serve as a guideline to the amount of inventory to order and to keep in stock. The actual figures that are used for purchasing purposes could be modified slightly in order to facilitate the purchasing operations of the company. For example, meeting the minimum purchase quantities of the supplier to gain a discount and increasing the ease of inventory management by rounding odd numbers to more easily managed figures. The methodology outlined in Chapter 4 will provide the method and information required to calculate similar inventory parameters for spare components from other value streams.

Lastly, in order to improve the management of data and to utilize the proposed framework adequately to realise the benefits, it is essential for the company to improve on their data collection methods. The necessary input data are past usage data and purchasing data for each spare component.

6.2 Future Work

6.2.1 Inventory Categorization

The AHP framework could be further developed with more criteria added on or more tiers added. This would allow a more detailed categorization of spare components with different categories of criticality. With the current framework that has been developed, there is a high proportion of total inventory that falls under the low volume and critical items. This could indicate that there is further scope for separating the spare components into different degrees of criticality. By developing a more complex framework, the benefit to the company would be the ability to assign different service levels for the various types of low volume, critical inventory. This would allow the company to manage its inventory costs better.

6.2.2 Inventory Modelling

The main aim of this study is to establish an initial framework which the Tool Room could utilize to improve on the management of its inventory of spare components. Therefore, many assumptions have been made in order to establish guidelines for the inventory parameters that are required. Future work in the following aspects could be done to improve the models used.

Forecasted Demand

A study could be done on the different methods to forecast demand based on the characteristics of the spare components and the molds that they are used in. More complex methods could be examined to determine which is more relevant in capturing inherent characteristics of demand for spare component inventory. In addition, other forecasting models which incorporate the forecast of trends should be tried. There is a possibility that a correlation exists between the age of the mold and usage of the spare components.

Inventory Costs

A more in-depth investigation can be done to define fixed ordering costs, inventory carrying costs and backorder costs. More time and resources are needed to derive a more accurate figure for these variables. The company has previously not tracked these costs.

The models themselves which have been introduced in this study have been applied based on characteristics of the various categories of spare component inventory which correspond to descriptions in the existing literature. More work could be done to examine their exact relevance to the situation in the company which could lead to changes made to the structure of the models to fit the company's unique needs.

7 Conclusion

This thesis created a framework to organize the inventory of spare components for the molds used in production. This categorization is crucial for the utilization of appropriate inventory models to improve inventory management. The thesis also defines these models which allow the company to derive the inventory parameters of reorder quantity, safety stock level and reorder point. Using these parameters would assist the company in making decisions easily and reliably on how much inventory to store and to purchase.

The new inventory management framework also introduces more visibility in managing inventory levels. Whereas there was no previous effort to properly categorize inventory, using this framework allows management to more effectively monitor spare components which are deemed important. These are spare components which have a high inventory value. It is necessary to balance the need to have these spare components for repair activities and the desire to achieve a high service level at the lowest cost possible. Conversely, inventory which has low value or is not considered as critical for repairs require less attention. Thus, less complicated mechanisms of inventory management can be applied to such spare components.

The inventory models introduced for the various categories of spare component inventory provide a quantitative method of determining order quantities and the reorder point. These have been calculated to act as guidelines. The previous arbitrary method of determining these quantities led to much ambiguity as to the "correct" amounts to follow. They also include much human bias and error and do not take into account variability in demand and hidden costs of inventory.

The proposed inventory policy recommended in this study would potentially allow the company to realise significant cost savings as well as improvements in the service level of providing spare components for repair activities. The targeted service level reached with the recommended inventory parameters is 97.5% while the company will be able to reduce their inventory costs for spare components used for the Product E molds by 9.1% per year. This translates to cost savings of $38.7K.

Last but not least, the key to using the framework and models in this study also lies in proper data collection of the usage of spare components during mold repair activities. These have been addressed to some extent in the process improvement of the mold repair process proposed by Lin [3]. The reliability study and preventive maintenance scheduling done by Mohd Fauzi [4] could also improve forecasts of future demand for spare components and will serve to enhance the inventory management practices that were introduced.

