Preventive Maintenance Scheduling based on Failure Data in a Medical Device Manufacturing Facility

by

Mohammed Faizal B Mohd Fauzi

B.Eng. Mechanical Engineering
Nanyang Technological University, 2008

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

MASTER OF ENGINEERING IN MANUFACTURING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2009

Signature of Author____
Department of Mechanical Engineering
August 18, 2009

Certified by____
Stephen C. Graves
Abraham J. Siegel Professor of Management Science
Thesis Supervisor

Accepted by____
David E. Hardt
Ralph E. and Eloise F. Cross Professor of Mechanical Engineering
Chairman, Committee on Graduate Students

Preventive Maintenance Scheduling based on Failure Data in a Medical Device Manufacturing Facility

By

Mohammed Faizal Mohd Fauzi

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

ABSTRACT

This study was conducted at a medical device production facility where analysis was done on the reliability of Product S barrel molds for the purpose of predicting preventive maintenance (PM) schedule. Pareto Rule was utilized to filter out the defect-types that are causing 80% of the defect occurrences. Defect density was introduced, i.e. the ratio between total number of defects occurred per cavity position to the total types of defects occurring on that same position, as a performance measure to track defects over the mold cavities . Statistical distribution tests on the failure times of the molds were carried out and found that the failure times for the molds differ. Mold failure times follow the lognormal or Weibull distribution. Parameter estimates obtained from probability plots of these distributions were used to obtain the mean-time-to-failure (MTTF) and reliability of the molds. Finally, this study looked into the scheduled preventive maintenance (PM) of the molds based on the current PM task list. Failure times based on individual mold PM task lists that correspond to the mitigation of the priority defect-types, were collected and assigned a statistical distribution. After which, we analyzed the expected number of annual mold failures based on the relevant parameters of the failure times distribution and the various PM scheduling policies proposed, to derive a recommendation on the optimal PM interval to be performed in a year.

Keywords: Preventive maintenance, reliability, injection molding

Thesis Supervisor: Prof. Stephen C. Graves
Title: Abraham J. Siegel Professor of Management Science

The content of this Thesis is modified to protect the identity of the attachment company. The name of company and any proprietary information have been disguised.

ACKNOWLEDGEMENT

My unfeigned gratitude goes to my thesis advisor, Prof. Stephen C. Graves, for his consistent guidance and encouragement throughout the project. His enthusiasm, dedication to excellence, and careful attention to details have been truly inspirational. My thanks go out to Dr. Brian W. Anthony too, for his constructive suggestions and encouragement during the initial phase of the project.

I extend my gratitude to CB Tuas for sponsoring this work. Specifically, I want to thank Mr. Hashim Baba and Mr. Tang Genming, our corporate supervisors, for giving us valuable feedback and suggestions. The help imparted by CB Tool Room staffs have been most valuable and I am sincerely appreciative for their assistance.

I would also like to take this opportunity to offer my heartfelt gratitude to Ms. Jennifer Craig for reviewing this thesis and providing valuable advices on the linguistic aspect.

Finally, a big shout-out to my team-mates, Mr. Gerard Lim and Mr. Manfred Lin, for their dedicated contributions to this project. It has been a pleasure working with them.

I feel that it is by divine intervention that I am able to be in the company of these dedicated people. I sincerely appreciate this God-given opportunity.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

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, Product N, and Product S 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, Product F, 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 are involved in manufacturing through injection molding which are Product S, Product N, Product E, Product F 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 under the care of the Tool Room that are dedicated to each of the VSs.

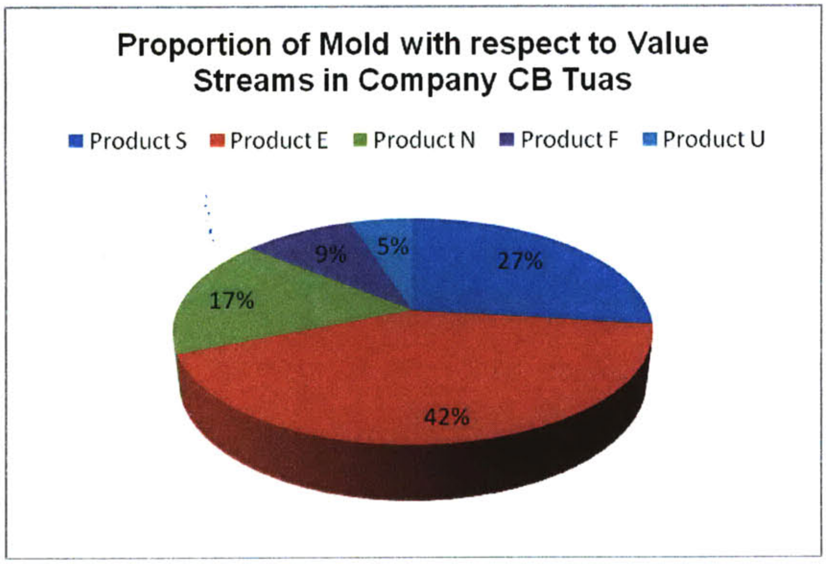


Figure 1.1: Overview of mold proportion by VS

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 of the processes that constitute injection molding.

1.1 Injection Molding Production Process

The medical devices made by CB are comprised of plastic components that are injection molded. The injection-molding 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.

Each 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.

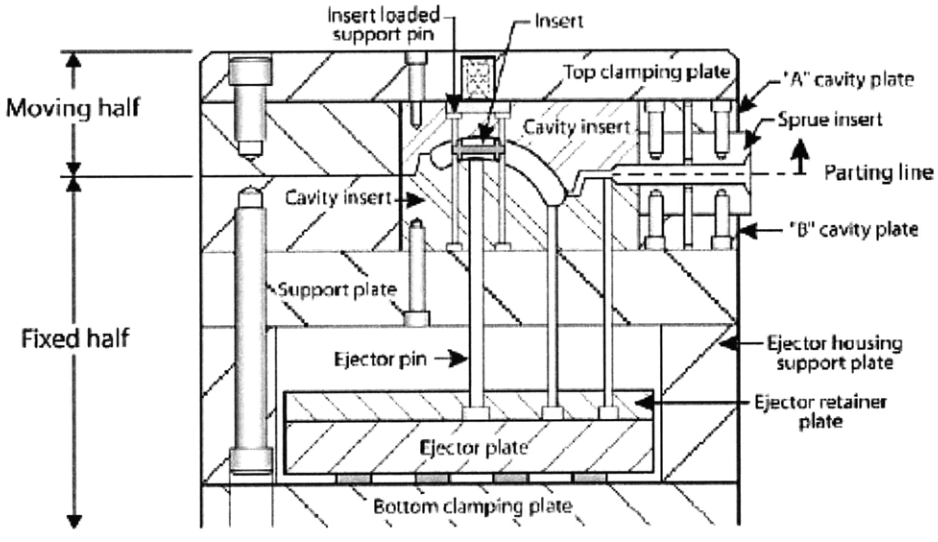


Figure 1.2: A schematic of a mold cross-section [1].

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 few as 4 cavities or as many as 96 cavities per mold. The complex geometry of CB products places 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.

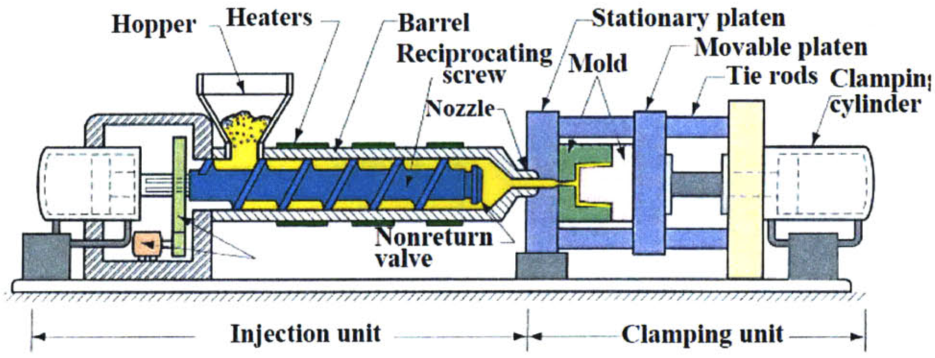


Figure 1.3: An injection molding machine [2].

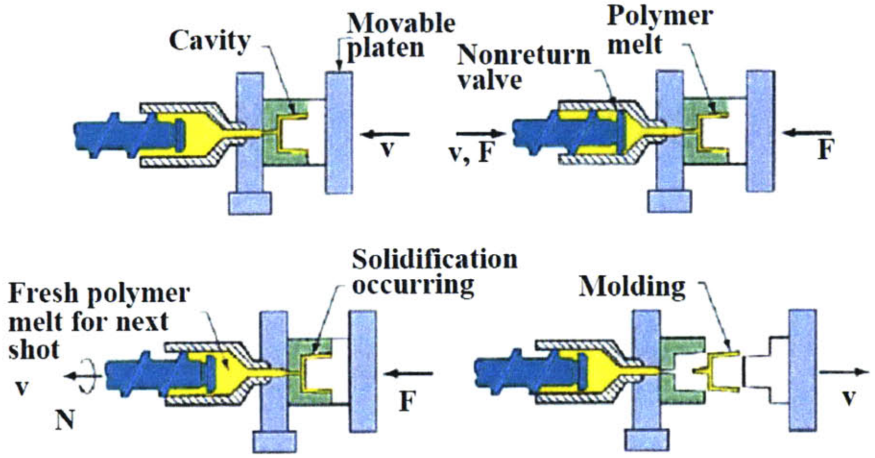


Figure 1.4: An injection molding cycle [2].

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

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

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

2. Solidifying the melt in the mold

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. At this point, the part would have frozen completely into the desired shape.

The above operations determine the 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 parts that make up the products are injection molded. Only the plastic parts are injection molded and then assembled with other non-plastic component to form the final product. The following section highlights the portions of the Product S, Product N, Product E, Product F and Product U which are injection molded and how defects in the plastic parts can affect the downstream production.

1.2 CB Product Types

A 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 Product S manufactured at CB. A Product S typically consists of the barrel, plunger and stopper.

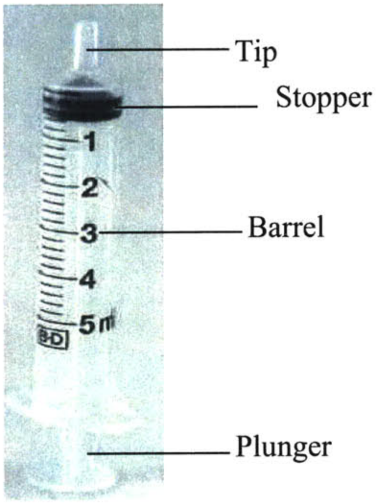


Figure 1.5: Parts of a Product S.

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

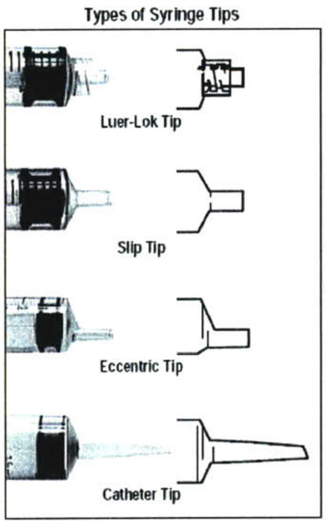


Figure 1.6: The various types of CB hypodermic Product S tip.

All parts of the Product S except the stopper are injection molded. The Tool Room supports the manufacturing operation of these parts by doing repair and maintenance on 22 different types of molds with 7 molds responsible for plungers and the remaining tasked to produce the barrels. 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 Product N hub and a stainless steel cannula. Both the hub and the shield are injection molded.

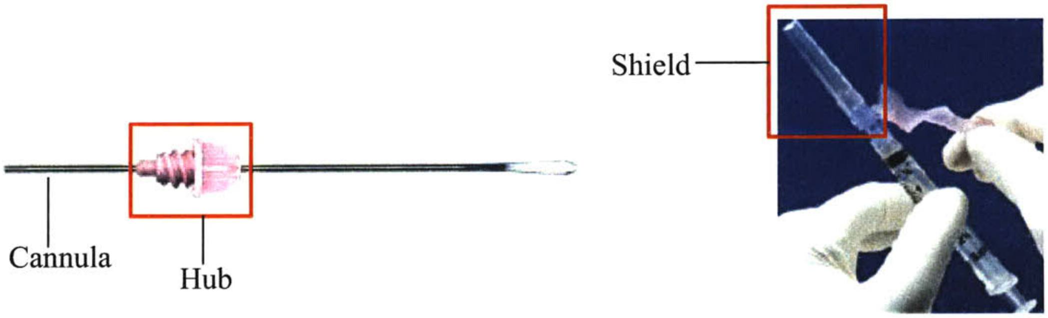


Figure 1.7: CB Product N configuration.

The 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, is comprised of the Product N with a safety shield that serves to cover the sharp Cannula after use.

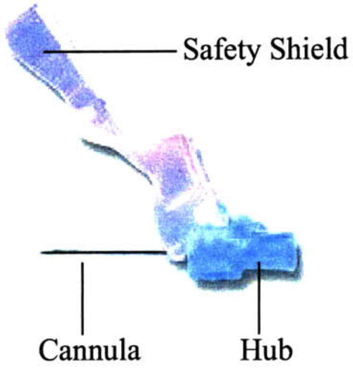


Figure 1.8: CB Product E configuration.

The safety shield and hub are injection molded. Tool Room supports Product E manufacturing operations by performing repairs and maintenance on 1 Product N 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.

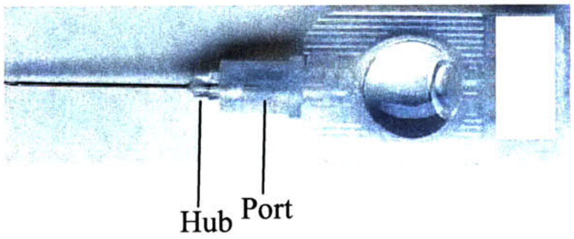


Figure 1.9: CB Product U configuration.

The CB Product U is consists 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 entails a luer and a shield which is injection molded.

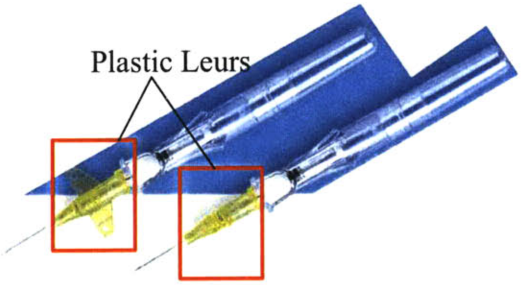


Figure 1.10: CB Product F products used in CB Catheters.

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	 Part	Mold
1	1 cc	Barrel	L6 (LS-Tip)
2			L23 (LL-Tip)
3			L75 (LL-Tip)
4			L78 (LL-Tip)
5		Plunger	LS1
6			L13
7	3 cc	Barrel	L40
8			L7
9			LS1
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 E		
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		LS2
74		L34
75	HP	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.

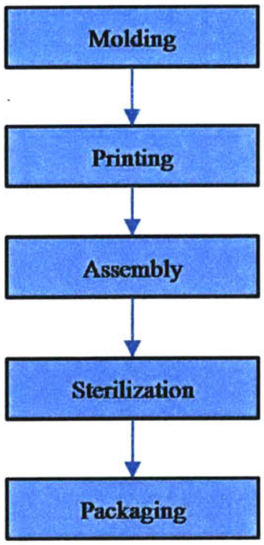


Figure 1.11: Overview of production flow in CB Tuas

Printing is responsible for the 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
- Investigate defects in molds and conduct Root Cause Analysis
- Purchase spares and other mold-related parts
- Control the quality of incoming parts
- Manage the inventory of spares and mold-related parts
- Keep records 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:

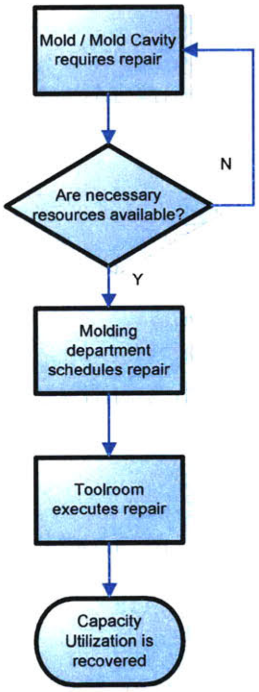


Figure 1.12: Simplified repair process flow

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 there is not a functional department for molding; rather each value stream independently manages their respective molding processes.

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, there are two Technical Specialists (TS) assigned to each VS to execute any required repair operations. 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 a single TS who is responsible for overseeing both value stream repair operations.

To perform the other functions of Tool Room, there is one TS with responsibility for 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 TSs in the Tool Room, and for checking 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 the Tool Room improve its operations so as to achieve this vision. The ultimate goal is to maintain and repair the molds so that each mold achieves close to 100% CU at all times. 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 the Tool Room diagnoses the problems and then carries 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

Another key function of the Tool Room is to manage spare component inventory. Inventory levels need to be managed 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 for each VS. 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 metrics. 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 to the 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 naming conventions 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 TSs 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 [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.

2.2.1 Inadequate Safety Stock Levels

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 manage the inventory of spare components, bases the amount that they should have on-hand on an arbitrary figure. 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.

2.2.2 Inconsistent Reorder Quantities

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 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 metrics 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.

2.2.3 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 metrics 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 [4].

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 which this study will look into.

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 handled by Lim [4].

The last component will look at the top few occurring mold defects that are unique to a pilot of 1cc Product S molds, M2 and M3, and a 3cc Product S mold, M1. 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 the past failure times data.
- Plan the preventive maintenance (PM) interval based on the available task list.

