การปรับปรุงอัตราผลตอบแทนการลงทุนด้านคุณภาพของกระบวนการผลิตแม่พิมพ์ยางรถยนต์

นายอนณ เทพศิลป์วิสุทธิ์

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ROQI OF A TIRE MOULD PRODUCTION IMPROVEMENT: A MACHINE TOOL COMPANY CASE STUDY

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Engineering Management
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อนณ เทพศิลป์วิสุทธิ์ : การปรับปรุงอัตราผลตอบแทนการลงทุนด้านคุณภาพของกระบวนการผลิตแม่พิมพ์ยางรถยนต์ (ROQI OF A TIRE MOULD PRODUCTION IMPROVEMENT: A MACHINE TOOL COMPANY CASE STUDY)
อ. ที่ปรึกษา: ผศ.ประเสริฐ อัครประถมพงศ์, 165 หน้า

การวิจัยนี้มีวัตถุประสงค์เพื่อปรับปรุงอัตราผลตอบแทนการลงทุนด้านคุณภาพของกระบวนการผลิตแม่พิมพ์ยางรถยนต์

ในเบื้องต้นทีมงานวิจัยได้ศึกษากระบวนการผลิตและสถิติของเสียจากข้อมูลการทำงาน และได้รวบรวมต้นทุนในการผลิตต่อจากนั้นได้เริ่มวิเคราะห์ข้อบกพร่องในกระบวนการผลิต(FMEA) และได้เลือกปัจจัยที่มีค่า RPN มากกว่า 150 มาใช้ในการวิเคราะห์ พบว่าความผิดพลาดในกระบวนการผลิตมาจากขั้นตอน M2, M3, T1 และ T2 จากผลการแสดงเหตุและผล (FISHBONE DIAGRAM) พบว่าปัญหาส่วนใหญ่เกิดจากผู้ปฏิบัติงานขาดทักษะในการทำงานและความบกพร่องในการควบคุมการผลิตซึ่งได้แก้ไขโดยการอบรมและใช้เอกสารควบคุม และทีมวิจัยยังพบด้วยว่าปัญหาของขนาดและผิวงานเกิดจากการใช้สว่านและรีมเมอร์ที่ไม่เหมาะสมกับงาน ได้แก้ไขโดยใช้สว่านคาร์ไบด์และรีมเมอร์คาร์ไบด์ จากนั้นนำการออกแบบการทดลอง (2^k และ 3^k แฟคทอเรียล)มาใช้พบว่าอัตราที่เหมาะสมของการเจาะคือ ความเร็วตัด (Vc) ที่ 95 มม./นาที และอัตราแรงป้อนของแกนหลัก (fz) ที่ 0.1404 มม./ฟัน ค่าที่เหมาะสมของการรีมเมอร์คือ VC ที่ 110 มม./นาที และ fz ที่ 0.0611 มม./ฟัน

ผลของการปรับปรุงอัตราผลตอบแทนการลงทุนด้านคุณภาพของกระบวนการผลิตแม่พิมพ์โดยรวมคือ 12.54 เท่า และอัตราผลตอบแทนจากการเปลี่ยนสว่านและรีมเมอร์คือ 42.5 เท่า

ศูนย์ระดับภูมิภาคทางวิศวกรรมระบบการผลิต ลายมือชื่อนิสิต..............................

สาขาวิชา การจัดการทางวิศวกรรม ลายมือชื่ออาจารย์ที่ปรึกษา..............................

ปีการศึกษา 2550

##48781648221 : MAJOR ENGINREERING MANAGEMENT
KEY WORD: RETURN ON QUALITY INVESTMENT/ FAILURE MODE AND EFFECT ANALYSIS/ DESIGN OF EXPERIMENT
ARNON THEPSILVISUTHI: ROQI OF A TIRE MOULD PRODUCTION IMPROVEMENT: A MACHINE TOOL COMPANY CASE STUDY
THESIS ADVISOR: ASST. PROF. PPRASERT AKKHARAPRATHOMPHONG, 165pp.

The objectives of this research is to reduce the number of defects in the tire mould production and calculating the return on quality investment of the process improvement.