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Appendix A1: BOM of Product E LL Hub Mold

Product E Hub LL Mold (L50 to L71)					
S/N	**SAP No.**	**Description**	**Drawing No.**	**Inventory Class**	**Order Lead Time (Weeks)**
1	-	Sprue (Ø22.0 X 23.8)	12	A	4
2	-	Runner Bushing	13	A	4
3	-	Gate Pin (Ø9.6 X 69.40)	14	A	5
4	-	Locating Ring (Ø60.0 X 12.0)	16	A	1
5	-	Sleeve (Ø6.5 X 23.80)	17	D	1
6	-	Spring Holder (Ø6 X 27.5)	19	D	2
7	-	Steel Chase (Ø17 X 13)	22	A	1
8	-	Steel Chase (Ø18 X 14)	23	A	1
9	-	Return Pin (Ø12 X 65)	25	A	2
10	-	Ejector Pin (Ø3.5 X 100)	27	A	1
11	-	Retaining Ring (Ø24.2 X 1.2)	34	D	1
12	-	Shoulder Bolts (M4/Ø6 X 30)	35	D	1
13	-	Spring (SWR 10.5 - 15 - MISUMI)	37	D	1
14	-	Spring (TF12 X 20 - S'pore Spring)	38	D	1
15	-	Spring (TF25 X 35 - S'pore Spring)	39	D	1
16	-	Coil Heater (ID 19 X OD 24 X L 40)	40	A	3
17	-	Wire Clamp (11 X 17 X 3.8)	42	D	1
18	-	Cavity Support Pillar (M5/Ø7.8 X 17)	48	A	2
19	-	Wire Connector	50	D	1
20	-	Cavity Plate (158 X 130 X 15)	100	A	3
21	-	Cavity Ejector Plate (148 X 40 X 7)	101	A	3
22	-	Cavity Ejector Backplate (148 X 40 X 7)	102	A	3
23	-	Angular Cam (SQ10 X 50)	104	A	1
24	-	Angular Cam Clamp (16 X 10 X 4)	105	A	1
25	-	Cavity Return Pin (Ø6 X 25)	108	A	5
26	-	Cavity Insert Back Plate (48 X 13 X 4)	110	D	3
27	-	Ball cage (765.06.150 - AGATHON)	111	A	1
28	-	Cavity Guide Bush (780.09.150 - AGATHON)	112	A	3
29	-	Cam Wear Plate (78 X 40.23 X 4)	113	A	5
30	-	Stripper Bush (Ø11 X 10)	201	A	3
31	-	Slide Guide Plate (56.5 X 10 X 6)	202	A	3
32	-	Guide Rail (230 X 17.5 X 24.5)	203	A	3
33	-	Slide Stepper	204	D	1
34	-	Core Insert (Ø13 X 38.570)	207	C	2
35	-	Core Holder Plate (Ø55 X 15)	209	A	1
36	-	Stripper Bush Insert (Ø6/Ø8, height = 3.5)	216	A	4
37	-	Slide Insert (11 X 13 X 3.79) (Small Insert)	219	C	2
38	-	Slide Insert (7.477 X 4 X 3)	220	A	1