This part of the project will be further elaborated on in subsequent sections of this thesis.

3. LITERATURE REVIEW

For any manufacturing organization involved in mass production, it is paramount that the machines/system are in good operating conditions to keep up with schedules in production. Injection molding machines and the mold are an example of mass production systems that must be maintained well. Defects that occur on the molded part could be related to one or more of the following factors – molding machine, mold, process, operating conditions, raw material and the operator. In a study conducted by Texas Plastic Technologies to determine which of these four factors would molded part defects be related to, they correlated 60% to be machine-related, 20% to be mold-related, 10% to be material-related and another 10% operator-related [5].

The mold components affect the duration of mold uptime. For instance, out-of-specification and defective mold components would yield molded parts that do not meet the acceptable quality standard. The mold would have to be removed from the machine for investigation and troubleshooting such as replacing the flawed component(s) with a new one or just polishing and reworking the component(s). It is essential to appreciate the fact that a defective mold component will lead to non-conformance and hence necessitating the need to remove the mold from production. A mold with more defective components will experience longer downtime thus affecting the manufacturing output of the organization. I have not found any specific mention in literature pertaining to the effect of defective mold components on an injection molding production performance.

Reliability, maintainability and availability of a component or subsystem govern the uptime of a machine system. Ebiling [6] defines the 3 terms as follow:

- Reliability – The probability that a component or system will perform a required function for a given period of time when used under stated operating conditions. It captures the probability of non-failure within a defined timeline. In observing and analyzing component reliability in a particular operation, the operation should run under normal operating conditions with detailed accounts of failure and time interval captured.

- Maintainability – The probability that a failed component or system will be restored or repaired to a specified condition within a period of time when maintenance is performed in accordance with prescribed procedures.
- Availability – The probability that a component is performing its required function at a given point in time when used under the stated operating conditions. It can also imply the percentage of components within a system that are operating at a given time.

Reliability only looks at the fraction of time there are no failures occurring whereas availability accounts for both repairs and failures. Reliability is closely associated with the quality of a product [6]. In the context of the spare components making up the mold, the better the quality of the spare components the more reliable they become. The desired level of reliability can only be achieved through proper scheduling and conduct of maintenance.

Maintenance can be generically classified into two types, scheduled or preventive maintenance (PM) and corrective maintenance (CM) [7, 8]. PM is conducted to decrease the failure probability of a certain system which involves adjusting operation parameters and repairing or replacing a component of the system before the system breaks down. Preventive replacement describes the action done during a PM. CM is the necessary action to be taken on the system immediately upon its failure to restore it back to its desired functioning condition. The frequency of conducting CM is not deterministic. The system is subjected to many factors during its operation. Fatigue-cycle properties of the components and operating parameters are just some examples of the factors that makes CM forecasting complex. Failure replacement describes the action done during a CM.

In conducting PM, it is crucial to identify the components which should be considered for replacement, even if they still appear to be in perfect working condition and the components which can be allowed to run until it fails or until the next PM [9]. Setting up an optimal replacement policy while performing a certain PM might help in maximizing profits and/or minimizing system downtime and cost. Subsequently, the time at which to carry out the PM will need to be considered. There are four maintenance policies [7] that industries have been adopting. Table 3.1 presents these policies with concise, self-explanatory notes.

Table 3.1: Maintenance policies that govern the replacement of components that makes up a system.

Failure-based maintenance (FBM)	• A corrective maintenance. • Maintenance to be carried out only on occurrence of failure or breakdown. (Replace Only on Failure) • For random breakdowns and low breakdown costs, FBM may be cost effective.
Use-based maintenance (UBM)	• Triggered by the event that a specified number of units of use (Fixed-period maintenance) or time is reached. • Assumes that failure behavior is known following a trend of increasing failure rate since the previous maintenance. • PM is economically more viable than CM.
Condition-based maintenance (CBM)	• Activated when the value of a given system parameter reaches or surpasses a preset value. • Assumes that there is a system parameter that can predict the failure behavior. • PM is economically more viable than CM.
Opportunity-based maintenance (OBM)	• Failure of a component opens up an opportunity to carry out PM on other components which have not yet failed. • Component choice depends on the probability distribution of their residual lives which may influence the process operating conditions.

3.1 A Case Study in Component Replacement Policy

Hastings [10] performed an optimization of preventive replacement intervals for a critical ore loader component called the axle bush. Although the study looked at the mining industry, it does illustrate relevance across other industries especially the injection molding industry. He looked at only one component which has been observed to possess a distinct wear-out pattern. Pareto analysis was used to identify the most frequent failure causes and failure modes were also ranked on a cost basis.

The study firstly proceeded with data extraction from maintenance records of the axle bush that show cumulative vehicle operating hours before an axle bush failure. Also available in the records are failure dates. In all, 6 ore loaders were investigated and each with similar data type. So, the data for the axle bush failures across all the loaders were consolidated into one list. The failure data was subjected to a Bi-Weibull hazard function to identify multiple failure patterns, which can be combinations of burn-in, random and/or wear-out failures. The ascertained shape parameter was used in determining such failure pattern which appears to be a component wear-out issue in this case. Reliability and hazard function plots were drawn to detect the duration of operation hours before wear-out occurred, which led to the conclusion that the time interval between axle bush wear-out was long enough for preventive replacement to be applied. The appropriate component replacement policy would need to be selected on a case-to-case basis. The mining company had to consider the costs in deciding whether to replace a component at a time when actual failure occurs or perform the replacement once failure symptoms show up. In reducing maintenance cost, the mining company decided to be selective towards the types of components to be replaced during a routine maintenance, whereby different replacement policy was assigned to components based on their criticality.

The case study has illustrated concepts of component reliability analysis, its replacement and the corresponding cost impact that the replacement can bring about. Although not all that the case study describes is relevant to the current project at CB, it does provide a useful framework in going forward in understanding the reliability of mold components and the replacement policy that can be applied.

4. METHODOLOGY

In any production industry, meeting customer demand is key to the success of a company. Machine systems that run well, where lesser downtime is experienced, will tend to meet demand better. In CB Tuas, injection molding forms the core manufacturing process. In ensuring that the production experiences as little disruptions as possible, both the mold and the injection molding machine need to be maintained. Product quality is controlled tightly. Flaws in the molded part can be attributed to many factors, as mentioned in Chapter 3. For the purpose of this study, we focus on only mold defects related to faulty or defective mold components. By mathematically analyzing the trend(s) of occurrence(s) in the component defect, we intend to develop ideas and guidelines for an improved maintenance policy. There are 3 main aspects to be conducted in this study. They are listed as follow:

1. Retrieve data from the Tool Room's Mold Defect Record for the specific molds
2. Analyze type of defects that a mold experiences and identify failure trends
3. Evaluate the possible maintenance policies and recommend a suitable preventive maintenance schedule for the individual mold.

4.1 Mold Defect Record Data Acquisition

The scope of this study is to look at the molds from the Product S Value Stream. The molds involved in this pilot are M1 (3 cc Barrel), M2 (1 cc Barrel) and M3 (1 cc Barrel). Figure 4.1 shows the physical appearance of the Product S barrel. The Product S molds are selected for this study because they are high-runners i.e. these molds produce high volumes of Product S parts. As high-runner molds, they are exposed to more molding and tooling problems and thus present this study with the opportunity to alleviate certain aspects of the problem. Improvements implemented on these pilot molds could perhaps be extended to the remaining molds used in CB Tuas.

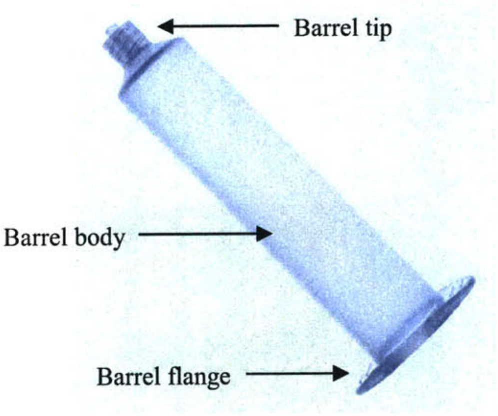
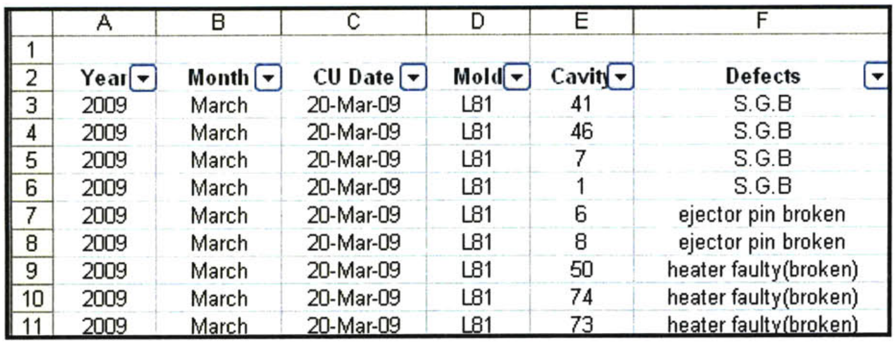


Figure 4.1: Plunger and Barrel of a Product S.

We first need to attain a list of these specific barrel defects to have a better understanding of the molded part defects from the defect data. In addition, a list of mold components corresponding to each of the mentioned defects has to be made available so that we are able to identify the components that could plausibly be defective. This requires a discussion with the Tool Room TS for that mold and the engineer involved.

When inspection is performed on Product S and defects are found, the mold manufacturing those defective products will be investigated for faults in the mold. The Molding TS would then provide an immediate diagnosis of the faults within the mold and the cavities affected would be blocked. When the mold is brought to the Tool Room, the Tool Room TS will conduct a more thorough investigation. The Molding TS and Tool Room TS record their observations in the Mold Cavity Chart Form and the Monthly Mold Report Form respectively. The Monthly Mold Report Form is attached in Appendix A. Since the Monthly Mold Report Form contains information on the condition of the molds after a thorough diagnostic done by the Tool Room TS, using the defect data from it gives a more accurate account of the problem the molds are facing. We use a Microsoft Office Excel spreadsheet to capture the relevant data for analysis. Table 4.1 shows a snapshot of the data tabulation.

Table 4.1: Data tabulation of mold defects.

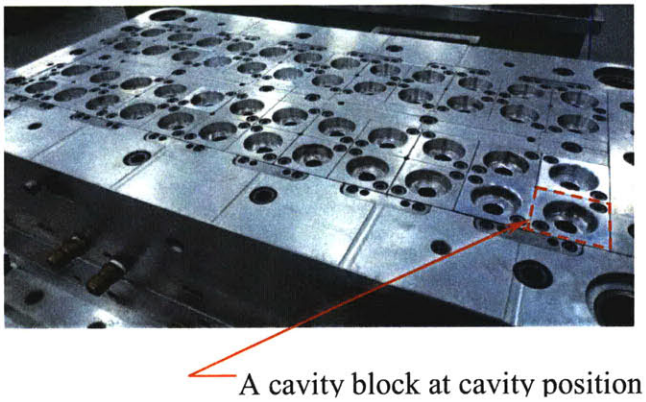


	A	B	C	D	E	F
1						
2	Year	Month	CU Date	Mold	Cavity	Defects
3	2009	March	20-Mar-09	L81	41	S.G.B
4	2009	March	20-Mar-09	L81	46	S.G.B
5	2009	March	20-Mar-09	L81	7	S.G.B
6	2009	March	20-Mar-09	L81	1	S.G.B
7	2009	March	20-Mar-09	L81	6	ejector pin broken
8	2009	March	20-Mar-09	L81	8	ejector pin broken
9	2009	March	20-Mar-09	L81	50	heater faulty(broken)
10	2009	March	20-Mar-09	L81	74	heater faulty(broken)
11	2009	March	20-Mar-09	L81	73	heater faulty(broken)

The "CU Date" is a record of the date a mold is brought into the Tool Room for repairing the mold. The numbers reflected under the "Cavity" column reflects the cavity within the mold where the corresponding defects are located. The "Defects" column records the defects that the Tool Room TS discovered.

4.1.1 Cavity Tracking

The core and cavity are actively involved in providing the final shape to the plastic product. When flaws are uncovered on the Product S, the first area within the mold worth investigating is the cavity and the core of the mold. Within the mold, the cavity positions are numbered. Figure 4.2 illustrates the cavity configuration of a Product S mold. Each cavity position contains a cavity block.



A cavity block at cavity position

Figure 4.2: A Product S barrel mold opened revealing the cavity blocks.

Figure 4.3 shows a cavity block commonly used to produce the barrel of a Product S. These cavity blocks are placed at the determined positions of the mold itself. All cavity blocks are numbered. The cavity number and mold number is engraved into the individual cavities for traceability. Cavity blocks may consists of 2 cavities but some like those shown in Figure 4.2 consist of only 1 cavity.

Confidential

Figure 4.3 A typical cavity block used for production of Product S barrels.

A new mold comes with each cavity block inscribed with a number similar to the cavity position. The cavity position is permanently assigned but the cavity block that fills the position can be changed for another one. This is visible in the presence of a defective cavity where a cavity block might need to be changed for another one with a different number. During a cavity block replacement procedure, the Tool Room TS indicates both the number of the new block and position in the Monthly Mold Report Form. The nomenclature of the documentation for the replacement procedure is as follow: $Y(X)$ where X is the cavity position number and Y is the new cavity block number. At the instance that cavity block Y has to be replaced by cavity block Z, the change will be reflected as $Z(X)$. The cavity position number will always be reflected so that there will be traceability of persistently problematic cavity positions.

There is a problem that one might face in trying to obtain the cavity information. Each TS might transpose the replaced cavity position with the original one – instead of writing $Y(X)$ during a cavity replacement procedure, the TS might write it as $X(Y)$. Fortunately, it is possible to troubleshoot this discrepancy – the number inscribed on a new cavity block is larger than the maximum cavity position number of the mold, hence solves the issue.

4.2 Analysis of Defect Data

In all, we found 52 types of defects that are specific to the Product S barrel mold. Of these, we propose to base our analysis on the priority defects occurring on molds M1, M2 and M3 based on a Pareto Rule such as the 80/20 rule. It is sensible to adopt this approach as it is not possible to study all the defects. However, there is a possibility to eliminate, for instance, 80% of the failures occurring to the mold by attempting to prevent certain major defect-types from occurring.

A mold failure is considered when a mold is stopped from production due to the discovery of defect(s) and/or an abrupt catastrophic failure affecting the mold and/or the injection molding machine. The repair process can consist of different subtasks and delay times [6]. Figure 4.4 shows the maintenance downtime timeline.

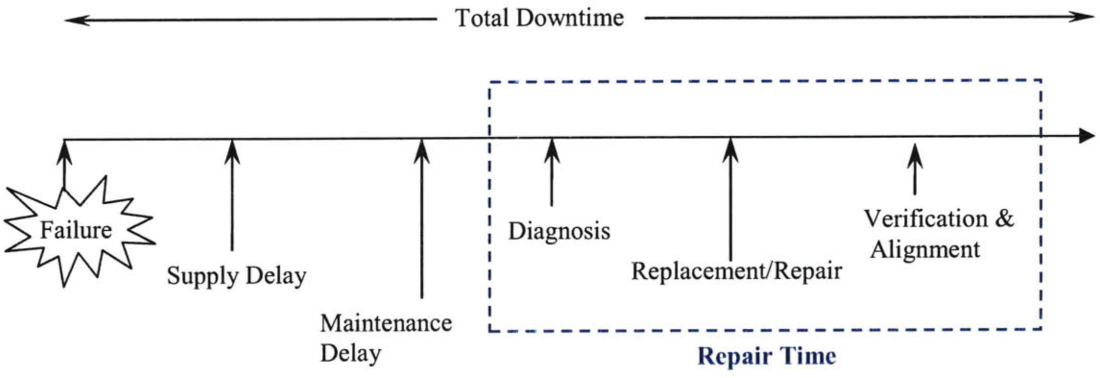


Figure 4.4: Maintenance downtime timeline.

Supply delays constitute delay time in obtaining the relevant spare parts to complete the repair process. The time that goes into the supply delay is influenced by the range of different components that are stocked and the number of spares of a given component. The supply delay may not necessarily occur early in the downtime period; rather it may occur at the diagnosis part of the downtime timeline. The availability of mold spare parts in inventory will ensure that downtime is reduced. This aspect of the study will be investigated by Lim [4].

During a production cycle, the mold will experience downtime and uptime. Figure 4.5 shows the definition of mean-time-to-repair (MTTR) and mean-time-to-failure (MTTF) along a production timeline. The MTTR is defined as the average time to restore a defective mold to its working condition. The mean time to failure (MTTF) indicates the average time a mold runs before the next plastic part defect is discovered and the mold is considered to have failed. The failure interval is the time between 2 failures, F_i and F_{i+1}.

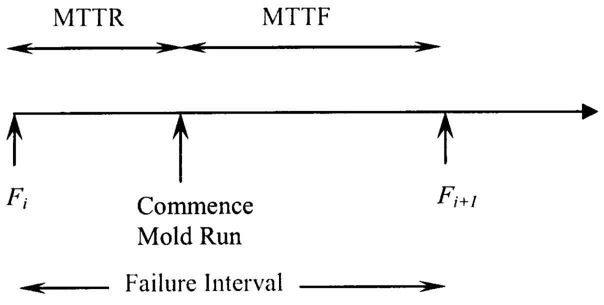


Figure 4.5: MTTR and MTTR definition in visual form.