Initially, the team study the production process, statistics and the cost calculation method. FMEA is used to investigate the failure modes. The failure modes with RPN above 150 are selected for further analysis. They are from 4 processes, machining M2 & M3 and turning T1& T2. Fishbone analysis revealed that most of the problem come from inadequate control system and unskill operator. Training are given and controll doccuments are introduced. The team also found that the drill and reamer used for maching M3 process is inappropriate, creating oversized hole with rough surface. The carbide drill and inserted reamer will be tested via DOE. From screening experiment (2^k factorial), cutting speed (Vc) and feed rate per tooth (fz) is found significant. 3^k factorial technique is then used to find the optimal cutting parameters to obtain diameter between 19.85-19.86mm. The calculated Vc and fz are 95mm/min and 0.1404mm/tooth respectively. 3^k factorial technique is employed to find optimal reamer condition. The optimal cutting parameters are 110mm/min for Vc and 0.0611mm/tooth for fz respectively with target diameter of 20.01mm. The calculated composite desirability of the new drill and reamer parameters are 1.

The ROQI is divided into 2 parts, the ROQI from the entire tire mould production process and ROQI from the change of the new drill and reamer. The over all ROQI on monthly basis is 12.54 times and the ROQI from new setting is 42.65 times.

The Regional Center for Manufacturing Systems Engineering — Student's signature.......
Field of study : Engineering Management — Advisor's signature.......
Acedamic year 2007

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CHAPTER I

INTRODUCTION

1.1 Introduction

The past decade has seen the recovery of the Thai economy from the 1997 financial crisis. The market is picking up and is now growing at a slow but steady rate. The government recognizes this economic trend and the potential of the Thai market; hence, they are trying to prepare the country for future global competition. To date, the government has come up with ways to attract foreign investors to set up their companies or plants in Thailand. Consequently, industries in Thailand will expand as advanced technology and high-tech equipment from abroad storm into the kingdom.

Thai manufacturers are now facing a more competitive market due to internal expansion and international challenges. For example, advancement in communication technology has overcome existing international barriers, thereby providing consumers with more choices. This situation is made worse when oil prices and raw material prices increase. Manufacturers are forced to compete on price as well, on top of quality and delivery. However, since production price determine the quality of the end product, it is therefore an important aspect that should not be overlooked. Quality and delivery should never be compromised for lower production costs. Therefore, in order to improve on production cost yet remain on the competitive edge, various tools and techniques have been developed. Only the most profitable investment should be selected.

In this thesis, the process analysis of the tire mould production will be conducted, in order to improve the productivity. Block diagrams will be implemented to study the flow process of production. Failure Mode and Effect Analysis (FMEA) will be used first to analyze and evaluate the potential failure mode of the production process. FMEA will also be accompanied by the use of cause and effect diagram (Fishbone diagram) to find the root cause of the failure. Pareto diagram will be used to identify the causes that are worth investigating, a few solutions will be studied. Design of Experiment (DOE) will be done to ensure the success of the solutions. After evaluation and investigation, the solution will be implemented and the entire process will be analyzed to improve on existing production methods. The Return on Quality Investment (ROQI) will then be calculated.

1.2 Statement of Problem

From the statistic, it was found that the company is currently facing many quality problems from both internal and internal aspects. The following table will show the production and the defects of 3 major product categories, the machine tool category, the side mould category and the tire mould category.

Part name	September (Pcs)		October (Pcs)		November Pcs)		December (Pcs)	
	Production	Defect	Production	Defect	Production	Defect	Production	Defect
Machine tool	5,319	66	5,644	188	7,436	137	7,934	85
Side mould	177	30	145	12	193	18	159	8
Tire mould	20	10	22	8	22	6	20	8

Table 1.1 : Monthly Production Report from June to September, 2006

The above table summarizes the amount of production in each category of the products. It can be seen that in term of the quantity, machine tool has the highest amount of production. However, the value of the products might be lower than the rest as it also consists of small turning and grinding parts which are ordered in large batches. The tire mould has the highest value as they are made from large casting.