39	-	Wear Plate Left (128 X 57.5 X 4)	200a	A	1
40	-	Wear Plate Right (128 X 57.5 X 4)	200b	A	1
41	-	Guide Bush (Z10/66/20)	31a	A	4
42	-	Guide Bush (Z10/66/18)	31b	A	4
43	-	Guide Pillar (Z00/36/20 X 115)	32a	A	4
44	-	Guide Pillar (Z00/36/18 X 115)	32b	A	4
45	-	Guide Bush (Z1100W/36 X 20)	33a	A	4
46	-	Guide Bush (Z1100W/36 X 18)	33b	A	4
47	-	O-ring (Z98/5.8/1.5)	36a	D	3
48	-	O-ring (Z98/5.8/1.5)	36b	D	3
49	-	Washer (Ø9.0 x 2.5)	20	D	1
50	-	Washer (Ø17.5 X 3)	21	D	1
51	-	Washer (Ø15.0 x 2.5)	18	D	1
52	-	Washer (Ø34.6 X 3)	24	D	1
53	-	Washer (Ø9 X 2)	28	D	1
54	-	Spring Washer (Ø9.9 X 1.6)	29	D	1
55	-	M4 x 15 HT Allen Cap Screw	-	D	1
56	-	M5 x 40 HT Allen Cap Screw	-	D	1
57	-	M6 x 50 HT Allen Cap Screw	-	D	1
58	-	M4 x 25 HT Allen Cap Screw	-	D	1
59	-	M5 x 18 HT Allen Cap Screw	-	D	1
60	-	M3 x 6 HT CSK Screw	-	D	1
61	-	M5 x 12 HT CSK Screw	-	D	1
62	-	M4 X 8 HT CSK Screw	-	D	1
63	-	M4 X 10 HT CSK Screw	-	D	1
64	-	M4 x 5 HT Set Screw	-	D	1
65	-	Dia 5 X 35 Shoulder Screw	-	D	1
66	-	Dia 5 X 40 Shoulder Screw	-	D	1
67	-	Viton O Ring (ID7 X 1.5)	-	D	3
68	-	Viton O Ring (ID10 X 1.5)	-	D	3
69	-	Set Screw (Ball Catch Stopper)	-	D	1
70	-	Safety Needle Epoxy Pin G30	-	A	2
71	-	Bush Carbide Gauge 30	-	A	5
72	-	Sleeve Carbide Gauge 30	-	A	8
73	-	Ball Catch	-	D	1
74	-	Manifold	10	A	7
75	-	Stainless Steel Plug M8x1.5x6mm	-	D	1
76	-	Cartridge Heater	-	A	3
77	-	Thermocouple (B31-13)(Ø1.5 X 150)	-	A	2
78	4018483	PINS EPOXY GAUGE 18	-	C	2
79	4018484	PINS EPOXY GAUGE 21	107a	C	2
80	4018485	PINS EPOXY GAUGE 22	107b	C	2
81	4018486	PINS EPOXY GAUGE 23 (ABG)	107c	C	2
82	4018487	PINS EPOXY GAUGE 25	107d	C	2
83	4018488	PINS EPOXY GAUGE 27	-	C	2
84	4018489	BUSH CARBIDE GAUGE 18	-	C	5
85	4018490	BUSH CARBIDE GAUGE 21	210a	C	5
86	4018491	BUSH CARBIDE GAUGE 22	210b	C	5
87	4018492	BUSH CARBIDE GAUGE 23	210c	C	5

88	4018493	BUSH CARBIDE GAUGE 25	210d	C	5
89	4018494	BUSH CARBIDE GAUGE 27	-	C	5
90	4018495	SLEEVE CARBIDE GAUGE 21	211a	C	8
91	4018496	SLEEVE CARBIDE GAUGE 22	211b	C	8
92	4018497	SLEEVE CARBIDE GAUGE 23	211c	C	8
93	4018498	SLEEVE CARBIDE GAUGE 25	211e	C	8
94	4018499	SLEEVE CARBIDE GAUGE 27	-	C	8
95	4018500	INSERT GATE	206	C	4
96	4018502	PIN CORE	215	A	2
97	4018503	CAVITY & INSERTS GAUGE18	106	A	4
98	4018504	INSERT CAVITY	106	A	2
99	4123980	INSERT SLIDE	213	A	4
100	4123981	BLOCK PRESSURE	109	A	5
101	4123982	INSERT HOLDER SLIDE	212	A	5