Referring to Table 4.1, the Tool Room TS will indicate the date at which they perform the repair for the defects. The onus is on the TS to enter the dates the repairs were conducted as accurately as possible. A pitfall to be mindful about is that the defect might be discovered or occurred at time $T_{discover}$ but the repair will only begin after a certain idle time period such that $T_{repair} = T_{discover} + T_{idle}$. There could be many reasons attributing to T_{idle} such as (1) other molds of higher priority that the TS has to repair first and (2) shortage of spare components such that the repair has to be delayed. Since T_{idle} was not captured in the form, we assume that $T_{repair} = T_{discover}$. This simply means that the repair is initiated upon discovery. Also, all repairs are considered to be performed in the Tool Room albeit some are carried out at the production line itself. No conscientious effort was made to record the repair time for each mold repair carried out. This makes it difficult to estimate the MTTR for the mold. As such, we assume that a mold that has failed is able to commence production on the same day. From this assumption, we can consider that MTTF is significantly larger than MTTR. Hence, we equate the average failure interval to the MTTF of the mold. Figure 4.6 illustrates the stated assumption.

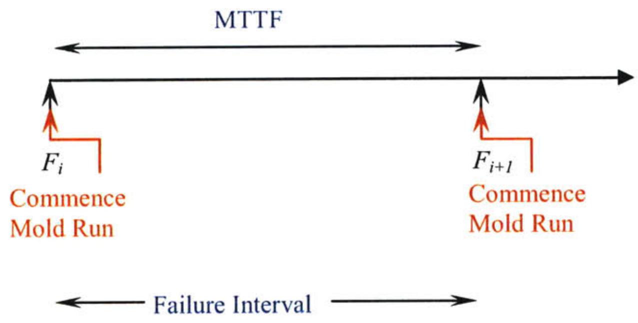
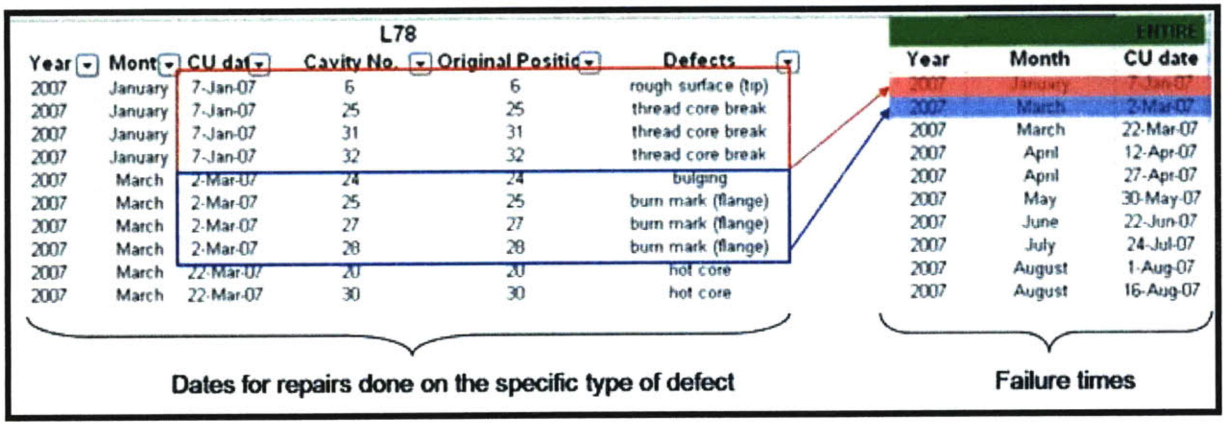


Figure 4.6: Assumed MTTF for this study in visual form.

From the mold defects spreadsheet such as that shown by Table 4.1, we can determine the mold failure times. The failure time is the interval of time between failures. In obtaining failure times, defect-types are ignored. Table 4.2 illustrates how the failure times are obtained.

Table 4.2: Obtaining mold failure times.



L78

Year	Mont	CU dat	Cavity No.	Original Positic	Defects
2007	January	7-Jan-07	6	6	rough surface (tip)
2007	January	7-Jan-07	25	25	thread core break
2007	January	7-Jan-07	31	31	thread core break
2007	January	7-Jan-07	32	32	thread core break
2007	March	2-Mar-07	24	24	bulging
2007	March	2-Mar-07	25	25	burn mark (flange)
2007	March	2-Mar-07	27	27	burn mark (flange)
2007	March	2-Mar-07	28	28	burn mark (flange)
2007	March	22-Mar-07	20	20	hot core
2007	March	22-Mar-07	30	30	hot core

Dates for repairs done on the specific type of defect

ENTIRE

Year	Month	CU date
2007	January	7-Jan-07
2007	March	2-Mar-07
2007	March	22-Mar-07
2007	April	12-Apr-07
2007	April	27-Apr-07
2007	May	30-May-07
2007	June	22-Jun-07
2007	July	24-Jul-07
2007	August	1-Aug-07
2007	August	16-Aug-07

Failure times

From Table 4.2, we see that there are a few defects occurring on the same day. As long as these defects occur within the same repair date, T_{repair}, the date of occurrence can be amalgamated. The reason for this is that as long as the mold is down from production, it would be considered as failed regardless of the type of defects which are causing it to fail. According to Table 4.2, after mold M3 was brought into the Tool Room for repairs on 7th January 2007, the next time the mold visited the Tool Room for repairs was 54 days later i.e. 2nd March 2007.

As a recommendation to model the failure data, we could use a general failure distribution given by a hazard function, or a statistical failure model such as the Weibull distribution, lognormal distribution and/or exponential distribution. Different models subject the nature of the defect occurrences to a unique characterization of the component failure process. Thus, it is necessary to perform statistical test on the failure times data to determine which distribution its failure times belong to. Figure 4.7 illustrates the sequence to follow in selecting the statistical distribution that fits the respective mold failure time data.

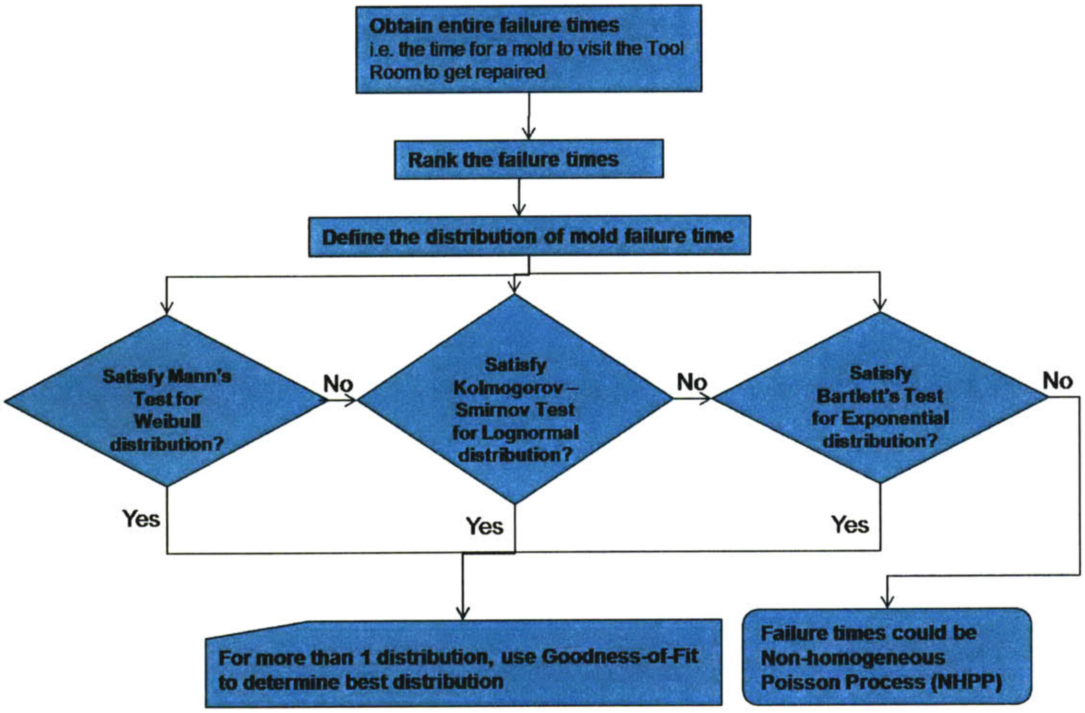


Figure 4.7: Flowchart is selecting statistical distribution for failure times data of individual mold.

Ideally, it is favorable to fit the model to the data. Applying a model to the failure process will help in determining how the failure behaves with respect to time, hence allowing us to predict the time a component of the mold wears out. This information will be of great use in determining the suitable preventive maintenance schedule to recommend for the individual mold.

5. RESULTS AND DISCUSSION OF MOLD DEFECTS AND RELIABILITY

In analyzing the defect data for a mold, we looked into the extent of defects occurrences over the cavity positions and the types of defects at a particular cavity position. Here, we shall pay close attention to deciphering trends from the past data from January 2007 to June 2009 for a more effective mold management for the future. As highlighted, only Product S barrel molds namely M1, M2 and M3 were studied. Schematics of these molds with the designated cavity positions are available in Appendix B1 – Appendix B3.

5.1 Defect Trends Across Product S Barrel Molds

5.1.1 Comparing Mold Cavity Positions to Overall Defects Occurrences Frequency

An investigation was first conducted on the frequency of occurrence of all defects across the cavities within the molds. Figure 5.1 – Figure 5.3 show the frequency of all defects occurring across the cavities of M1, M2 and M3 molds.

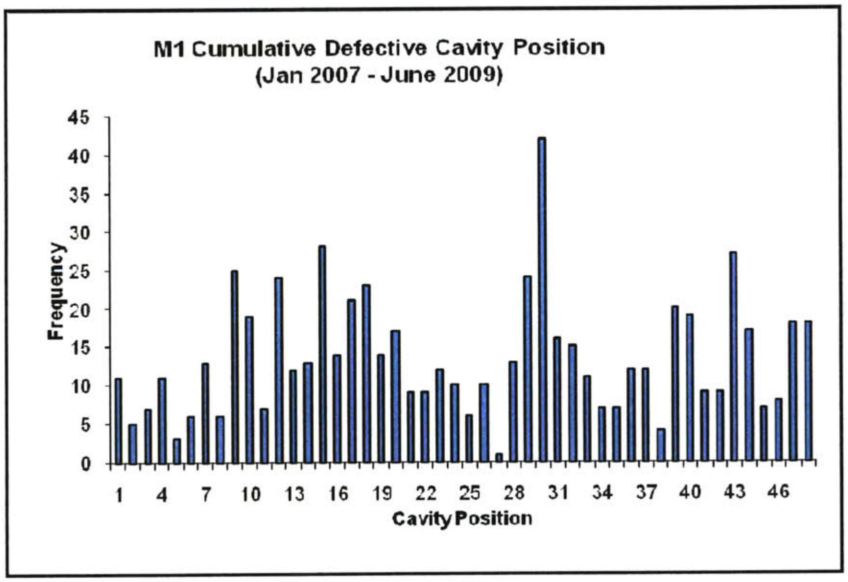


Figure 5.1: Cumulative data for defective cavity positions in M1 mold.

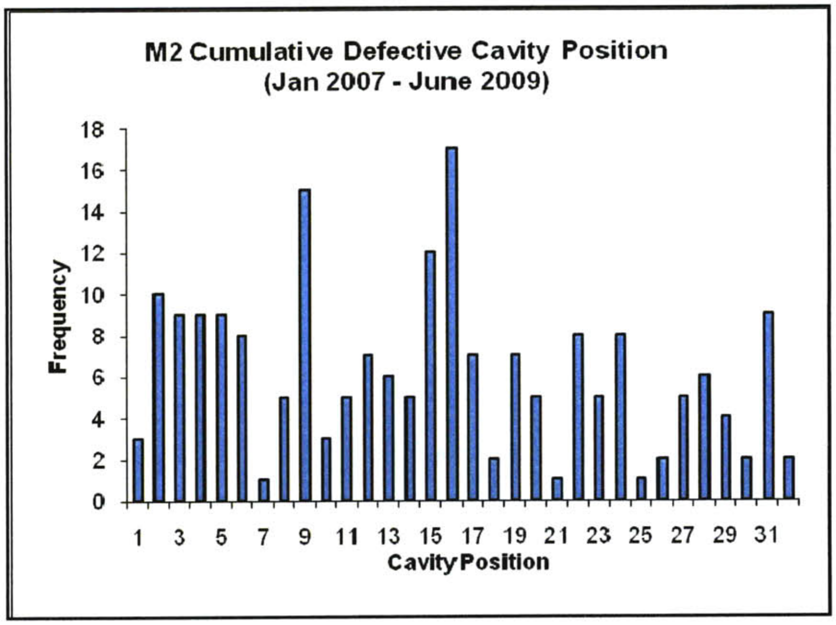


Figure 5.2: Cumulative data for defective cavity positions in M2 mold.

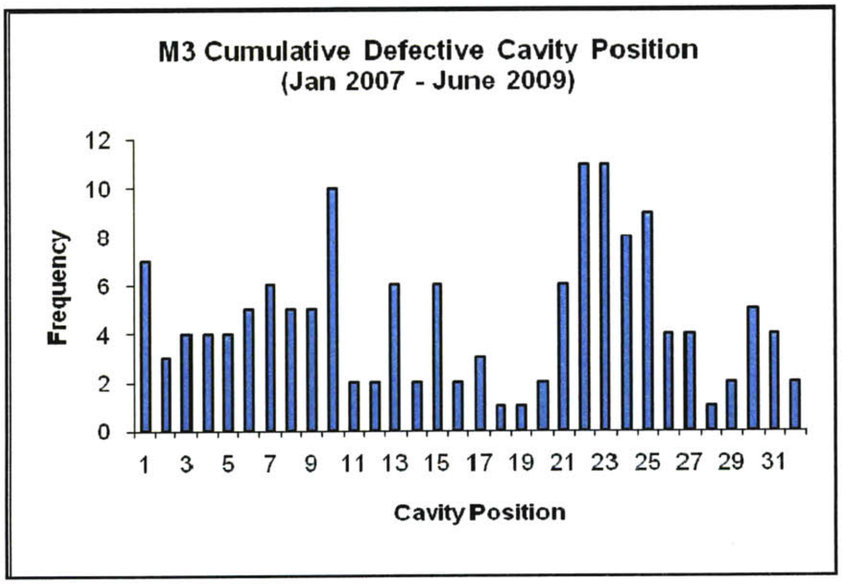


Figure 5.3: Cumulative data for defective cavity positions in M3 mold.

Within each mold, there are cavity positions that appear to have experienced more defects than other cavity positions. Table 5.1 records the cavity position(s) where defects occur the most. The production volumes for each mold are estimates of monthly production between October 2008 and May 2009. The specific monthly production for the mentioned period is contained in Appendix B4.

Table 5.1: Cavity position(s) with maximum defect counts.

				Maximum Defects Occurrences		
Mold	**No. of Cavities**	**Estimated Production Volume (hr/mth)**	**Total No. of Defects**	**Cavity Position(s)**	**Frequency**	**Percentage (%)**
M1	48	633	651	30	42	6.45
M2	32	580.5	198	16	17	8.59
M3	32	670.5	147	22 and 23	11	7.48

Table 5.1 gives an overview for the location of the cavities that are facing the most problem with mold defects. In absolute terms, the total defects that occurred on M1 is approximately 3 times that of M2 and 4 times that of M3. Of the 3 molds, M3 has the highest production volume which is followed by M1 and M2 consecutively. In terms of mold component complexity, M2 and M3 consists of components that are more complex than M1. The probable reasons for the higher defects occurrences for M1 are the large number of cavities it possess and the high production run which it had to meet. In terms of the percentage of maximum frequency of defects affecting cavity position(s), M1 had only 6.45% of its defects occurrences affecting cavity position 30. M3 had 7.48% of all its defects occurring at cavity position 22 and 23 each. M2 had 8.59% of all its defects concentrated at cavity position 16. Engineers and TS performing repair analysis of the mold can now pay more attention to the cavities that are most problematic by thoroughly inspecting and cleaning the components within the vicinity of the highlighted cavity position. However, the information communicated by Table 5.1 did not sufficiently convey the spread of the defects occurrences data within the mold. An examination of Figure 5.1 – Figure 5.3 finds that there are no clusters of cavity positions that are heavily defective. Therefore, it is not quite possible to isolate the region(s) of the mold for scrutiny. Hence, it seems that the occurrence of defects is random over the locations of the cavity positions.

5.1.1 Prioritizing Mold Defects for Repair Action

A total of 52 types of mold defects were collected for Product S barrel molds. A list of the all the 52 defects are tabulated and contained in **Error! Reference source not found.** as reference. It will be demanding to commit resources and time to repairing each of the defects although that is probably the most ideal situation. We believe that prioritizing the defects should increase the effectiveness of the repair and/or maintenance. A way to do this would be to apply the Pareto Rule to the situation.

A Pareto analysis is usually used for identifying failures responsible for the majority of equipment maintenance cost and downtime. Pareto analysis is widely used in the maintenance engineering field. We create Pareto charts for the 3 molds. We are interested in how frequent certain types of defects would occur within the respective molds. Cavity positions are omitted in this analysis. We obtain the following Pareto charts as shown by Figure 5.4 – Figure 5.6.