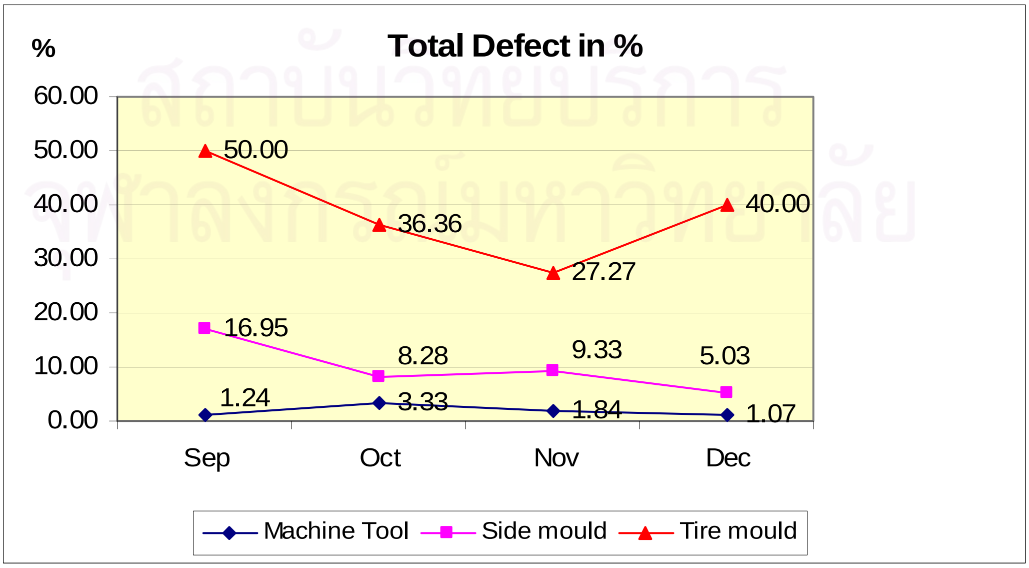


Figure 1.1 : Graph of Production Defects in Percentage

In Figure 1.1, the graph shows the percentage of the defects in each section. The defect percentage of the machine tool section is the lowest when compared to the others. The highest defect rate is from the tire mould category. The average rate for the tire mould during the 4 months period is 38.1%, which is the highest in the company, side mould has the average value of 10.29% and the value for machine tool is 1.81%.

Currently, the managements have a high concern over the production of the tire mould, because of the high defect rate. The production of the tire mould is expected to double in 2007 and more customers with similar products are expected. Large amount of valuable resources will be lost if the defect rate is not reduced. Therefore, the managements would like to look into the production of the tire mould and try to improve the productivity.

1.3 Objectives

1. To reduce the defect in tire mould production for customer A.
2. To find various ways to improve the production, and choose the most appropriate solution.
3. To evaluate the return on quality investment of the selected solution.

1.4 Scope of Study

1. The study will be conducted base on the production of the tire mould for customer A only.
2. Only quality costs that are applicable will be included. These costs will be calculated from non-conformance products which have been found by the customers.

   External failure costs that will be included are defects, and claim.

   Internal failure cos t such as scrape, repair, rework, re-inspection, and rework will be used.

Prevention costs that will be taken into account are quality planning, production planning, calibration, maintenance of quality measurement tools, and test equipment.

1.5 Expected Benefit

1. Increase the productivity and reduce the defect rate of the product in the case study.
2. Increase the profitability of the company by choosing solution which provide the best ROQI.
3. Act as guideline for the defect reduction and finding of ROQI for other model.

1.6 Methodology

1. Study PAF Model, FMEA, DOE, Cause and Effect diagram, Pareto analysis and Block diagram, and relevant information. Data collection on defect and quality cost.
2. Study the production process in the case study company as well as the production techniques from literature.
3. Set up block diagram of production process.
4. Evaluate PAF model of product in term of non-conformity at customer's side. Study the problems of the part, the main causes and product failure.
5. Evaluate the failure and cause of failure of production process using FMEA.
6. Investigate the main cause of failure using cause & effect diagram and Pareto analysis.
7. Gather information and conduct DOE to test weather the hypothesis is correct.
8. Study the cost of quality improvement prior the implementation. Calculate the ROQI.
9. Solution implementation and study the outcome of the solutions.
10. Plan evaluation and modification.
11. Complete thesis and submit