Appendix A2: BOM of Product E L43 Mold

L43 IV Shield 128 Cavity Mold					
S/N	SAP No.	Description	Drawing No.	Inventory Class	Order Lead Time (Weeks)
1	-	Sprue Bush	22	A	3
2	-	HR Sleeve (Ø16.00 X 16.00)	27	B	3
3	-	Cal Rod Heater (230V/1000W)	30	A	5
4	-	Cartridge Heater (230V/600W) (Ø12.7 X 76.2)	31	A	3
5	-	Thermocouple Type J (Ø1.50 X 150)	32	A	5
6	-	Cavity Insert (Ø19.0 X 41.20)	39	A	4
7	-	Gate Insert (Ø20 X 5.311)	40	A	3
8	-	Cavity Insert Plate (150 X 150 X 47.00)	42	B	1
9	-	Brass Plug (For Bubbler Tube)	49	D	1
10	-	Wear Plate (51.0 X 57.0 X 8.00)	53	B	1
11	-	Leader Pin (Z03/66/32X175)	67	B	1
12	-	Leader Pin (Z03/66/30X175)	68	B	1
13	-	Leader Bushing (Z10W/136/32)	69	B	1
14	-	Leader Bushing (Z10W/136/30)	70	B	1
15	-	Leader Bushing (Z11W/46/32)	71	B	1
16	-	Leader Bushing (Z11W/46/30)	72	B	1
17	-	Dowel Pin (Ø16 X 80)	76	D	1
18	-	Dowel Pin (Ø12 X 50)	77	D	1
19	-	Dowel Pin (Ø12 X 40)	78	D	1
20	-	Dowel Pin (Ø8 X 24)	79	D	1
21	-	Dowel Pin (Ø8 X 22)	80	D	1
22	-	Dowel Pin (Ø6 X 18)	81	D	1
23	-	Flat Head Screw (M8 X 20)	83	D	1
24	-	Flat Head Screw (M5 X 14)	84	D	1
25	-	Shoulder Screw (Z38/16 X 30)	92	D	1
26	-	S.H.C Screw (M8 X 20)	94	D	1
27	-	S.H.C Screw (M16 X 60)	97	D	1
28	-	S.H.C Screw (M16 X 110)	98	D	1
29	-	S.H.C Screw (M12 X 60)	99	D	1
30	-	S.H.C Screw (M10 X 85)	100	D	1
31	-	S.H.C Screw (M8 X 80)	101	D	1
32	-	S.H.C Screw (M8 X 60)	102	D	1
33	-	S.H.C Screw (M8 X 40)	103	D	1
34	-	S.H.C Screw (M8 X 35)	104	D	1
35	-	S.H.C Screw (M8 X 30)	105	D	1
36	-	S.H.C Screw (M8 X 25)	106	D	1
37	-	S.H.C Screw (M6 X 30)	107	D	1
38	-	S.H.C Screw (M6 X 20)	108	D	1
39	-	S.H.C Screw (M6 X 14)	109	D	1

40		S.H.C Screw (M5 X 16)	-	D	1
41	-	S.H.C Screw (M5 X 14)	110	D	1
42	-	S.H.C Screw (M5 X 12)	111	D	1
43	-	S.H.C Screw (M4 X 12)	112	D	1
44	-	S.H.C Screw (M4 X 8)	-	D	1
45	-	S.H.C Screw (M3 X 25)	-	D	1
46	-	S.H.C Screw (M3 X 12)	113	D	1
47	-	S.H.C Screw (M3 X 5)	-	D	1
48	-	S.H.C Screw (M10 X 35)	114	D	1
49	-	S.H.C Screw (M12 X 170)	115	D	1
50	-	M3 x 8 HT CSK Screw	-	D	1
51	-	M3 x 10 HT CSK Screw	-	D	1
52	-	O-Ring (Ø18 X 2.4)	122	D	3
53	-	O-Ring (Ø14 X 2)	123	D	3
54	-	O-Ring (Ø8 X 2)	124	D	3
55	-	O-Ring (Ø6 X 2)	125	D	3
56	-	Viton O Ring (ID7 X 1.5)	-	D	3
57	-	Viton O Ring (ID8 X 1.5)	-	D	3
58	-	Viton O Ring (ID8.5 X 1.5)	-	D	3
59	-	Thermocouple Connector (Han 40D)	134	A	2
60	-	Power Connector (Han 25D)	135	A	2
61	-	Sub-manifold	25	A	7
62	-	Main Manifold	18	A	7
63	4123973	INTERLOCK MALE (IV SHIELD)	57	A	3
64	4123974	INTERLOCK FEMALE (IV SHIELD)	58	A	3
65	4123975	PINS GATE (IV SHIELD)	28	C	5
66	4123976	PINS SLEEVE GATE (IV SHIELD)	29	C	5
67	4123983	CORE MAIN (IV SHIELD)	36	A	2
68	4123984	STRIPPER A (IV SHIELD)	37	A	8
69	4123985	STRIPPER B (IV SHIELD)	38	A	8