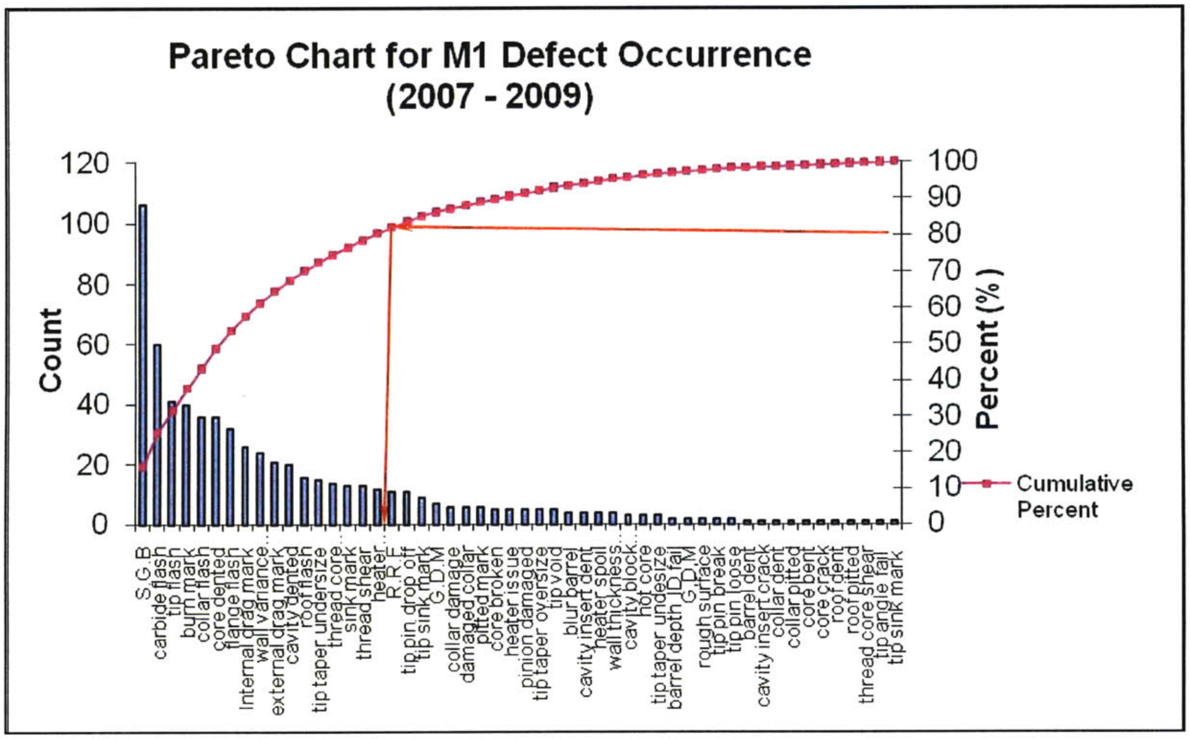


Figure 5.4: Pareto chart for M1 with 80% cumulative defects occurrences.

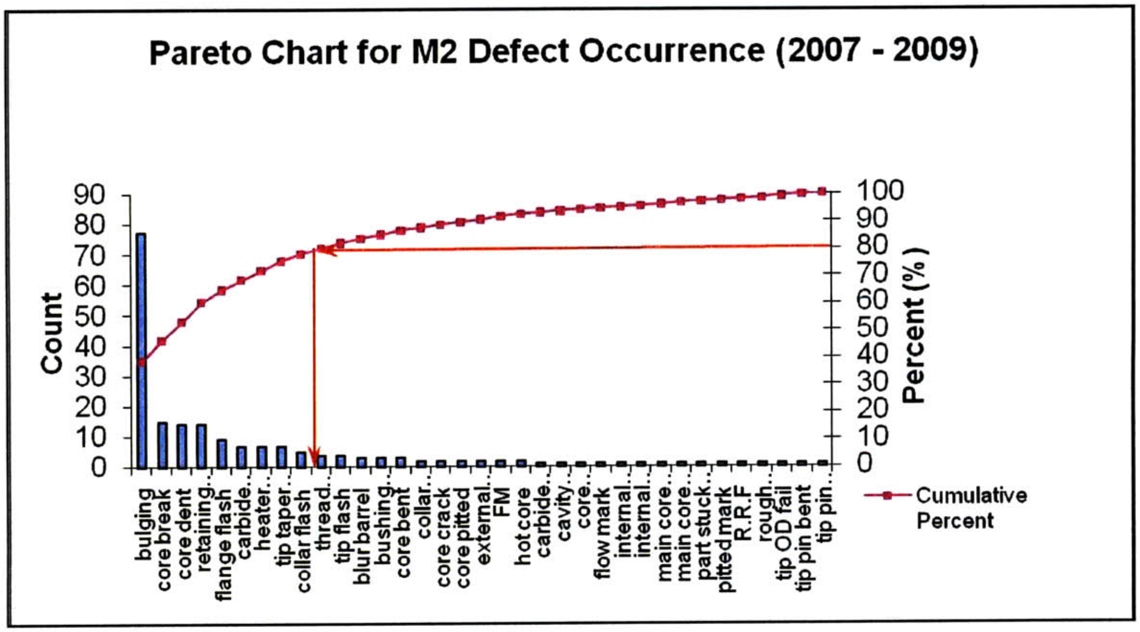


Figure 5.5: Pareto chart for M2 with 80% cumulative defects occurrences.

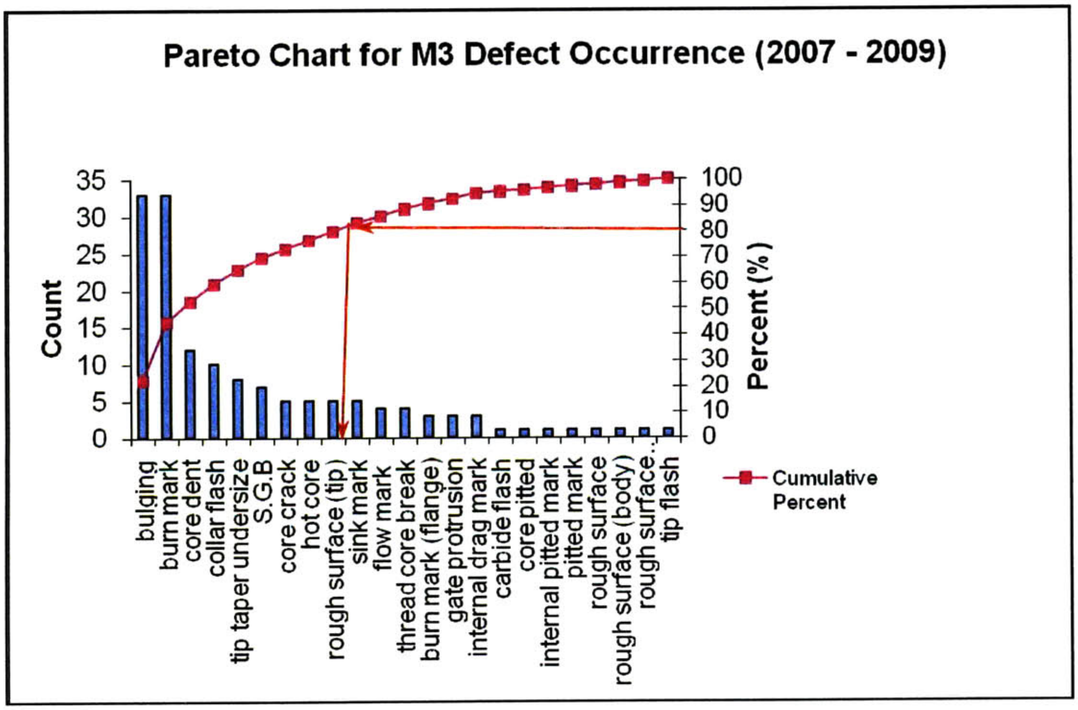


Figure 5.6: Pareto chart for M3 with 80% cumulative defects occurrences.

As Figure 5.4 shows, M1 experiences the most number of defect-types i.e. 52 defect-types. M3 has the least number of defect types, see Figure 5.6. The priority defects for each mold would be selected according to defect-types that constitute 80% of all mold failures. Hence, the Pareto Rule for M1, M2 and M3 approximates to 30/80, 25/80 and 40/80 respectively. The Pareto Rule for each mold differs from one another since different molds are affected by different types of defects occurring at different frequencies. The intention of deriving a Pareto distribution for a mold is to highlight to the molding engineers that it might be possible to reduce 80% of the failures occurring to the mold by attempting to prevent only a limited number of defect-types from occurring. For instance, M1 sustained 52 types of defects. Compared to molds M2 and M3, M1 needs the most attention in order to prevent all of its defects from occurring. This is not feasible. Thus, through the Pareto Rule, we find that eliminating approximately 30% of the defect-types could probably result in decreasing the defect occurrences by 80%. The 3 Pareto Rules specified on each mold give a direction for molding engineers to adopt during repair and maintenance activities.

These defects may come from the flaws in the mold components. In Table 5.2 we identify for each defect type the component(s) that is (are) responsible for the defect to occur. The list of defect-types in Table 5.2 is taken from the Pareto charts in Figure 5.4 – Figure 5.6 based on their individual Pareto Rule. The types of components attributing to the respective defect-types are based on the experiences and opinions of the Tool Room engineers. There has not been any work done, in literature, in mapping the types of mold components to the respective defect-types. The list of mold components in Table 5.2 is only as accurate as the opinions of the engineers but it does provide a basic guide for the Tool Room TS. Although the list is not exhaustive, the list will provide an ease of reference for the individuals working on the mold. This thesis only focused on the defect-types and not on the mold components associated to them. Thus, the accuracy in mapping the mold components to the defect-types will not affect the accuracy of the analyses done in this thesis.

A possible example of its use is as follow: Consider that a quality control production technician found flash on the flange of Product S barrel. A flange flash has occurred to the Product S barrel. Apart from looking into the parameters that govern the injection molding process of that batch of Product S barrels, the engineers and Tool Room TS can investigate the mold components, which are the stripper bush and cavity block in this case, as a possible culprit for the defect.

Table 5.2: Priority defects with the associated primary mold components for M1, M2 and M3.

Arbitrary Defect Code	Selected Defects	M1	M2	M3	Primary Components Responsible		
D1	**bulging**		X	X	bubbling tube	core pin	cavity wall
D2	**burn mark**	X		X			
	location at barrel tip				roof insert	tip pin	carbide
	location at barrel body				cavity block	main core	
	location at barrel flange				gate pin	stripper bush	cavity block
D3	**carbide flash**	X	X		carbide bush	tip pin	
D4	**cavity dented**	X			core	thread core	
D5	**collar flash**	X	X	X	sliding bush	thread core	
D6	**core break**		X		core		
D7	**core crack**			X	core		
D8	**core dented**	X	X	X	core	thread core	
D9	**external drag mark**	X			gate pin		
D10	**flange flash**	X	X		stripper bush	cavity block	
D11	**heater faulty(broken)**	X	X		heater resistance		
D12	**hot core**			X	bubbling tube	core pin (hole offset)	
D13	**internal drag mark**	X			core	main core	
D14	**retaining ring ID fail**		X		core	stripper bush	
D15	**roof flash**	X			roof insert	cavity block	
D16	**rough surface (tip)**			X	roof insert	tip pin	
D17	**S.G.B**	X		X	gate pin	cartridge heater	
D18	**sink mark**	X					
	location at barrel tip				roof insert	tip pin	
	location at barrel body				cavity block		main core
	location at barrel flange				stripper bush	gate pin	gate hole
D19	**thread core damage**	X			thread core	pinion	
D20	**thread shear**	X					
D21	**tip flash**	X			tip pin	carbide	
D22	**tip taper undersize**	X	X	X	thread core	gate hole	
D23	**wall variance failed**	X			Molding Process		

LEGEND: X Indicates defect presence

As shown in Table 5.2, defects occurring in a certain mold might not occur in the other molds and some defects are common in all the 3 molds. Collar flash, core dent and tip taper undersize are common defects amongst the 3 molds. We acknowledge that defects cannot be completely eliminated especially when systems are dynamic, which in this case the molds are constantly subjected to thermal extremes and moving mechanical stresses. It is not unusual for practitioners to find it difficult in determining which faults that they should be working towards reducing or eliminating first. Often, including observations made from the repair operations in CB Tuas, engineering practitioners tend to wait for the defects to occur before troubleshooting it as quickly as possible. Then, during periodic maintenance, task lists are not adequately instructing technicians the relevant parts to clean and inspect based on the priority of occurring defects. Therefore, any maintenance programs pertaining to M1, M2 and M3 can be structured based on attempting to reduce the occurrences of these priority mold defects.

5.1.2 Defect Density over Mold Cavity Positions

So far, we have discussed our data for the frequency of defects occurrences by the cavity positions affected and for the frequency at which various types of defects occur. This section shall introduce the concept of defect density and a possible application for the Tool Room engineers and TS. Defect density per cavity position can be defined as:

$$\text{Defect Density} = \frac{\sum_{j=1}^{n} D_j}{n} \qquad \textbf{(5.1)}$$

where D_j represents the number of defects of type j that occur at cavity position C_i and n represents the total types of defects that occur at cavity position C_i. Equation (5.1) is best explained through the following example – if a certain cavity position, C_i, was defective 2 times due to a certain defect A and 4 times due to a certain defect B, then that cavity would have been defective 3 times per defect-type on average. This would mean that for each type of defect that occurs at C_i, there is a possibility of it occurring at least 3 times.

Figure 5.7 shows a scatter plot of a defect density for the 3 molds over the respective cavity positions. Figure 5.8 shows the defect density histogram based on the priority defects population.

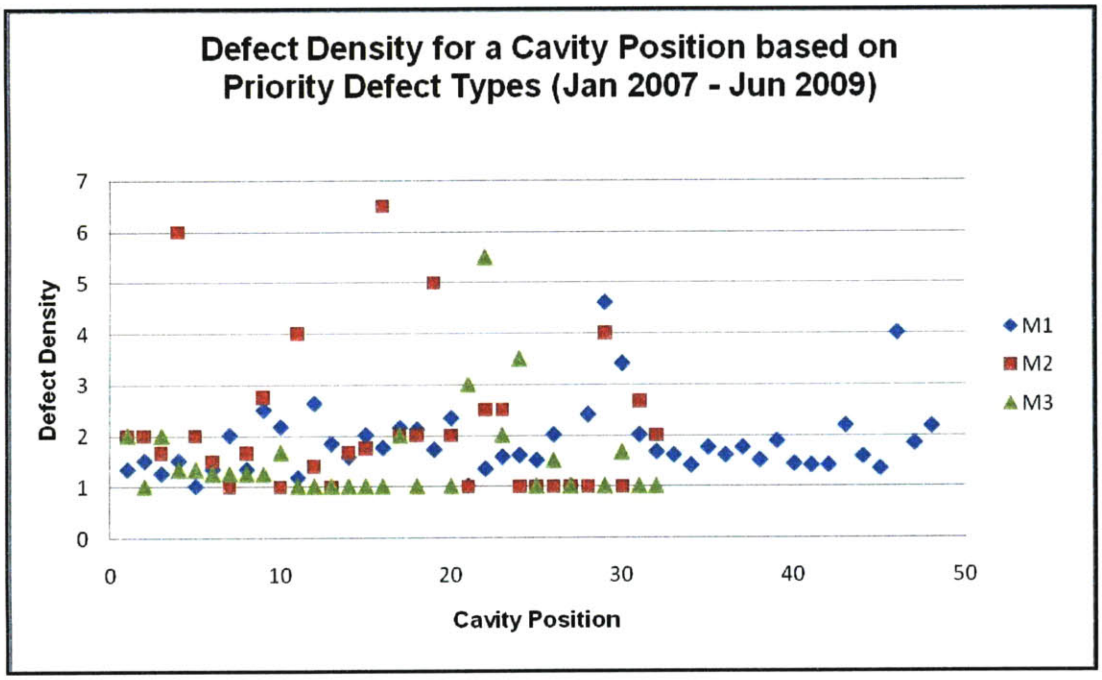


Figure 5.7: Priority Defect Density scatter for 3 molds.

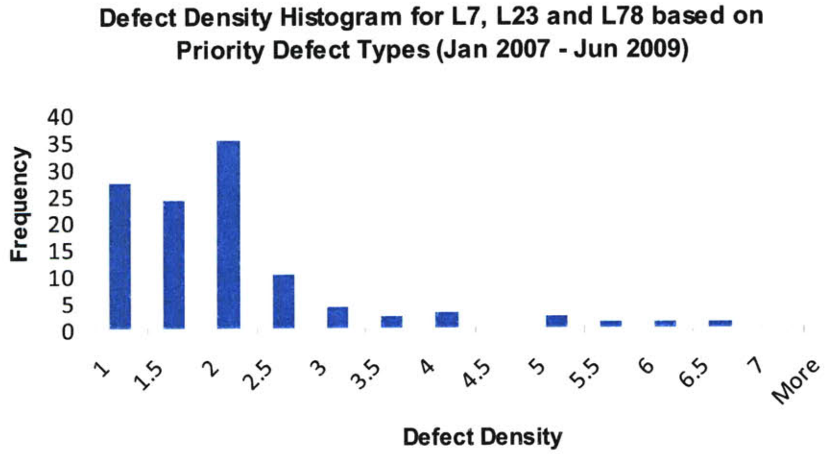


Figure 5.8: Defect density based on priority defects population.

Based on both Figure 5.7 and Figure 5.8, ~ 87% of the cumulative cavity positions for the 3 molds had defect densities between 1.0 – 2.5. Table 5.3 describes the statistics for the defect density population of the priority defect-types.

Table 5.3: Defect Density Statistics for Priority Defect-Types.

Defect Density Statistics	
Mean	1.85
Median	1.60
Standard Deviation	1.05
Kurtosis	6.31
Skewness	2.35

The defect density distribution is skewed to the right with a long tail extending out in the right. The skewness value of 2.35 agrees with the observation of the histogram in Figure 5.8. Amongst the 3 molds, M2 was found to possess the highest average defect density of ~ 2.2. M1 has an average defect density of ~ 1.8 and M3 has an average defect density of 1.55. On the average, the defect density is found to be 1.85.