1.7 Research Schedule

Task Description	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1. Study PAF Model, FMEA, DOE, Cause&Effect Diagram, Pareto Analysis, Block Diagram. Data collection								
2. Study production process & from block diagram								
3. Evaluate PAF Model of external non-conformity product								
4. Set up FMEA team								
5. Investigate the problem of parts, cause & failure by FMEA								
6. Set up hypothesis & confirm with DOE								
7. Calculate ROQI								
8. Solution implementation								
9. Process evaluation and modification, Compare cost of quality								
10. Complete thesis & submit								

Table 1.2 : Research Schedule

Chapter II

Theories and Literature Reviews

2.1 Prevention, Appraisal and Failure Model, PAF Model

Prevention, appraisal and failure model (PAF Model) is a systematic approach in building quality and reducing the quality cost of the products. PAF model will focus on the cost related to quality of the products, calculating and analyzing the actual cost of the product, so that the organization can react accordingly.

According to BS 6143: Part 2 (British Standards Institute, 1990), quality related cost can be divided into 3 major costs, prevention cost, appraisal cost and failure cost. Failure cost can be subdivided into internal failure cost and external failure cost.

Prevention cost is the cost associated with the action/process taken to reduce, prevent the defect/failure of the product.

Appraisal cost is the cost related to the evaluation of the product to ensure that the product will meet the required quality.

Internal failure cost is the cost associated with the failure of the product which happened or found within the organization.

External failure cost is the cost of non-conformity of the product after it has been delivered to the customers.

BS6143: Part 2 also gives examples on the cost elements of prevention, appraisal and failure model.

Prevention costs - Quality planning, Design and development of quality measurement and test equipment, Quality review and verification of design, Calibration and maintenance of quality measurement and test equipment, Calibration and maintenance of production equipment used to evaluate quality, Supplier assurance, Quality training, Quality auditing, Acquisition and reporting of quality data, and Quality improvement programs.

Appraisal costs – Pre-production verification, Receiving inspection, Laboratory acceptance testing, Inspection and testing, Inspection and test equipment, Analysis and reporting of tests and inspection results, Field performance testing, Approval endorsements, Stock evaluation, and Record storage.

In this thesis, the focus will be mainly on the failure costs. The following paragraphs taken from BS6143: Part 2 (British Standards Institute, 1990) will summarize the type of failure costs as well as providing a brief description on each failure costs.

Internal Failure Costs

"Scrape – Materials, parts, components, assemblies and product end items which fail to conform to quality requirements and which cannot be economically reworked. Included is the labor and labor overhead contents of the scrapped items.

Replacement, rew ork, repair – The activity of replacing or correcting defectives to make them fit for use including requisite planning and the cost of the associated activities by material procurement personal.

Troubleshooting or de fect/failure analysis – The costs incurred in analyzing non-conforming materials, components or products to determine causes and remedial or products to determine causes and remedial action, whether non-conforming products are usable and to decide on their final deposition.

Reinspection and retes ting – Applied to previously failing material that has subsequently been reworked.

Fault of subcontractor – The losses incurred due to failure of purchased material to meet quality requirements and payroll costs incurred. Credits received from the subcontractor should be deducted, but costs of idle facilities and labor resulting from product defects should not be over looked.

Modification permits and concessions – The cost of the time spent in reviewing products, designs and specification.

Downgrading – losses resulting from a price differential between normal selling price and reduced price due to non-conformance for quality reasons.

Downtime – The cost of personal and idle facilities resulting from product defects and disrupted production schedule.

External Failure Cost

Complaints – The investigation of complaints and provision of compensation where the later is attributable to defective products or installation.

Warranty/Claims – Work to repair or replace items found to be defective by the purchaser and accepted as the supplier's liability under the terms of the warranty.

Product rejected and returned – The cost of dealing with returned defective components. This may involve action to either repair, replace or otherwise account for the items in the question. Handling charges should be included.

Note. While loss of purchaser goodwill and confidence is normally associated with external failure costs, it is difficult to quantify.

Concessions – Cost of concessions, e.g. discounts made to purchaser due to non-conforming products being accepted by purchaser.