Appendix A3: BOM of Product E L44/L45 Mold

L44 Pivot Shield 64 Cavity Mold					
S/N	SAP No.	Description	Drawing No.	Inventory Class	Order Lead Time (Weeks)
1	-	Gate Pin Ampco 940 (Ø11.95 X 33.00)	4	C	2
2	-	Melt flow bushing W720 (Ø12.05 X 10.70)	5	C	2
3	-	Cal rod 230V/1250W (Ø8.2)	12	A	5
4	-	Cartridge heater 230V/250W (Ø9.55 X 63.5)	13	A	3
5	-	Thermocouple Type J (Ø1.5 X 120)	15	A	2
6	-	Male Rectangular Inter lock (75 X 42 X 20)	18	A	3
7	-	Female Rectangular Inter lock (75 X 28.5 X 20)	19	A	3
8	-	Male Rectangular Inter lock (100 X 65 X 25)	20	A	3
9	-	Female Rectangular Inter lock (100 X 45 X 25)	21	A	3
10	-	Shoulder Bolt (Z38/12 X 40)	40	D	2
11	-	Guide Pillar (Z00/96/32 X 95)	41	A	3
12	-	Guide Bush (Z10/96/32)	42	A	3
13	-	EJ. Guide Pillar (Leader Pin) GPH 25-140	46	B	1
14	-	EJ. Leader Bushings EGBB 25-20	47	B	1
15	-	Brass Plug (3/8" NPT)	54	D	1
16	-	SHCS (M16 X 140)	55	D	1
17	-	SHCS (M10 X 50)	56	D	1
18	-	SHCS (M16 X 120)	57	D	1
19	-	SHCS (M10 X 35)	58	D	1
20	-	SHCS (M16 X 50)	59	D	1
21	-	SHCS (Z30 / 8 X 50)	60	D	1
22	-	SHCS (Z30 / 10 X 35)	61	D	1
23	-	SHCS (Z30 / 10 X 30)	62	D	1
24	-	SHCS (Z30 / 8 X 30)	63	D	1
25	-	SHCS (Z30 / 6 X 35)	64	D	1
26	-	SHCS (Z30 / 8 X 50)	65	D	1
27	-	SHCS (Z30 / 10 X 25)	66	D	1
28	-	SHCS (Z30 / 6 X 25)	67	D	1
29	-	SHCS (Z30 / 8 X 50)	68	D	1
30	-	SHCS (Z30 / 6 X 25)	69	D	1
31	-	SHCS (Z30 / 5 X 10)	70	D	1
32	-	SHCS (Z30 / 5 X 16)	71	D	1
33	-	CSK (Z33 / 6 X 20)	72	D	1
34	-	CSK (Z33 / 8 X 30)	73	D	1
35	-	SHCS (Z31/20 X 60)	83	D	1
36	-	SHCS (Z30/10 X 25)	84	D	1
37	-	SHCS (Z30/10 X 70)	85	D	1

38	-	Dowel (Z26/10 X 40)	86	D	1
39	-	O' Ring (Z98/13.9/2.4)	88	D	3
40	-	"O" Ring (ID=Ø6.0, TH=Ø1.50)	-	D	3
41	-	Dowel Pin (Z25/6 X 14)	92	D	1
42	-	"O" Ring (ID=Ø4.1, TH=Ø1.50)	106	D	3
43	-	Ejector Pin (Z41/3X 200)	505	D	3
44	-	Stepped Ejector Pin (Z44/1.2 X 160)	506	D	3
45	-	Stepped Ejector Pin (Z44/1.4 X 160)	507	D	3
46	-	Sub-manifold	-	A	4
47	-	Main Manifold	-	A	7
48	4123977	INSERT CORE (PIVOT SHIELD) (503A)	503A	A	6
49	4468581	INSERTION MAIN CAVITY M101 (L44&L45)	M101	C	2
50	4468582	CORE LOCAL M106-L&R (L44&L45)	M106	C	6
51	4468583	CORE LOCAL 503 (L44 & L45)	503B	A	6
52	4468586	CORE LOCAL 511-TAIL INSERT (L44 & L45)	511	A	2
53	4468587	CORE LOCAL 504 A&B (L44 & L45)	504	A	2
54	4468588	INSERT CAVITY 103 (L44 & L45)	103	C	6
55	4468589	MAIN CORE INSERT 501 (L44 & L45)	501	A	1