The defect density could be used as a measure of effectiveness of repair or maintenance towards a certain cavity position. For a cavity position to be affected by the same defect-type, i.e. defect density > 1, could suggest that there might be repeated negligence in repair, persistent complacency in laying out tight quality control of incoming/replaced components and/or the inability to find root cause solution as yet. Although this section covers only defect density for priority defects, this concept may be extended to the entire population of defects affecting a mold.

5.2 Failure Trends and Prediction across Product S Barrel Molds

5.2.1 Determining the Distribution of Failure Times

The distribution of the failure times might help to predict mold reliability. The data were first subjected to a histogram analysis to identify the time range at which the molds would most frequently fail. The data used here refer to the mold run time until it is stopped from production due to any spotted defects and brought for repair to the Tool Room. Failure time data are complete, i.e. no data censoring involved, and all defect-types are considered. Re-call Chapter 4.2 for an explanation on mold failure time. Failure time data for this histogram analysis are found in Appendix B6. Figure 5.9 – Figure 5.11 show the failure times for each mold.

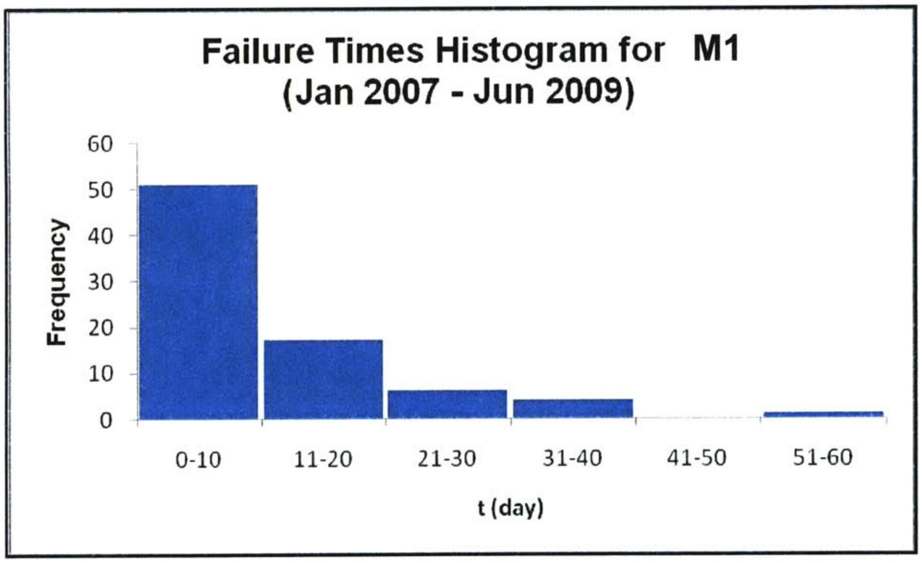


Figure 5.9: Failure times histogram for M1 with 79 samples.

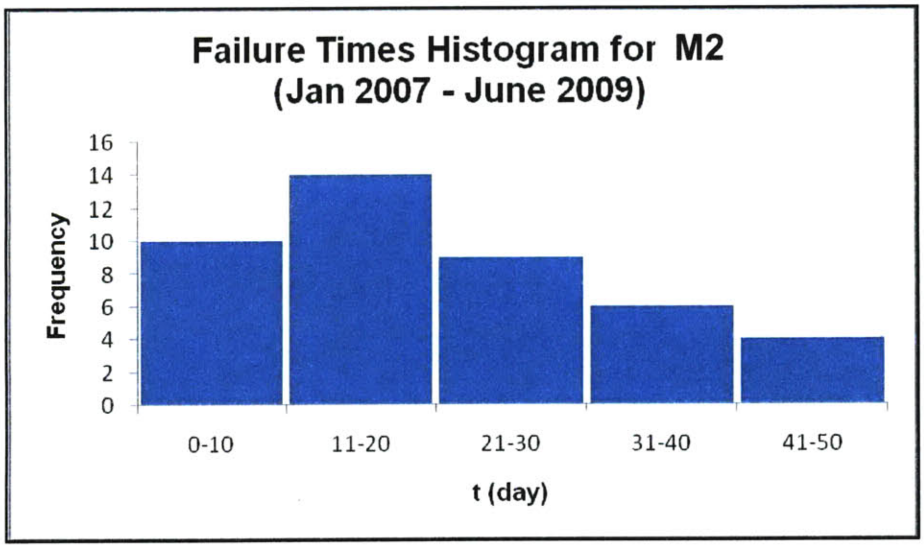


Figure 5.10: Failure times histogram for M2 with 43 samples.

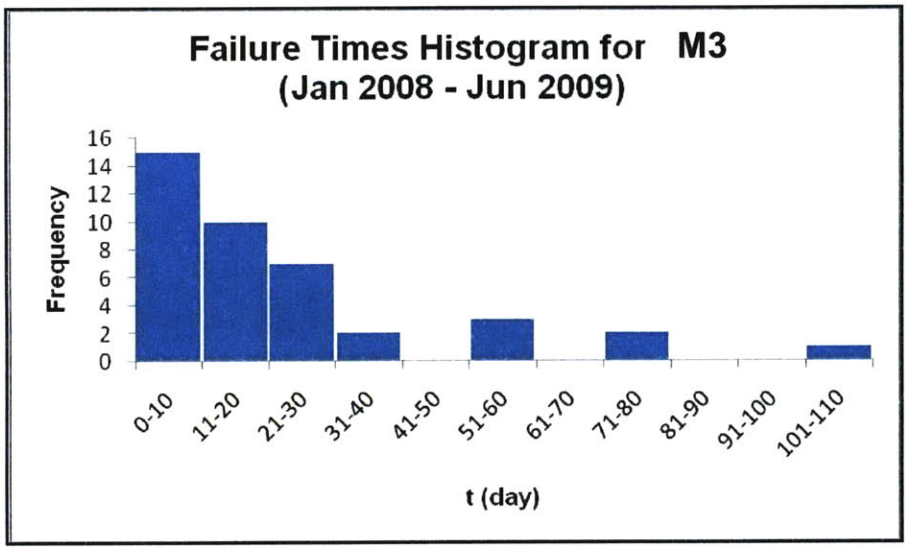


Figure 5.11: Failure times histogram for M3 with 40 samples.

It is evident that failure times for M1 and M3 has a heavy right tail as compared to failure times for M2. A skewness test was performed and it agreed with this observation. M1 and M3 have skewness values of 1.64 and 1.98 respectively whereas M2 has a skewness value of 0.55. On the average, molds M1, M2 and M3 fail after 11, 20 and 22 days on average. M1 and M3 experienced most of their failures within 10 days of production run. M2 experienced most of its failures within 11 to 20 days of its production run. The histogram analysis could not show how each failure times would conform to a specific statistical distribution. The distribution of the defect occurrences (failure times) may differ from one mold to another. As such, we proceeded with testing out the distribution of failure times on the lognormal, Weibull and exponential test statistic.

Each distribution test would require for the data of failure times to satisfy a certain hypotheses based on the test statistic subjected to the failure times. The null hypothesis is accepted if the test statistic is satisfied, hence, the failure times conform to the particular distribution. Appendix C1 contains the test statistic of the Mann's test for the Weibull distribution, Kolmogorov – Smirnov test for the lognormal distribution and Bartlett's test for the exponential distribution. Based on the test statistics, failure times for M1 follow the lognormal distribution while failure times for M2 follow the 2-parameter Weibull distribution. The probability plot for M1 and M2 are shown in Figure 5.12 and Figure 5.13 respectively.

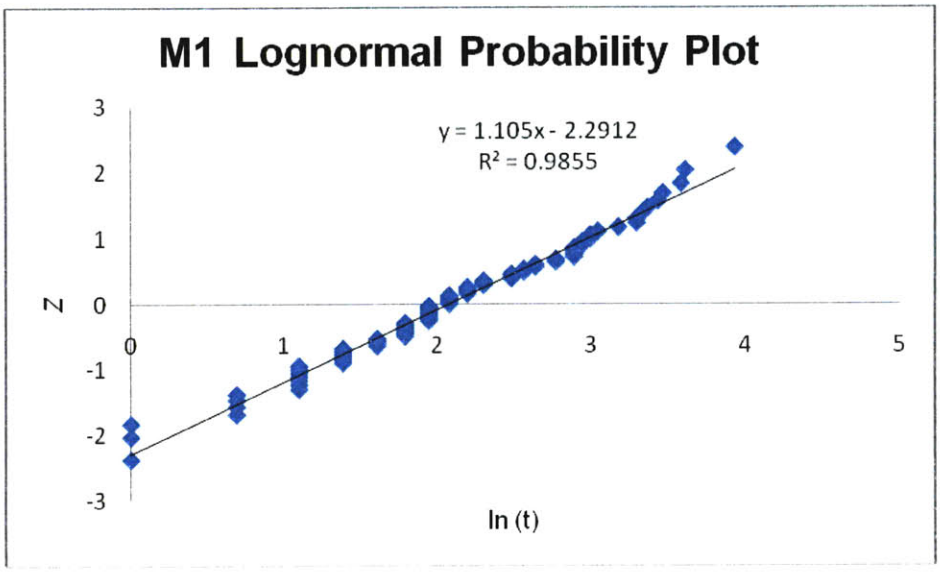


Figure 5.12: M1 Lognormal probability plot.

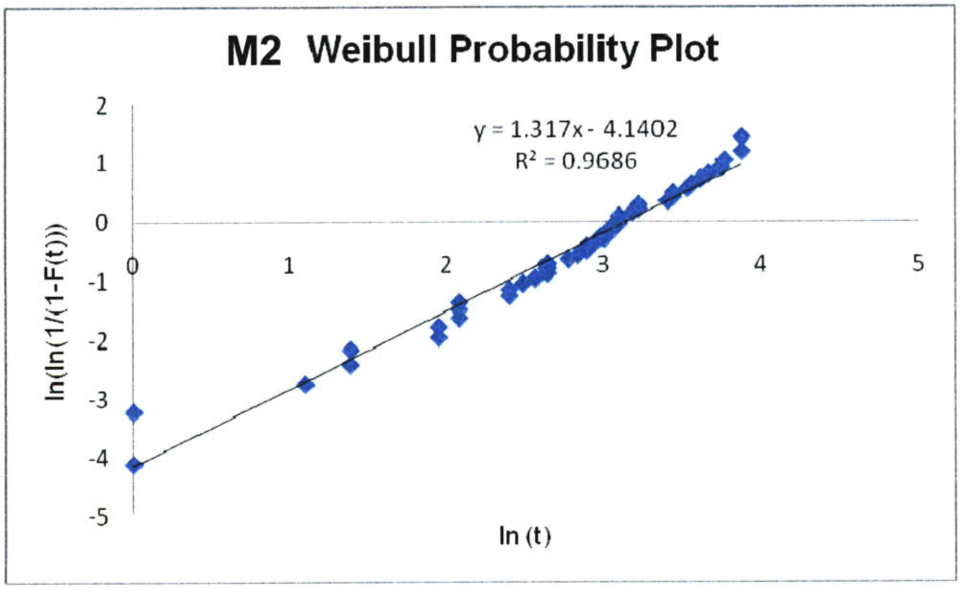


Figure 5.13: M2 Weibull probability plot.

The goodness-of-fit is $R^2 = 0.9855$ and $R^2 = 0.9686$ for M1 and M2 respectively. This indicates that the data points do conform to the defined distribution well. Unlike M1 and M2, M3 satisfied the null hypothesis of all 3 distributions. A decision has to be made to choose the most suitable distribution for M3. We proposed to base our selection from the distribution with the best goodness-of-fit for the M3 failure time data. M3 probability plots of exponential, Weibull and lognormal are plotted as shown in Figure 5.14 – Figure 5.16.

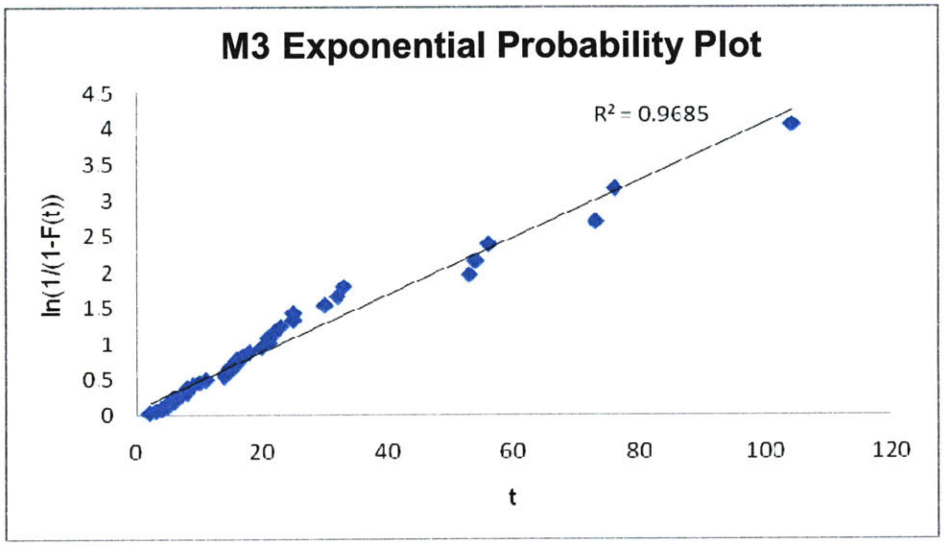


Figure 5.14: M3 exponential probability plot.

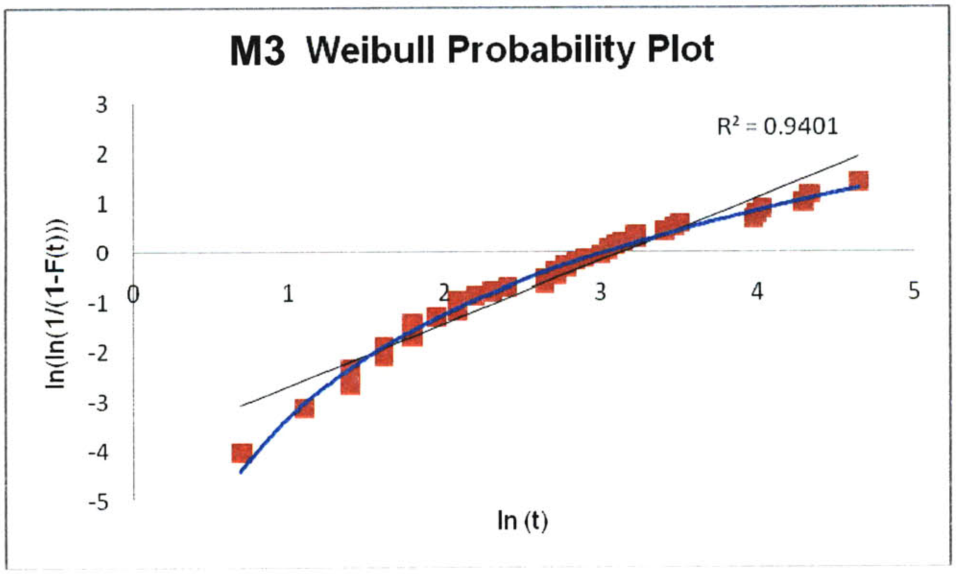


Figure 5.15: M3 Weibull probability plot.

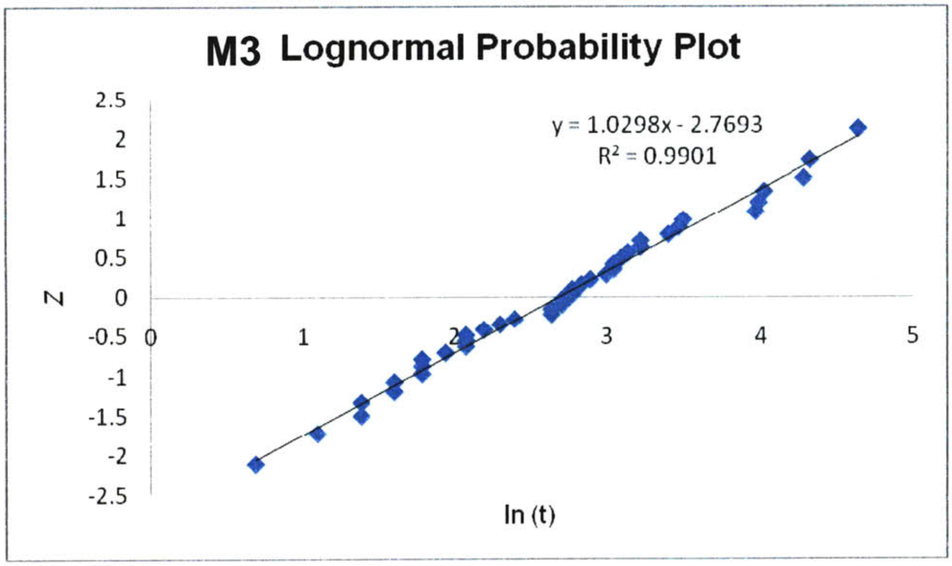


Figure 5.16: M3 lognormal probability plot.

M3 failure times estimated by a Weibull distribution yield $R^2 = 0.9401$ which is the lowest amongst the 3 distributions. In addition, as shown by Figure 5.15, the straight regression line does not conform to the data spread as well as the curved regression line. This is indicative that alternative distributions should be considered. We observe from Figure 5.14 that, although the exponential probability plot has a goodness-of-fit higher than that of the Weibull distribution, it still does not conform that well to the regression line as seen by the spread of data points for $t > 40$. Hence, attempting the lognormal probability plot, as shown in Figure 5.16, on M3 yields the best solution with an extremely high goodness-of-fit of $R^2 = 0.9901$. From the available regression equations, the parameters could then be estimated and the MTTF for each mold can be calculated.