Loss of sales – Loss of profit due to cessation of existing markets as a consequence of poor quality.

Recall costs – Costs associated with recall of defective or suspect product from the field including the cost of preparing plans for product recall.

Product liability – Cost incurred as a result of a liability claim and the cost of premiums paid for insurance to minimize liability litigation damages."

PAF model will begin with the planning and classification of the data. Each cost categories have to be clearly classified and the format of the reported cost clearly understood. Next process is the collection of the data and the identification of the data source. The cost data can then be analyzed. The actual quality cost of each product can be obtained. BS 6143 Part 2 (British Standards Institute, 1990) suggests that there are various method which the data can be analyzed. They are labor base, cost base, sales base, unit base, etc. These measurements are very useful as they can determine the performance of the organization. The PAF model will also reveal the critical area of the product and its process, which can be improved. The concept of the PAF is to increase the prevention cost and appraisal cost. At the same time, it also aims to minimize the failure cost. PAF model can also be accompanied by the use of graphs, charts, table and histogram to clearly illustrate the finding of the cost.

The cost of quality can be calculated periodically to monitor the performance of the organization. It can also be used as a comparison before and after the process improvement or cost-cutting program.

2.2 Failure Mode and Effect Analysis, FMEA

Failure mode and effect analysis was first developed by NASA to analyze the potential failure modes for its space mission during 1950s. It has also been used for its Apollo mission in the 60s. It was used to analyze "the impact on mission success and personal/equipment safety" (Wikimedia Foundation, Inc, 2007). FMEA soon spread to the automotive industry. The first pioneer to implement the use of FMEA was FORD Motor. In the 70s, FORD introduces FMEA to their quality training program. Following that, the use of FMEA soon followed by the other car manufacturers and to other industry. FMEA is widely used by aerospace industry, electronic industry and automotive industry. Later, FMEA was also included in popular quality management standard such as ISO 9000, TS 16949 and BS 5760. This has helped to increase the implementation of FMEA.

"Failure Mode and Effect Analysis (FMEA) is an analytical technique (a paper test) that combines technology and experience of people in identifying foreseeable failure modes of a product or process and planning for its elimination"(Dale, Carol, Glen, Mary, 1999).

"Failure modes and effect analysis (FMEA) and failure modes, effects and criticality analysis (FMECA) are methods of reliability analysis intended to identify failures which have consequences affecting the function of a system within the limits of a given application, thus enabling priorities for action to be set"(British Standards Institute, 1991)

From the above definitions, FMEA can be defined as a systematic and logical product/process analysis method which aims to identify the potential failure modes, study the effect and find measures to prevent/reduce the failure modes before they occur with the help of technology and human experience.

The main purposes of FMEA are as followed.

- To identify and evaluate the potential failures in the product design or production process as well as studying their effects.
- To come up with solution that could eliminate or reduce the potential failure modes of the product process or product design.
- To record and document the process for further analysis and implementation.

In general, FMEA can be classified into 2 broad types, Design FMEA and Process FMEA.

Design FMEA is intended to evaluate the potential failure modes as well as the feasibility of the product design. Design FMEA is usually conducted during the design stage of the product development process. Apart from locating the potential failure mode, design FMEA will also correct the error or reduce the foreseeable problems of the product.

Process FMEA is used to find potential failure modes in the manufacturing process. Process FMEA can be use when designing new manufacturing process and to evaluate existing process. The focus of the process FMEA would be mainly base on human, raw material, machine, production method, measurement and the environment of the production process.

FMEA procedures

Both design FMEA and process FMEA is a time consuming process which require a significant amount of man power, resources and time. As a result, more often than not, FMEA can not be done for every manufacturing process or product design. Therefore the process or design to be analyzed must be carefully considered. Here are some points to be considered when planning to use FMEA.

- There is a significant change in processing technology or a major breakthrough in product design.
- Persistent manufacturing process failures, repeated defective found.
- Product or process failure with unknown cause.
- Large fluctuation in manufacturing process by unknown cause.