Appendix B: % Loading of Molds

Frequency of Usage per Month

	Mold	% Loading	Comments
Product E	Product E Hub Molding (LL): L50 - L71	80.83%	
	Product E Hub Molding (LS): LS1 - LS10	93.67%	
	Product E Needle Shield: L43	65.17%	
	Product E Safety Shield: L44/L45	68.17%	
Product N	Product N Short Shield: L20, L77, L79, L1	56.25%	*L1, L77 not in use*
	Product N Regular Shield: L19, L2	57.17%	**L1 and L2 share the same press; Take L2 as running on dedicated press*
	Product N Hub: L3, L4, L5, L73, L82	56.46%	**L73 not in use*
	Product N Hypoint Shield: L24, L25	55.33%	**L25 not in use*
Product S	Product S 1ml LL: L23, L75, L78	89.47%	**L75 not in use*
	Product S 1ml LS: L6	43.52%	
	Product S 1ml PLG: L13, L81	73.41%	**L13 not in use*
	Product S 3ml BBL: L7, L8, L40	69.52%	
	Product S 3ml PLG: L21, L41	45.14%	
	Product S 5ml BBL: L9, L10, L15	36.39%	
	Product S 10ml BBL: L11, L12, L42	67.33%	
	Product S 10ml PLG: L16	84.17%	
	Product S 20ml BBL: L27	52.99%	
	Product S 20ml PLG: L26	39.20%	
	Product S 50ml BBL: L29	11.96%	
	Product S 50ml PLG: L28	7.84%	
Product U	Product U L30	8.72%	
	Product U L31	20.80%	
	Product U L32	13.25%	
	Product U L33	4.72%	
Product F	Product F F1	80.25%	
	Product F F2	93.92%	
	Product F F3	0.00%	
	Product F F4	0.00%	
	Product F F5	95.40%	
	Product F F6	47.88%	
	Product F F7	31.96%	

Appendix C: Saaty's Intensity of Importance Scale

Saaty's Intensity of Importance Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above non-zero numbers	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then has the reciprocal when compared with *i*	

Source: Saaty, T.L., 1980, "The Analytic Hierarchy Processes," McGraw-Hill, New York.

Appendix D: Derivation of Eigenvalue of Matrix A

Given Matrix A: $\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$ which is imperfect/inconsistent

$(A - \lambda I)w = 0$:

$$(a_{11} - \lambda)w_1 + a_{12}w_2 + a_{13}w_3 = 0$$

$$a_{21}w_1 + (a_{22} - \lambda)w_2 + a_{23}w_3 = 0$$

$$a_{31}w_1 + a_{32}w_2 + (a_{33} - \lambda)w_3 = 0$$

Solutions exist only if the determinant of the coefficient matrix is 0:

$$Det(A - \lambda I) = \begin{bmatrix} a_{11} - \lambda & a_{12} & a_{13} \\ a_{21} & a_{22} - \lambda & a_{23}w_3 \\ a_{31} & a_{32} & a_{33} - \lambda \end{bmatrix} = 0$$

Using cofactor expansion:

$$(a_{11} - \lambda)\begin{bmatrix} a_{22} - \lambda & a_{23}w_3 \\ a_{32} & a_{33} - \lambda \end{bmatrix} - a_{12}\begin{bmatrix} a_{21} & a_{23}w_3 \\ a_{31} & a_{33} - \lambda \end{bmatrix} + a_{13}\begin{bmatrix} a_{21} & a_{22} - \lambda \\ a_{31} & a_{32} \end{bmatrix} = 0$$

Finally, solve for λ. Once the Eigenvalue is obtained, the weights w_1, w_2 *and* w_3 can be derived.

Appendix E: Derivation of Composite Weights and Eigenvalues

Pair wise Comparison of Criteria

			Geometric Mean	Normalized Weights
1	8	5	3.420	0.733
0.125	1	0.250	0.315	0.068
0.2	4	1	0.928	0.199
		Total:	4.663	
		λ =	3.094	

Pair wise Comparison of Modes

1. Replenishment lead time

			Geometric Mean	Normalized Weights
1	0.25	0.111111111	0.303	0.061
4	1	0.166666667	0.874	0.176
9	6	1	3.780	0.763
		Total:	4.956	
		λ =	3.108	

2. Commonality across Molds

			Geometric Mean	Normalized Weights
1	0.5	0.25	0.500	0.136
2	1	0.333333333	0.874	0.238
4	3	1	2.289	0.625
		Total:	3.663	
		λ =	3.018	

3. Importance of Mold

			Geometric Mean	Normalized Weights
1	0.142857	0.111111111	0.251	0.057
7	1	0.5	1.518	0.346
9	2	1	2.621	0.597
		Total:	4.390	
		λ =	3.022	