5.2.2 Parameter Estimation

From the previous section, we assign a lognormal distribution to M1 and M3 failure times and we fit a 2-parameter Weibull distribution to the M2 failure times. Parameters within a lognormal and a Weibull distribution are comprised of a shape parameter, scale parameter and location parameter. A shape parameter determines the failure rate of a distribution. For a Weibull distribution, the shape parameter of less than 1, equal to 1 and greater than 1 yields a decreasing, constant and increasing failure rate respectively. The scale parameter influences the mean and the spread of the distribution. The scale parameter is not present in the lognormal distribution. Finally, the location parameter is seen as a minimum time before failure can occur but it is not present in a 2-parameter Weibull. In a lognormal distribution, the location parameter determines the median time to failure. Table 5.4 summarizes the equations for lognormal and Weibull density function as well as the respective nomenclature of the parameters, MTTF and variance equations [6]. The gamma function Γ(x) is defined as $\Gamma(x) = \int_0^\infty y^{x-1}e^{-y}dy$.

Table 5.4: Summary of lognormal and Weibull Density Function, Parameters, MTTF and Variance.

		Parameters				
	Density Function *f*(*t*)	**Shape**	**Scale**	**Location**	**MTTF**	**Variance**
Lognormal	$\frac{1}{\sqrt{2\pi}st}\exp\left[-\frac{1}{2s^2}\left(\ln\frac{t}{t_{\text{med}}}\right)^2\right]$ for $t \geq 0$	s	-	t_{med}	$t_{med}\exp(\frac{s^2}{2})$	$t^2_{med}\exp(s^2)[\exp(s^2)-1]$
Weibull	$\frac{\beta}{\theta}\left(\frac{t-\delta}{\theta}\right)^{\beta-1}\exp(-\frac{t-\delta}{\theta})^{\beta}$ for $t \geq \delta$ and $\delta = 0$ for 2 - parameter Weibull	β	θ	δ	$\theta\Gamma\left(1+\frac{1}{\beta}\right)$	$\theta^2\left[\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma^2\left(1+\frac{1}{\beta}\right)\right]$

The parameters can be estimated from their respective distribution probability plot best-fit line equations. The Weibull distribution plot is derived from a cumulative distribution function F(*t*) defined as

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \tag{5.2}$$

where *F(t)* = 1- *R(t)* with *R(t)* as the reliability of a system. Manipulating equation (5.2), yields the following:

$$\ln\left[\ln\left(\frac{1}{1-F(t)}\right)\right] = \beta\ln(t) - \beta\ln\theta \tag{5. 3}$$

Equation (5.3) above is analogous to a straight line plot in the form of $Y = mX + c$. Hence, the x-axis will be $\ln(t)$ plotted against y-axis in the form of $\ln\left[\ln\left(\frac{1}{1-F(t)}\right)\right]$. $F(t)$ is a median rank estimate. Failure times have to be arranged in ascending order to obtain the median rank of each failure time. The median rank [11] can be approximated to be

$$F(t) = \frac{i-0.3}{n+0.4} \quad \text{for rank}, i = 0,1,2,3,\ldots,\text{n} \tag{5. 4}$$

The parameter estimates of a lognormal distribution can be retrieved from a lognormal probability plot. The lognormal distribution plot is derived as follow

$$F(t) = \Phi\left(\frac{1}{s}\ln\frac{t}{t_{med}}\right) = \Phi(z) \tag{5.5}$$

$$\therefore z = \Phi^{-1}[F(t)] = \frac{1}{s}\ln(t) - \frac{1}{s}\ln(t_{med}) \tag{5.6}$$

where $\Phi(z)$ is the cumulative distribution function of a standardized normal variate, z. Equation (5.6) above is analogous to a straight line plot in the form of $Y = mX + c$. Hence, the x-axis will be $\ln(t)$ plotted against y-axis which is z. Similar to that of a Weibull probability plot, a median rank is a pre-requisite for a lognormal probability plot. Table 5.5 contains the calculated parameters along with the approximated MTTF and variance.

Table 5.5: Estimates of the Distribution Parameters for Entire Failure Data of each Mold.

Mold	Data Sample Size	Failure Times Distribution	R^2 value	Parameters				MTTF	σ^2
				β	θ	s	t_{med}		
M1	79	Lognormal	0.9855	-	-	0.905	7.95	11.97	181.82
M2	43	Weibull	0.9686	1.317	23.18	-	-	21.35	267.76
M3	40	Lognormal	0.9901	-	-	0.971	14.72	23.58	871.82

Table 5.5 shows that M3 is most reliable since its MTTF is the largest at ~ 24 days and M1 seems to be the least reliable since its MTTF is ~ 12 days. In the case of M1 and M3, the standard deviations (σ) of failure for each mold are larger than their respective MTTF values. However, the standard deviation of failure for M2 is observed to be lesser than its

MTTF. Although M2 has a standard deviation of failure of ~ 16 days, which is less than its MTTF, it is still considered large. The large standard deviation of failure for each mold is indicative that the failure times of the molds vary tremendously with large differences between the minimum and maximum MTTF. This poses a challenge in assigning a preventive maintenance scheme.

5.2.3 Mold Reliability

It is useful to observe how the molds perform its required functions over time. The reliability function $R(t)$ equals the probability that the mold survives (does not fail) until time t; that is, it is the probability the failure time is greater than t. The reliability equations [6] for a lognormal distribution and Weibull distribution are:

$$R(t) = 1 - \Phi\left(\frac{1}{s}\ln\frac{t}{t_{med}}\right) \tag{5.7}$$

$$R(t) = \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \tag{5.8}$$

Figure 5.17 shows the reliability of the molds based on the entire failure data. It is clear that M1 has the poorest reliability since the reliability curve decreases at a faster rate as opposed to those representing M2 and M3. M2 and M3 demonstrate similar reliability. Upon closer observation, M3 exhibits poorer reliability than M2 for $5 < t < 32$ days but for $t > 32$ days, the reliability of M2 deteriorates more quickly than M3. The mold reliability curve can help engineers identify the performance trend of the mold in anticipation to prepare for failures.

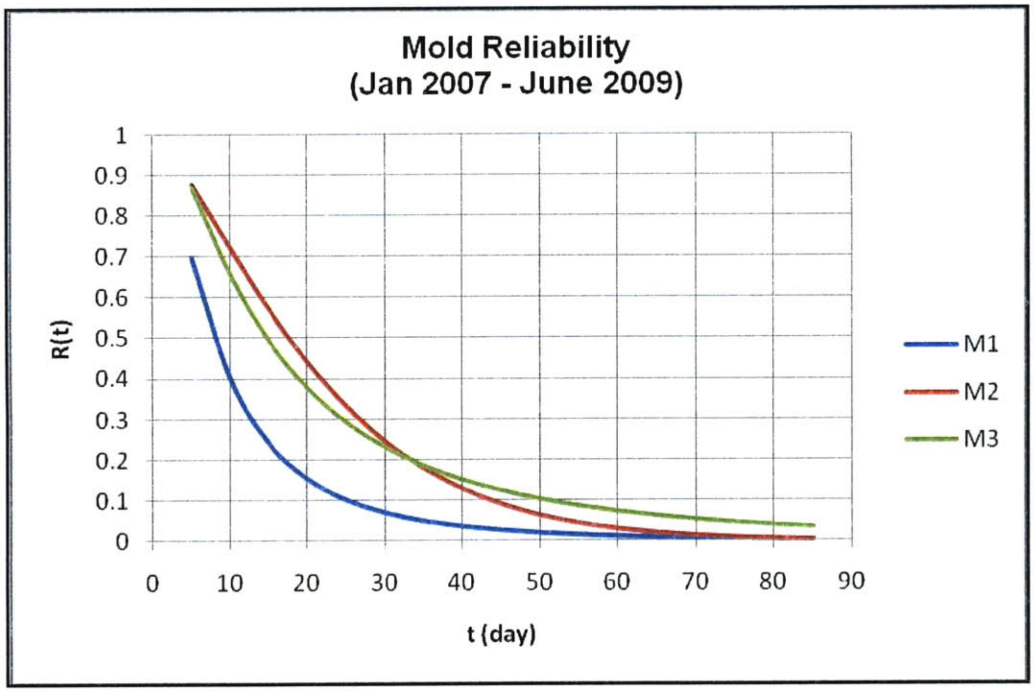


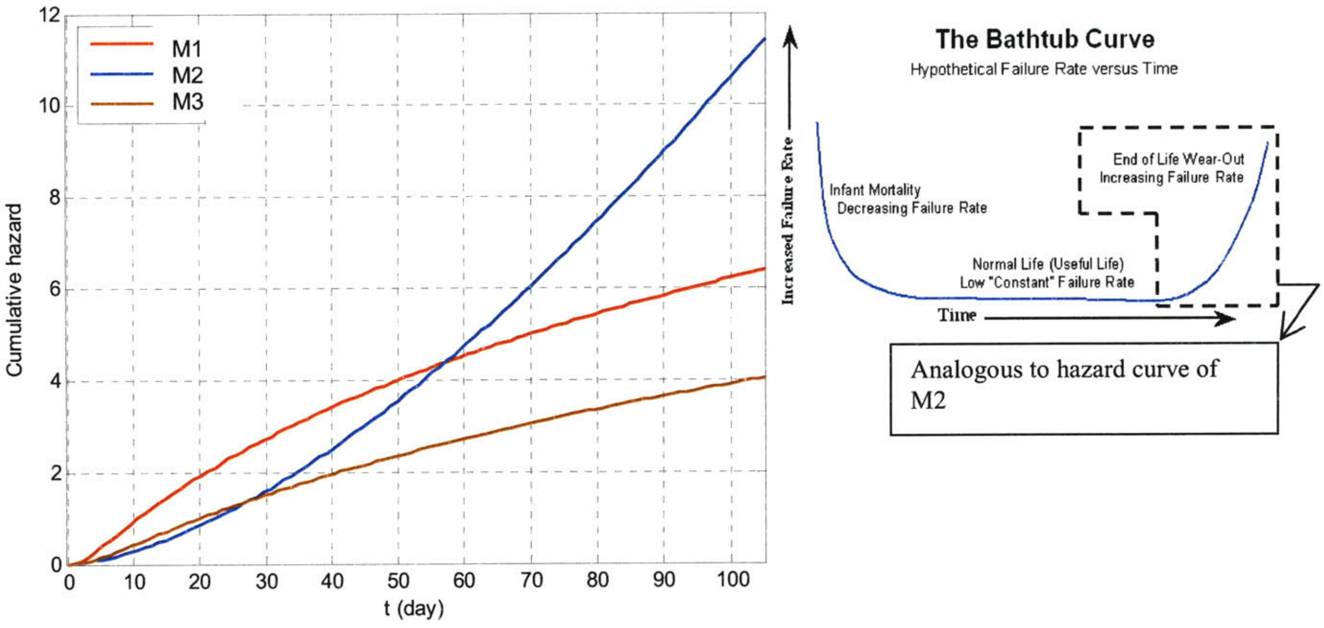
Figure 5.17: Mold reliability plot.

Besides the reliability curve, we explored the hazard rate, λ(t), of the molds. The hazard rate equals the instantaneous rate of failure at time *t*. The hazard rate equations [6] for a lognormal distribution and Weibull distribution are:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\left[\frac{1}{\sqrt{2\pi}st}\exp\left(-\frac{1}{2s^2}\left(\ln\frac{t}{t_{med}}\right)^2\right)\right]}{\left[1-\Phi\left(\frac{1}{s}\ln\frac{t}{t_{med}}\right)\right]} \tag{5. 9}$$

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \tag{5. 10}$$

Figure 5.18 below shows the hazard curve for the 3 molds.



Analogous to hazard curve of M2

Figure 5.18: Hazard function plot with Bathtub Curve plot [12].

Figure 5.18 also includes the Bathtub curve which is not a depiction of a failure rate of a single component or subsystem; rather it describes the relative failure rate of an entire population of products or system over time [12]. All the 3 molds have an increasing hazard funtion unlike the Bathtub curve which has a decreasing and constant function. The Bathtub curve is proportioned into 3 distinct regions. Table 5.6 lists the regions along with a brief description of each.

Table 5.6: Explanation to the 3 different regions of the Bathtub Curve.

Bathtub Curve Region	Description
Region 1	• Infant mortality • Decreasing hazard rate • Product failure could be due to manufacturing or design error.
Region 2	• Useful life • Constant hazard rate (exponential distribution of failure times valide here)
Region 3	• Wear-out • Increasing hazard rate • Represents Weibull distribution well • Typical for mechanical systems after a long run time

The hazard function of M2 conforms closely to the wear-out stage as can be seen from its increasing hazard funtion with time. Since M2 is given by a Weibull distribution , its shape differs entirely from the hazard function curves of M1 and M3 which are described by a lognormal distribution. Between the range of $0 < t < 10$ days, hazard rates of M1 and M3 increase and at approximately $t > 10$ days, continue to increase, albeit at a decreasing rate. By far, this is significantly different from the distribution depicted by M2 where chances of survival diminishes with increasing time. Despite the approximately similar shape parameter, s, for M1 and M3 of 0.905 and 0.971 respectively, there is an obvious deviation of the hazard curve away from each other which could be attributed to the location parameter, t_{med}. Since location parameter of M3 is greater than of M1, it implies that M3 has a lower failure chance than M1, hence the observation that the hazard rate of M3 rises slower compared to M1.

The information found in Chapter 5.2 will serve as a tool in predicting how the molds should be maintained. We shall attempt to study the feasibility of scheduling the maintenance for these 3 molds in the following chapter.

6. PREDICTING SCHEDULED PREVENTIVE MAINTENANCE

It might be possible to increase the reliability of the molds by better scheduling of the preventive maintenance (PM). Since each of the 3 molds follows a different failure-time distribution, we would not expect the PM for the molds to be the same. For molds that are problematic, as in those that fail more often, PM can be scheduled more regularly. For molds that are less problematic, less frequent PM can be scheduled for them, reducing the production disruption of these molds.

The TS performing the PM would have a specific task list to conform to. PM task lists for M1, M2 and M3 can be found in Appendix D1 – Appendix D3. The tasks to be undertaken during a PM include checking of critical dimenions of some mold components, cleaning the mold components and replacing defective components wherever necessary. Each task is planned out, in a hope to prevent defects from occuring which might affect the product and/or the mold itself. However, the task list is not exhaustive; thus it is difficult to prevent all the defects from occuring. Even if the task list was complete, the complexity and unpredictability of the injection molding process will still leave many defects unprevented. It must be made clear that the PM cannot totally eradicate defects from occurring. It seeks only to mitigate the defects occurrences.

In our recommendation, we propose to use the current PM task list alongside the priority defects list of Table 5.2 for each corresponding mold to filter out (1) which of the priority defect-types can be mitigated by performing the tasks described in the PM task list and (2) based on the failure times of these defect-types, schedule a suitable PM interval.

Table 6.1 contains the possible priority defect-types that might be mitigated upon following the PM task list. It is worth noting that the priority defect-types addressed by the PM task lists may only be a portion of all priority defect-types that were defined in Table 5.2. In addition, not all of the activities in the task list are relevant in preventing and/or reducing the occurrences of priority defect-types.

Table 6.1: Relevant PM Task List for Priority Defect-Types Mitigation.

	M1	M2	M3
Possible Defect-Types Mitigated *(Based on Priority Defects Only)*	burn mark	bulging	bulging
	carbide flash	carbide flash	burn mark
	core dent	core break	collar flash
	external drag mark	core dent	core dent
	flange flash	flange flash	tip taper undersize
	internal drag mark	retaining ring ID fail (R.R.F)	
	roof flash		
	self gate block (S.G.B)		
	sink mark		
	tip flash		

The consolidated failure times of the defects in Table 6.1 can be found in Appendix E. Here, a mold failure is considered when a mold experiences any of the mentioned defect-types in Table 6.1. Similar to consolidating mold failure times of entire defect-types, as long as these mentioned priority defect-types occur within the same repair date, the date of occurrence can be combined. The distribution which best describes each mold failure times needs to be verified. We should not assume that the distribution here would be similar to the distribution of the mold's entire failure times as obtained in Chapter 5.2. The failure times of the defects from Table 6.1 are an extracted sample from the population of all failure times. The failure time samples for M1 and M3 were found to follow the lognormal distribution whereas failure time samples for M2 was found to conform to the 2-parameter Weibull distribution. As before, for mold sample failure times that satisfy more than 1 distribution, goodness-of-fit R^2 values were used in selecting the best distribution that describes the sample failure times. Table 6.2 below describes the calculated parameters along with the approximated MTTF and variance of the sample failure times for each mold.

Table 6.2: Estimates of the distribution parameters for sample failure data of each mold based on relevant PM task list for priority defect-types mitigation. Table 5.5 is included for ease of comparison.

Mold	Data Sample Size	Failure Times Distribution	R^2 value	Parameters				MTTF	σ^2
				β	θ	s	t_{med}		
M1	76	Lognormal	0.9879	-	-	0.879	8.44	12.42	179.78
M2	39	Weibull	0.9888	1.70	25.11	-	-	22.40	183.89
M3	30	Lognormal	0.9861	-	-	1.08	17.69	31.70	2219.68

Information from Table 5.5

Mold	Data Sample Size	Failure Times Distribution	R^2 value	Parameters				MTTF	σ^2
				β	θ	s	t_{med}		
M1	79	Lognormal	0.9855	-	-	0.905	7.95	11.97	181.82
M2	43	Weibull	0.9686	1.317	23.18	-	-	21.35	267.76
M3	40	Lognormal	0.9901	-	-	0.971	14.72	23.58	871.82

Comparing Table 6.2 with Table 5.5 reveals that MTTF values between the consolidated priority defect-types targeted by the PM task lists and the entire failure occurrences show differences. This is apparent as the data sample size for the entire failure occurrences is larger than that of the priority defect-types from the PM task lists. Hence, the priority defect-types from the PM task lists reflect fewer failures. As a consequence, the MTTF values for the distribution of priority defect-types from the PM task lists are larger than the MTTF values of the distribution of the entire failure data. Most apparent is the MTTF value of prioirty defect-types for M3 where 25% fewer failures correspond to a 27% increase of the MTTF value.