Appendix F: Inventory Parameters of High Volume Items

		*Without Inventory Model**		*With Inventory Model*	
Mold Number	**Spare Component**	**Reorder Quantity, Q**	**Reorder Point, s**	**Reorder Quantity, Q**	**Reorder Point, s**
L43/L44/L45	Gate Pin	30	20	21	35
L43/L44/L45	Melt Flow Bush	30	20	20	33
L44/L45	Local Core Insert M106	20	12	17	61
L44/L45	Cavity Insert 103	30	10	12	19
L44/L45	Main Cavity Insert M101	10	10	1	4
Hub LL	Gate Insert	4	5	2	7
Hub LL	Core Insert (Ø13 X 38.570)	8	10	6	11
Hub LL	Slide Insert 219 (Small Insert)	16	80	7	12
Hub LL	Pins Epoxy Gauge 18	30	48	11	27
Hub LL	Pins Epoxy Gauge 21	30	48	13	14
Hub LL	Pins Epoxy Gauge 22	30	48	12	10
Hub LL	Pins Epoxy Gauge 23	30	48	14	14
Hub LL	Pins Epoxy Gauge 25	30	48	15	13
Hub LL	Pins Epoxy Gauge 27	30	48	13	11
Hub LL	Bush Carbide Gauge 18	30	48	13	34
Hub LL	Bush Carbide Gauge 21	30	48	12	34
Hub LL	Bush Carbide Gauge 22	30	48	11	24
Hub LL	Bush Carbide Gauge 23	30	48	13	35
Hub LL	Bush Carbide Gauge 25	30	48	12	28
Hub LL	Bush Carbide Gauge 27	30	48	12	30
Hub LL	Sleeve Carbide Gauge 21	30	48	12	34
Hub LL	Sleeve Carbide Gauge 22	30	48	11	24
Hub LL	Sleeve Carbide Gauge 23	30	48	13	35
Hub LL	Sleeve Carbide Gauge 25	30	48	12	28
Hub LL	Sleeve Carbide Gauge 27	30	48	12	30

***Figures highlighted in red indicate that these parameters are higher than those previously adhered to**

Appendix G: Inventory Parameters of Low Volume Items

		*Without Inventory Model**		*With Inventory Model*	
Mold Number	**Spare Component**	**Reorder Quantity, Q**	**Reorder Point, s**	**Reorder Quantity, Q**	**Reorder Point, s**
Hub LL	Sprue (Ø22.0 X 23.8)	10	8	2	3
Hub LL	Runner Bushing	10	2	1	2
Hub LL	Gate Pin (Ø9.6 X 69.40)	10	8	2	3
Hub LL	Locating Ring (Ø60.0 X 12.0)	-	0	1	1
Hub LL	Steel Chase (Ø17 X 13)	-	2	1	1
Hub LL	Steel Chase (Ø18 X 14)	-	2	1	1
Hub LL	Return Pin (Ø12 X 65)	20	4	1	1
Hub LL	Ejector Pin (Ø3.5 X 100)	2	27	1	1
Hub LL	Coil Heater (ID 19 X OD 24 X L 40)	10	10	1	2
Hub LL	Cavity Support Pillar (M5/Ø7.8 X 17)	20	8	1	1
Hub LL	Cavity Plate (158 X 130 X 15)	1	1	1	1
Hub LL	Cavity Ejector Plate (148 X 40 X 7)	-	8	1	2
Hub LL	Cavity Ejector Backplate (148 X 40 X 7)	-	8	1	2
Hub LL	Angular Cam (SQ10 X 50)	4	15	1	1
Hub LL	Angular Cam Clamp (16 X 10 X 4)	-	0	1	1
Hub LL	Cavity Return Pin (Ø6 X 25)	4	6	1	2
Hub LL	Ball cage (765.06.150 - AGATHON)	30	10	1	1
Hub LL	Cavity Guide Bush	30	7	1	2
Hub LL	Cam Wear Plate (78 X 40.23 X 4)	4	8	1	2
Hub LL	Stripper Bush (Ø11 X 10)	-	4	1	2
Hub LL	Slide Guide Plate (56.5 X 10 X 6)	-	0	1	2
Hub LL	Guide Rail (230 X 17.5 X 24.5)	-	0	1	2
Hub LL	Core Holder Plate (Ø55 X 15)	-	2	1	1
Hub LL	Stripper Bush Insert	-	5	1	2
Hub LL	Slide Insert (7.477 X 4 X 3)	16	10	1	1
Hub LL	Wear Plate Left (128 X 57.5 X 4)	8	2	1	1
Hub LL	Wear Plate Right (128 X 57.5 X 4)	4	2	1	1
Hub LL	Guide Bush (Z10/66/20)	4	6	3	6
Hub LL	Guide Bush (Z10/66/18)	12	2	1	2
Hub LL	Guide Pillar (Z00/36/20 X 115)	4	6	3	6
Hub LL	Guide Pillar (Z00/36/18 X 115)	12	2	1	2
Hub LL	Guide Bush (Z1100W/36 X 20)	4	6	3	6
Hub LL	Guide Bush (Z1100W/36 X 18)	12	2	1	2
Hub LL	Safety Needle Epoxy Pin G30	50	48	8	2
Hub LL	Bush Carbide Gauge 30	50	48	8	2
Hub LL	Sleeve Carbide Gauge 30	50	48	8	2
Hub LL	Manifold	-	4	1	3
Hub LL	Cartridge Heater	30	20	6	5
Hub LL	Thermocouple (Ø1.5 X 150)	30	10	2	2
Hub LL	Pin Core (Slider Insert Pin)	4	5	1	1