The study made on the targeted priority defect-types by the individual mold PM task lists shows that priority defect-types do not occur at the same intervals as compared to the entire defect-types. As such, in planning for a mold PM, planners must be specific as to the defects that they intend to mitigate. This highlights the importance of setting the PM task lists properly.

Ideally, the PM interval has to be shorter than the specified MTTF before any improvement on mold reliability can be noticed. Performing PM at short intervals might be disruptive to the production runs but this does not necessarily mean that the PM interval for a particular mold has to remain short forever. Perhaps, when mold reliability begins to improve, the PM interval for that mold can be lengthened.

The following section analyzes how frequently the respective mold PMs, following the current task list, should be conducted. The expected number of mold failures with performing the different PM schedules would be used as a measure of effectiveness of the PM.

6.1 Validity of PM Schedule for Current PM Task List

Technical Specialists performing PM on molds M1, M2 and M3 follow the PM task list very closely. The previous section summarized the possible priority defect-types that might be alleviated by following the task list. However, MTTF values for cumulative priority defects occurrences of each mold are small. These defects are still occuring often despite the conformance to the PM task list. It is possible that the PM interval is not properly set for each mold. At present, PM for each mold is scheduled to be performed once in every 6 months. Chapter 6.1 shall investigate the expected number of failures for each mold for various PM intervals based on parameters found in Table 6.2. The expected number of failures for a mold would serve as a metric to justify the scheduling of the PM interval for the particular mold.

6.1.1 Estimating Expected Number of Mold Failures within Specified PM Interval

In this investigation, we assume that the state of the mold to be restored to its new condition following a maintenance activity. This assumption can also be extended to the mold components that make up the mold. This assumption is one of the common defining features of models of the behavior of repairable systems [13]. We have already filtered out the priority defect-types that the PM task lists are capable of mitigating. From the failure times of these priority defect-types, we managed to assign a statistical distribution to them which enabled us to derive the MTTF (μ) and variance (σ^2) of their occurrences. We proceed with using the available assumption and relevant data to estimate the expected number of failures for each mold using the renewal process theory.

Based on a renewal process, the failure times are assumed to be independent and identically distributed (IID). We consider that a mold is operated until failure occurs and the ensuing repair activities are carried out until the mold is able to resume operating to an "as-good-as-new" condition. Then, the expected number of failures, $M(t)$, in the interval (0, t] can be expressed as [14]:

$$M(t) = F(t) + \int_0^t M(t-x) f(x) dx \tag{6.1}$$

Equation (6.1) is refered to as the fundamental renewal equation. It is a continuous time, parametric renewal function. To simplify our analysis, we adopted the continuous time, non-parametric renewal function to estimate the mold failure within 1 PM interval. The equation is as follow:

$$N_f \approx \frac{T}{\mu} + \frac{\sigma^2 - \mu^2}{2\mu^2} \tag{6.2}$$

where N_f represents the expected number of mold failures within a PM interval, T represents the PM time interval, μ represents the MTTF of the specified mold failure distribution and σ represents the mold failure-time standard deviation. A more detailed derivation of Equations (6.1) and (6.2) can be found in Appendix C2 with references made to El-Sayed [14].

Using Equation (6.2), we estimated the expected number of mold failures within 1 PM interval. Following that, we obtain the expected number of mold failures within 1 year:

$$E[N_{f,\text{annual}}] = \frac{T_{\text{annual production}}}{T} \times N_f \qquad \textbf{(6. 3)}$$

The expected number of mold failures occuring annually for the various proposed PM schedules are compiled in Table 6.3 and Figure 6.1 depicts this graphically. The terms "annual" and "production year" are analogous to each other and are interchangeably used.

Table 6.3 Estimated number of mold failures for the proposed PM intervals.

Proposed PM Interval, T (day)	Number of Mold Failures in 1 PM Interval			Expected Annual Production Run (Day)			Expected Number of Mold Failures Annually		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
10	0.89	0.13	0.92	316.5	290.25	335.25	28.1	3.8	30.8
20	1.69	0.58	1.24				26.8	8.4	20.7
30	2.50	1.02	1.55				26.4	9.9	17.3
60	4.91	2.36	2.50				25.9	11.4	14.0
90	7.33	3.70	3.44				25.8	11.9	12.8
120	9.74	5.04	4.39				25.7	12.2	12.3
150	12.16	6.38	5.34				25.7	12.3	11.9
180	14.58	7.72	6.28				25.6	12.4	11.7
210	16.99	9.06	7.23				25.6	12.5	11.5
240	19.41	10.40	8.17				25.6	12.6	11.4
270	21.82	11.73	9.12				25.6	12.6	11.3

Legend: ▨ $T <$ MTTF period

Intuitively as MTTF increases, the number of mold failure within a PM interval should decrease. Comparing M1 with M2 in Table 6.3 gives proof to this deduction. However, comparing M2 with M3 exhibited a different outcome. With an MTTF greater than M2, M3 should have lesser number of mold failures within a PM interval than M2. But for

$10 \leq T \leq 60$ days, the number of mold failures within a PM interval of M3 is greater than M2. Only for $T > 60$ days, could we see that the number of failures within a PM interval for M3 to be lesser than M2. This anomaly could be attributed to the significantly large variance for M3. Based on Equation (6.2), not only is N_f governed by the MTTF of the distribution, the variance of the failure distribution affects as well. In the case of M3, for $10 \leq T \leq 60$ days, the variance of 2219 days^2 dominates hence subjecting the mold to a higher likelihood of failure.

This investigation which attempted to uncover the expected number of mold failures within a production year sought to help out PM planners in scheduling mold PM quantitatively rather than using intuition. It would be ideal to conduct PM minimally yet ensuring mold failures to remain minimal; as such production runs can be less frequently disrupted by PM activities and mold failures.

6.1.2 Recommendation for PM based on Expected Number of Annual Mold Failures

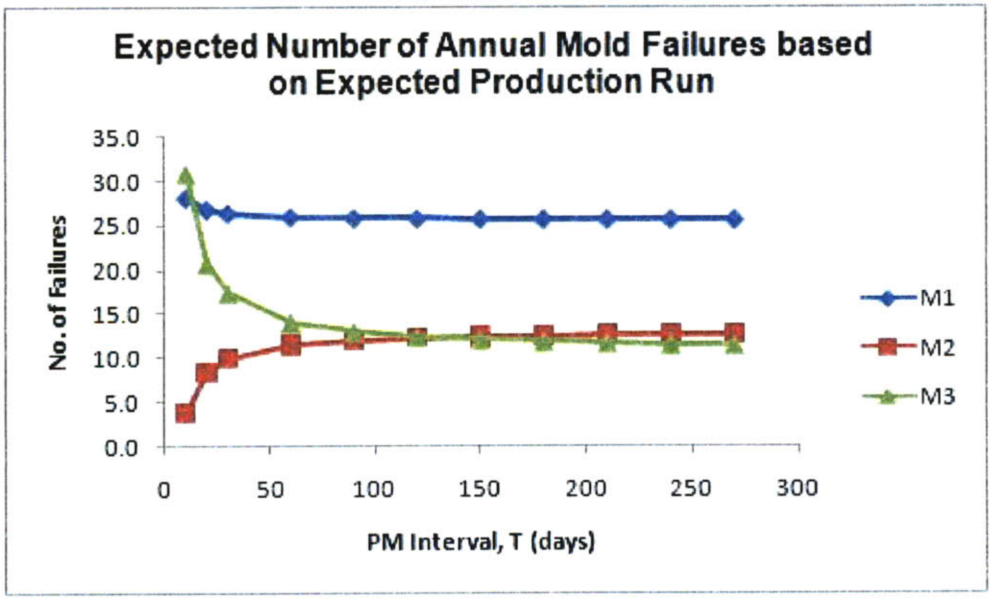


Figure 6.1: Graphical interpretation of the expected number of annual mold failures.

Figure 6.1 shows the expected number of mold failures for a year based on information in Table 6.3. We shall first look at the expected number of annual mold failures for PM intervals lesser than the MTTF for each mold. From Table 6.2, molds M1 and M3 has an MTTF value of 12.4 and 32.4 days respectively. When we performed the analysis for a PM interval of 10 days for M1 and 10 – 30 days for M3, where these are values lesser than their MTTF periods, we found that the molds suffer more failure in a production year as compared to scheduling PM at longer intervals. Meanwhile, performing analysis for a PM interval of 10 and 20 days for M2, which are lesser than its MTTF of 22.4 days, indicates that the number of mold failures within a production year remain small as compared to scheduling PM at longer intervals.

From the above differences, scheduling a PM interval lesser than the MTTF of the failure distribution may not necessarily be applicable to all mold types. It really depends on the failure distribution of the particular mold. In addition, scheduling a PM interval lesser than the MTTF of the failure distribution increases the number of PM within a production year. This will be very disruptive to production and hence, might strain the already tight production schedule. Customer demands might not be met on time.

Based on the considerations made above and from data found in Table 6.3, we shall determine a suitable PM schedule for each of the 3 molds. Figure 6.1 shows that for $10 \leq T \leq 30$ days, M1 exhibits a rapidly decreasing number of expected annual mold failures. For $T \geq 60$ days, $E[N_{f,\text{annual}}]$ for M1 begins to show little change. In choosing a suitable PM schedule for M1, we recommend that M1 can resume having PM conducted once in every 6 months (i.e. $T = 180$ days) since at $T = 180$ days, $E[N_{f,\text{annual}}]$ is the lowest.

M3 exhibits a rapidly decreasing number of expected annual mold failures for $10 \leq T \leq 90$ days. For $T > 100$ days, $E[N_{f,\text{annual}}]$ continues to decrease slightly at a constant rate. Similar to the case of M1, we find that if M3 resumes its current PM practice of once in every 6 months, $E[N_{f,\text{annual}}]$ will still be amongst the lowest. Hence, there is no necessity to change the current PM schedule for M3.

M2, on the other hand, shows a trend opposite to that of M1 and M3. From Figure 6.1, we observe that the expected number of annual mold failures increase at a decreasing rate for $10 \leq T \leq 90$ days. For $T > 100$ days, $E[N_{f,\text{annual}}]$ continues to increase slightly at a constant rate. For M2, performing PM once in every 10 days or 20 days will definitely be the ideal choice as the annual number of mold failures is estimated to be as low as 3.8 and 8.4 respectively but practically, it could be too disruptive to production. So, the next best alternative would be to recommend for PM performed once in every month, i.e. $T =$ 30 days, which would provide for 2.5 less mold failures as compared to the current PM practice performed once in every 6 months.

6.2 Future Work

A possible area of study is to formulate a PM task list that is sectioned according to the priority level of the tasks. Tasks that are intended to target high priority defect-types should be performed more frequently to ensure reduction of high-occurring defects. Tasks that target low priority defect-types should be performed less frequently so that unnecessary time will not be spent on elaborately inspecting and cleaning mold components responsible for the low priority defect-types. The failure time data used for the respective defect-types has to be more extensive, i.e. use mold history data that spans 5 years, so as to better predict the distribution of the low-occurring defect types.

7. CONCLUSION

This thesis examined the reliability of Product S barrel molds M1, M2 and M3 for the purpose of predicting PM. Available for this study was mold defects and mold failure times data between January 2007 and June 2009.

We looked at the distribution of mold defects affecting the cavity positions. The analysis conducted pointed out that at least 6% of all defects within a particular mold affect a single cavity position. This might seem insignificant but if we consider that each mold has either 32 or 48 cavity positions and there are a total of 52 mold defects, we might find this percentage to be quite substantial. There were no clusters of cavity positions that were heavily defective. Therefore, it is not possible to isolate the region(s) of the mold for scrutiny. Hence, cavity positions can randomly become defective. Mold defects for each mold were subjected to a Pareto Chart analysis. The priority defects for each mold would be selected according to defect-types that constitute 80% of all mold failures. A list of components was mapped to these mold defects to give a better appreciation of the possible parts that might need to be replaced in the occurrence of each defect. In addition, this thesis brought up an idea of using defect density, i.e. the ratio between total number of defects occurred per cavity position to the total types of defects occurring on that same position, as a performance measure to cavity defects tracking. Assessing the 3 molds, we found the mean defect density to be 1.85 which led us to conclude that each cavity has a high probability to be affected at least twice by the same mold defect. Possible reasons could include repeated negligence in repair or simply the inability to find root cause solution as yet.

We performed statistical distribution tests on the failure times of the molds and found that failure times of M2 follow a Weibull distribution whereas failure times of M1 and M3 conform well to a lognormal distribution. Based on these distributions, parameter estimates were obtained. This would eventually be used in the reliability study of the molds. The reliability of M1 diminishes more rapidly than M2 and M3. Plotting of a cumulative hazard function showed that M2 conformed to Region 3 of the bathtub curve with increasing failure rate while M1 and M3 follow the hazard function for a lognormal distribution where it increases at a decreasing rate.

Finally, this thesis looked into the scheduled preventive maintenance (PM) of the molds based on the current PM task list. Failure times based on individual mold PM tasks that correspond to the mitigation of the priority defect-types, were recorded and assigned a statistical distribution. The obtained parameters were used to attain the expected number of mold failures in a production year. Currently, all 3 molds had PM performed on them once in every 6 months. We assumed a renewal process for these molds where each repair or maintenance activity restores the mold to an "as-new" condition. These sample failure times were assumed to be independent and identically distributed. This study showed that scheduling a PM interval smaller than the MTTF of the mold's failure distribution may not necessarily derive the best outcome. Even if performing a PM at an interval less than the MTTF produces the least expected mold failures annually, it may not be practical as more disruptions will be incurred on the production thus creating the possibility of not fulfilling customer demands on time. As such, we recommend for PM on M1 and M3 to continue at once in every 6 months. We recommend PM on M2 to be performed once every month. PM intervals were selected based on (1) the number of expected annual mold failures that are as low as possible and (2) production practicality.

REFERENCES

[1] E. A. Campo, "Complete Part Design Handbook – For Injection Molding of Thermoplastics", Hanser Publishers © 2006, pp. 588.

[2] W. Zhou, "Manufacturing Technology and Materials", Nanyang Technological University Lecture Notes © 2005.

[3] Y. C. Lim, "Setting Optimal Inventory Policy for Mold Spare Components in a Medical Device Production Facility", M. Eng. (Manufacturing) Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 2009.

[4] Y. L. Lin, "Improving Information Flow Process for Molding Maintenance Operations in a Medical Device Manufacturing Facility", M. Eng. (Manufacturing) Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 2009.

[5] D. M. Bryce, *Plastic Injection Molding: Manufacturing Process Fundamentals.* Dearborn, Michigan : Society of Manufacturing Engineers, 1996.

[6] C. E. Ebiling, *Reliability and Maintainability Engineering.* Singapore : McGraw-Hill Publication, 1997.

[7] L. M. Pintelon and F. L. Gelders, *Maintenance Management Decision Making.* European Journal of Operational Research, Issue 58, Elsevier Science Publishers, 1992, pp. 310-317.

[8] K. S. Wang, Y. T. Tsai and H. C. Lin, *A study of replacement policy for components in a mechanical system..* Reliability Engineering and System Safety, Vol. 58, Elsevier Science, 1997, pp. 191-199.

[9] A. K. S. Jardine and A. H. C. Tsang, *Maintenance, Replacement and Reliability: Theory and Applications.* Boca Raton, Florida: CRC Taylor & Francis, 2006.

[10] W. R. Blischke and D. N. P. Murthy, "Case Studies in Reliability and Maintenance" in *Component Reliability, Replacement, and Cost Analysis with Incomplete Failure Data,* N. A. J. Hastings, Ed. Hoboken, NJ : John Wiley and Sons Inc., 2003, pp. 353-375.

[11] G. S. Wasserman, *Reliability Verification, Testing and Analysis in Engineering Design.* New York : Marcel Dekker, 2003.

[12] D. J. Wilkins, "The Bathtub Curve and Product Failure Behavior". *Reliability Hotwire.* [Online] Available: www.weibull.com/hotwire/issue21/hottopics21.htm. [Cited: July 16, 2009.]

[13] J. A. Nachlas, *Reliability Engineering: Probabilistic Models and Maintenance Methods.* 1st Edition. New York : CRC Taylor & Francis, 2005.

[14] E. A. Elsayed, *Reliability Engineering.* 1st Edition. Reading : Addison Wesley Longman, Inc, 1996.

Appendix A Monthly Mold Report Form

CONFIDENTIAL

Appendix B1 M1 Mold Cavity Chart

CONFIDENTIAL

Appendix B2 M2 Mold Cavity Chart

CONFIDENTIAL

Appendix B3 M3 Mold Cavity Chart

CONFIDENTIAL

Appendix B4 Estimated Monthly Production

		Mold		
Year	**Month**	**M1 (hr)**	**M2 (hr)**	**M3 (hr)**
2008	October	600	444	732
2008	November	576	636	624
2008	December	672	564	732
2009	January	672	588	684
2009	February	564	528	456
2009	March	720	708	744
2009	April	660	576	720
2009	May	600	600	672
	Average Production (hr/mth)	633	580.5	670.5
	Annual Production Run (day)	316.5	290.25	335.25

Appendix B5 List of 52 Defect Types with Possibly Defective Mold Components

		Spare Components Affected		
Defects List Data 2007-2009	**Remarks**	**1**	**2**	**3**
blur barrel		main core	cavity block	
bulging		bubbling tube	core pin	cavity
burn mark (tip)		roof insert	tip pin	carbide
burn mark (body)		cavity block	main core	
burn mark (flange)		gate pin	stripper bush	cavity block
carbide bush break		carbide bush	tip pin	
carbide flash		carbide bush	tip pin	
cavity block dented		cavity block	thread core	main core
collar damage		sliding bush	thread core	
collar flash		sliding bush	thread core	
core bent		core		
core break		core		
core crack		core		
core dent		core	thread core	
core pitted		core		
external drag mark	FM can cause this defect	gate pin		
internal drag mark		core	main core	
flange flash		stripper bush	cavity block	
flow mark		gate pin		
G.D.M	FM can cause this defect	gate pin		
gate protrusion		gate pin		
heater faulty(broken)		heater resistance		
hot core		bubbling tube	core pin (hole offset)	
part stuck in cavity		cavity		
pitted mark (tip)		tip pin	roof insert	
pitted mark (body)		main core	cavity block	
pitted mark (flange)		stripper bush	cavity block	
poor drop		main core	core cooling	
R.R.F		core	stripper bush	
retainer ring oversize		core		
retainer ring undersize		core		
roof flash		roof insert	cavity block	
roof void		roof insert	roof insert	

rough surface (tip)		roof insert	tip pin	
rough surface (body)		main core	cavity block	
rough surface (flange)		stripper bush	cavity block	
S.G.B		gate pin	cartridge heater	
short molding		gate pin	gate hole	cavity block
sink mark (tip)		roof insert	tip pin	
sink mark (body)		cavity block	cavity	main core
sink mark (flange)		stripper bush	gate pin	gate hole
thread core break		thread core	pinion	sliding bush
tip block		tip pin	main core	carbide
tip flash		tip pin	carbide	
tip OD fail		thread core		
tip OD oversize		thread core		
tip pin chip off		tip pin	carbide bush	
tip pin damage		tip pin	carbide bush	
tip pin drop off		tip pin	main core	
tip taper oversize		thread core	gate hole	
tip taper undersize		thread core	gate hole	
water mark		main core	cavity block	

Appendix B6 Failure Times Data for All Defects Occurrences

Rank, i	Failure time, t_i (days)		
	M1	M2	M3
1	1	1	2
2	1	1	3
3	1	3	4
4	2	4	4
5	2	4	5
6	2	7	5
7	2	7	6
8	3	8	6
9	3	8	6
10	3	8	7
11	3	11	8
12	3	11	8
13	3	12	8
14	3	13	9
15	4	14	10
16	4	14	11
17	4	14	14
18	4	16	14
19	4	17	15
20	4	18	15
21	5	18	16
22	5	19	16
23	5	20	17
24	5	20	18
25	6	21	20
26	6	21	21
27	6	22	21
28	6	22	22
29	6	22	23
30	6	24	25
31	6	25	25
32	7	25	30
33	7	30	32
34	7	31	33
35	7	31	53
36	7	34	54
37	7	35	56
38	7	37	73
39	7	39	76
40	8	42	104
41	8	43	
42	8	48	
43	8	48	
44	8		
45	9		
46	9		
47	9		
48	9		
49	10		
50	10		
51	10		
52	12		
53	12		
54	12		
55	13		
56	13		
57	14		
58	14		
59	16		
60	16		
61	18		
62	18		
63	18		
64	18		
65	19		
66	19		
67	20		
68	20		
69	21		
70	24		
71	27		
72	27		
73	28		
74	29		
75	31		
76	32		
77	36		
78	37		
79	51		

Appendix C1 Statistical Distribution Tests Formulae

Mann's test for Weibull Distribution

Mann's test for Weibull Distribution is based on the following test statistic:

$$M = \frac{k_1 \sum_{i=k_i+1}^{r-1} [(\ln t_{i+1} - \ln t_i)/M_i]}{k_2 \sum_{i=1}^{k_1} [(\ln t_{i+1} - \ln t_i)/M_i]}$$

$$M_i = Z_{i+1} - Z_i$$

$$Z_i = \ln\left[-\ln\left(1 - \frac{i-0.5}{n+0.25}\right)\right]$$

where $k_1 = \left[\frac{r}{2}\right], k_2 = \left[\frac{r-1}{2}\right]$, n = total no. of samples, r = no. of failures and i = rank position

The hypotheses are:
H_0: The failure times are Weibull
H_1: The failure times are not Weibull

Based on a 95% confidence interval, H_o is accepted if $M < F_{\text{crit}, 0.05, v_1, v_2}$.

Kolgomorov-Smirnov test for Lognormal Distribution

Kolgomorov-Smirnov test for Lognormal Distribution is based on the following test statistic:

$D_n = \max\{D_1, D_2\}$, where

$$D_1 = \max_{1 \le i \le n}\left\{\Phi\left(\frac{t_i - \bar{t}}{s}\right) - \frac{i-1}{n}\right\}, \quad D_2 = \max_{1 \le i \le n}\left\{\frac{i}{n} - \Phi\left(\frac{t_i - \bar{t}}{s}\right)\right\}$$

$$D_{crit,\alpha=0.05} = \frac{0.886}{\sqrt{n}} \text{ (based on K - S test for Nomality (Lilliefors test))}$$

$$\bar{t} = \sum_{i=1}^{n} \frac{t_i}{n} \text{ and } s = \sqrt{\frac{\sum_{i=1}^{n} (t_i - \bar{t})^2}{n-1}}$$

The hypotheses are:
H_0: The failure times are Lognormal with the specified $\bar{t}$ and s.
H_1: The failure times are not Lognormal with the specified $\bar{t}$ and s.

H_0 accepted if $D_n < D_{crit}$.

Bartlett's test for Exponential Distribution

Bartlett's test for Exponential Distribution is based on the following test statistic:

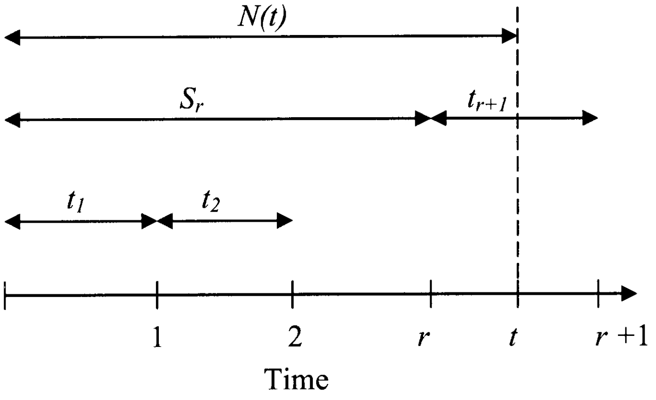
$$B = \frac{2r\left[\left(\ln\left(\frac{1}{r}\right)\sum_{i=1}^{r} t_i\right) - \left(\left(\frac{1}{r}\right)\sum_{i=1}^{r} \ln t_i\right)\right]}{1 + \left(\frac{r+1}{6r}\right)}$$

The hypotheses are:
H_0: The failure times are exponential.
H_1: The failure times are not exponential.

The selection of the hypotheses is based on the chi-square distribution with r-1 degrees of freedom.
H_0 accepted if $\chi^2_{1-\alpha/2,r-1} < B < \chi^2_{\alpha/2,r-1}$.

Appendix C2 Renewal Process Formulation

The fundamental renewal equation can be derived via the parametric renewal function estimation using continuous time.



Nomenclature:

$N(t)$: the number of failures in interval $(0, t]$ where t can be the PM interval

$M(t)$: the expected number of failures in interval $(0, t] = E[N(t)]$, where $E[\ ]$ denotes expectations

t_i: length of time interval between failures $i - 1$ and i

S_r: total time up to the r^{th} failure

The probability that the number of failures $N(t) = r$ is the same as the probability that t lies between rth and $(r + 1)$th failure. Hence,

$P[N(t) < r] = 1 - F_r(t)$

where $F(t)$ is the cumulative distribution function of S_r i.e. $F_r(t) = P[S_r \leq t]$, then $P[N(t) > r] = F_{r+1}(t)$.

However, $P[N(t) < r] + P[N(t) = r] + P[N(t) > r] = 1$, thus $P[N(t) = r] = F_r(t) - F_{r+1}(t)$.

The expected value $N(t)$ is

$$M(t) = \sum_{r=0}^{\infty} rP[N(t) = r]$$

$$= \sum_{r=0}^{\infty} r[F_r(t) - F_{r+1}(t)]$$

$$= \sum_{r=1}^{\infty} F_r(t)$$

$= F(t) + \sum_{r=1}^{\infty} F_{r+1}(t)$ where $F_{r+1}(t)$ is the convolution of $F_r(t)$ and F.

Letting f be the probability distribution function of F, $F_{r+1}(t) = \int_0^t F_r(t-x)f(x)dx$

$$\therefore M(t) = F(t) + \sum_{r=1}^{\infty} \int_0^t F_r(t-x)f(x)dx$$

$$= F(t) + \int_0^t \left[\sum_{r=1}^{\infty} F_r(t-x) \right] f(x)dx \tag{C2.1}$$

$= F(t) + \int_0^t M(t-x)f(x)dx$ (FUNDAMENTAL RENEWAL EQUATION)

The fundamental renewal equation can be estimated using the mean (μ) and standard deviation (σ) of the failure times distribution within interval (0, *t*]. A non-parametric renewal function estimation for continuous time can be derived as described below.

Consider the form of M(t) as $t \to \infty$. The Laplace transform of the p.d.f. of the failure time *f*(*t*) is *f**(*s*). From the Laplace Transform properties, μ and σ of failure time can be determined by using the following equations:

$$\left.\frac{df^*(s)}{ds}\right|_{s=0} = -\mu \text{ and } \left.\frac{d^2 f^*(s)}{ds^2}\right|_{s=0} = \sigma^2 + \mu^2,\ f^*(0) = 1$$

So from the above equation, we can express *f**(*s*) as a Taylor series expansion around point

s = 0:

$$f^*(s) = 1 - s\mu + \frac{1}{2}s^2(\sigma^2 + \mu^2) + O(s^2) \tag{C2.2}$$

where O(s^2) denotes a function of s tending to 0 as $s \to 0$ faster than s^2.

From Laplace transforming the fundamental renewal equation of (C2.1), we get

$$M^*(s) = \frac{f^*(s)}{s[1 - f^*(s)]} \tag{C2.3}$$

Substituting (C2.2) into (C2.3), $M^*(s) = \dfrac{1 - s\mu + \frac{1}{2}s^2(\sigma^2 + \mu^2) + O(s^2)}{s^2\mu - \frac{1}{2}s^3(\sigma^2 + \mu^2) + O(s^3)}$ (C2.4)

By subjecting (C2.4) to partial-fraction-expansion form of

$$g(s) = \frac{N(s)}{D(s)} = \frac{N(s)}{\prod_{i=1}^{n}(s + r_i)} = \frac{A_1}{s + r_1} + \frac{A_2}{s + r_2} + \ldots + \frac{A_n}{s + r_n}$$

and then performing an inverse Laplace transform as $t \to \infty$, we obtain the approximated expected number of failures for (0, *t*],

$$M(t) \approx \frac{T}{\mu} + \frac{\sigma^2 - \mu^2}{2\mu^2}$$

Appendix D1 M1 PM Task List

CONFIDENTIAL

M1 PM Task List (2of 2)

D

CONFIDENTIAL

Personnel Number NA

Comments NA

20.05.2009 **30NGP** **Copy** **2** **Page** **2/ 2**

Appendix D2 M2 PM Task List

CONFIDENTIAL

12.05.2009 30NGP Original Page 1/ 2

M2 PM Task List (2of 2)

CONFIDENTIAL

Personnel Number NA

Comments NA

12.05.2009 **30NGP** **Original** **Page** **2/ 2**

Appendix D3 M3 PM Task List

CONFIDENTIAL

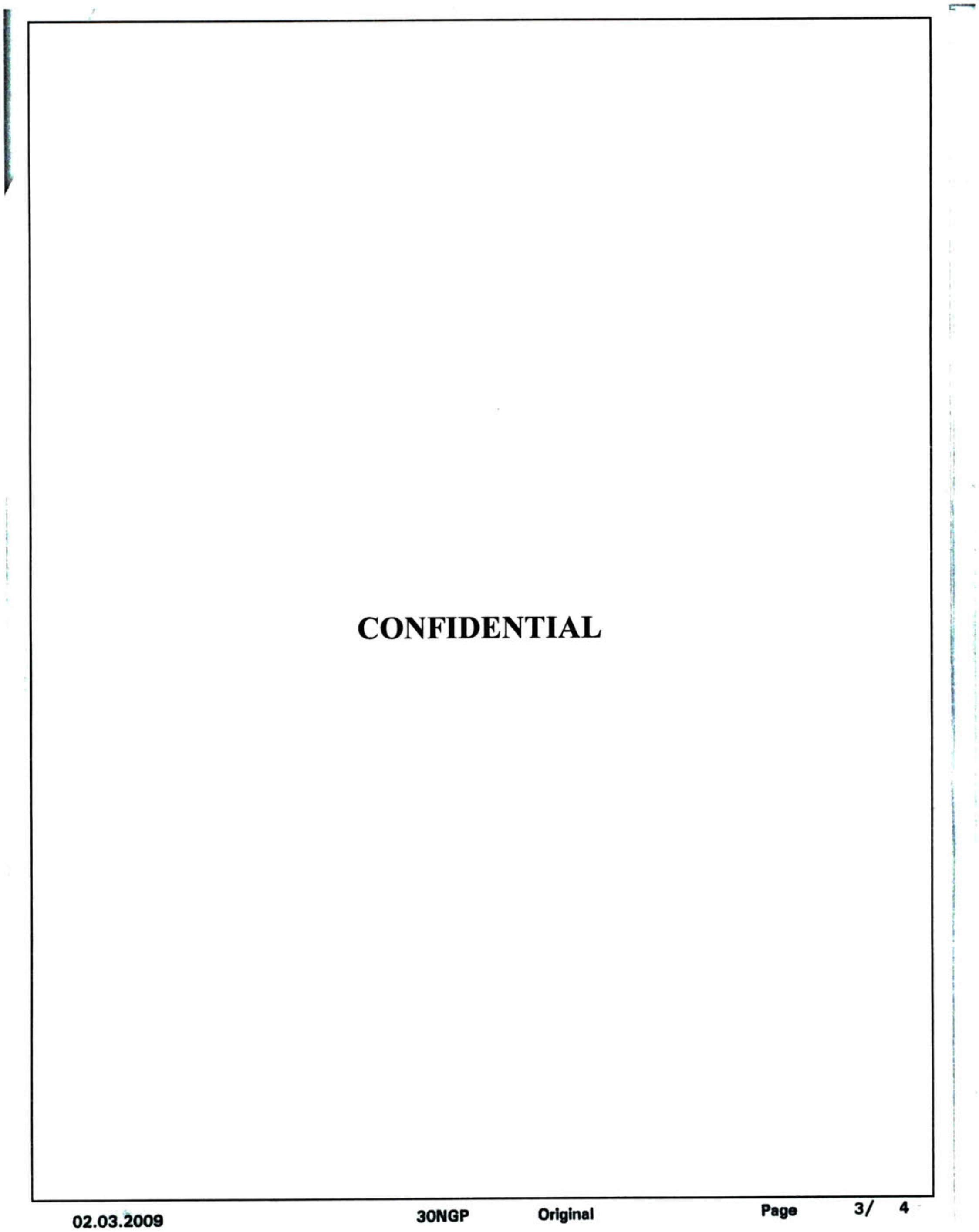
02.03.2009 30NGP Original Page 1/ 4)

M3 PM Task List (2 of 4)

CONFIDENTIAL

02.03.2009 30NGP Original Page 2/ 4

M3 PM Task List (3 of 4)



CONFIDENTIAL

02.03.2009 30NGP Original Page 3/ 4

M3 PM Task List (4 of 4)

CONFIDENTIAL

Personnel Number NA

Comments NA

02.03.2009 **30NGP** **Original** **Page** **4/ 4**

Appendix E Failure Times for Priority Defect-Types based on PM Task List

Rank, i	Failure time, t_i (days)		
	M1	M2	M3
1	1	3	2
2	1	4	3
3	2	5	5
4	2	7	5
5	2	7	6
6	2	8	7
7	3	8	8
8	3	8	8
9	3	11	9
10	3	12	11
11	3	14	14
12	3	14	14
13	4	14	15
14	4	16	15
15	4	17	16
16	4	18	17
17	4	18	18
18	5	19	21
19	5	20	22
20	5	21	22
21	5	21	25
22	5	22	33
23	6	22	41
24	6	22	48
25	6	24	55
26	6	25	56
27	6	25	76
28	6	30	84
29	7	31	95
30	7	32	104
31	7	33	
32	7	34	
33	7	35	
34	7	37	
35	8	39	
36	8	42	
37	8	43	
38	8	48	
39	8	59	
40	9		
41	9		
42	9		
43	9		
44	9		
45	10		
46	10		
47	10		
48	12		
49	12		
50	12		
51	13		
52	13		
53	14		
54	14		
55	14		
56	16		
57	16		
58	18		
59	18		
60	18		
61	18		
62	19		
63	19		
64	20		
65	20		
66	21		
67	24		
68	27		
69	27		
70	28		
71	29		
72	31		
73	32		
74	36		
75	37		
76	51		