Hub LL	Cavity Insert Gauge 18	8	17	1	7
Hub LL	Cavity Insert	4	4	1	4
Hub LL	Insert Slide	16	21	1	5
Hub LL	Block Pressure	4	4	1	2
Hub LL	Insert Holder Slide	4	4	1	3
L43	Sprue Bush	-	1	1	2
L43	HR Sleeve (Ø16.00 X 16.00)	10	16	8	2
L43	Cal Rod Heater (230V/1000W)	5	8	1	2
L43	Cartridge Heater (230V/600W)	30	30	5	4
L43	Thermocouple Type J (Ø1.50 X 150)	30	30	3	4
L43	Cavity Insert (Ø19.0 X 41.20)	-	16	1	2
L43	Gate Insert (Ø20 X 5.311)	-	20	1	2
L43	Cavity Insert Plate (150 X 150 X 47.00)	1	1	1	1
L43	Wear Plate (51.0 X 57.0 X 8.00)	-	8	1	1
L43	Leader Pin (Z03/66/32X175)	3	0	3	3
L43	Leader Pin (Z03/66/30X175)	1	0	1	1
L43	Leader Bushing (Z10W/136/32)	3	0	3	3
L43	Leader Bushing (Z10W/136/30)	1	0	1	1
L43	Leader Bushing (Z11W/46/32)	6	0	6	6
L43	Leader Bushing (Z11W/46/30)	2	0	2	2
L43	Thermocouple Connector (Han 40D)	5	4	1	1
L43	Power Connector (Han 25D)	5	4	2	1
L43	Sub-manifold	-	4	1	2
L43	Main Manifold	1	1	1	2
L43	Interlock Male (IV SHIELD)	4	4	4	12
L43	Interlock Female (IV SHIELD)	4	4	4	12
L43	Core Main (IV SHIELD)	10	15	1	1
L43	Stripper A (IV SHIELD)	10	20	4	5
L43	Stripper B (IV SHIELD)	10	20	2	5
L44/L45	Cal rod 230V/1250W (Ø8.2)	5	12	1	2
L44/L45	Cartridge heater 230V/250W (Ø9.55 X 63.5)	40	30	6	3
L44/L45	Thermocouple Type J (Ø1.5 X 120)	30	20	5	2
L44/L45	Male Rectangular Inter lock (75 X 42 X 20)	6	2	4	2
L44/L45	Female Rectangular Inter lock (75 X 28.5 X 20)	6	2	4	2
L44/L45	Male Rectangular Inter lock (100 X 65 X 25)	6	2	4	2
L44/L45	Female Rectangular Inter lock (100 X 45 X 25)	6	2	4	2
L44/L45	Guide Pillar (Z00/96/32 X 95)	8	4	5	2
L44/L45	Guide Bush (Z10/96/32)	4	4	7	2
L44/L45	EJ. Guide Pillar (Leader Pin) GPH 25-	8	4	10	1
L44/L45	EJ. Leader Bushings EGBB 25-20	8	4	7	1
L44/L45	Sub-manifold	-	4	1	2
L44/L45	Main Manifold	-	1	1	2

L44/L45	Insert Core (PIVOT SHIELD) (503A)	4	5	2	7
L44/L45	Core Local 503B	4	5	2	9
L44/L45	Core Local 511 – Tail Insert	2	10	1	1
L44/L45	Core Local 504 A&B	4	10	1	3
L44/L45	Main Core Insert 501	4	5	1	2

*If a dash is indicated, information on past usage and purchasing history is not available.