FMEA is not the method to be used individually. FMEA works best with team. The quality and accuracy of FMEA rely on the ability of the tram member, not on and individual. FMEA require a group of people who are involved in the product or process. The team can sometime be composted of people from various functions such as, management, sales, financial, designer, human resources, engineer, shop floor operator, supervisor, quality control. It is becoming more popular for supplier and even customer to be included in the team. They will be able to share their experience, view and thoughts towards the subject to be analyzed. The team members must be able to cover all issues regarding the discussed matter as there will be a number of brains storming session during the process. Member can be added onto the team later if their expertise are required. It is very important to select the member and the size of the team. An undersize team might be lack of knowledge, leading to a poor result. An oversize team may cause the analyzing process to be slow, with too many ideas and disagreements.

After the formation of the team, the team members have to meet up and discussed on the FMEA. The members have to know have basic understanding on FMEA and its purpose. The members then have to know the objective of the FMEA that they are going to do, what is expect of them, and agree on it. They will then look into the process or product in detail. For example, the production process to be analyzed must be studied closely. Statistics and important must be collected. Some elements to be considered might include input, output, raw material, machine, man, processing and measuring method, and the environment. The use of graph, table, and block diagram will help the researchers to gather and classified useful information from the unwanted ones. It will also enable the researchers to record the information systematically.

With the background information well established and clearly understood. The team has to move on to the next stage, identifying the potential failure modes. Not only the potential failure modes are discussed, failure modes from the past record should be included too. Brain storming is a good technique to extract the potential failure modes from the members. In this process, the ideas and suggestion should be allowed to share freely without interruption. Participation of the members should be encouraged. After the brain storming process, each failure modes can be discussed to check if they are relevant with the topic under study. The related failure modes can be kept for further analysis.

The next step is the analysis of each of the failure modes. The failure modes can de classified according to the production process in the block diagram. Then the effect of each failure modes to the customers can be determined. Customers can be both internal and external. End-user can be considered as external customer, while the next production department can be taken as internal customers. The effects of the failure modes will have to be recorded. The researcher can then determine the severity (S) of the effect towards the customer.

"Severity is the assessment of the seriousness of the effect of the potential failure mode to the neat component, sub-system, or customer if it occurs." (Dale, Carol, Glen, Mary, 1999)

The scales of the severity are usually between 1 to 10 with 1 being the least and 10 being the most. It is essential that the members understood the ranking scale and their criteria clearly. Only one scale must be used throughout the FMEA process. This is to make sure that everyone follows the same standard and to reduce the misunderstanding between members. Unclear ranking scale can lead to in accurate FMEA result and the important failure modes left out. The following table taken from Laosrimongkol (Laosrimongkol, 2004) will illustrate the severity scale provided by QS 16949.

Ranking	Description	Criteria
1	None	Slight inconvenience to operation or operator or no effect.
2	Very Minor	A portion (less than 100%) of the product may have to be reworked, with no scrap, on-line but in-station.
3	Minor	A portion (less than 100%) of the product may have to be reworked, with no scrap, on-line but out-of-station.
4	Very Low	The product may have to be sorted, with no scrap, an a portion (less than 100%) reworked.
5	Low	100% of product may have to be reworked, or vehicle/item repaired offline but does not go to repair department.
6	Moderate	A portion (less than 100%) of the product may have to be scrapped with no sorting, or vehicle/item repaired in repair department with repair time less than half an hour.
7	High	Product may have to be sorted an a portion (less than 100%) scrapped, or vehicle/item repaired in repair department with repair time between half an hour and an hour.
8	Very High	100% of product may have to be scrapped, or vehicle/item repaired in repair department with repair time more than 1 hr.
9	Hazardous with warning	May endanger operator (machine or assembly) with warning.
10	Hazardous without warning	May endanger operator (machine or assembly) without warning

Table 2.1 : Scale of Severity level (S), (Laosrimongkol, 2004)

The potential cause(s)/ mechanism(s) of failure are the next factor to be considered. The researcher must find the root cause of the failure modes so that the cause can be analyzed. The description should be brief and accurate.

The researchers can then use the information to determine the occurrence (O) of the failure modes. The scale of the occurrence is between 1 to 10, with 1 as rarely and 10 as very high. The members can determine the occurrence level by looking at the past statistics or use experience and gut feeling. Just like the scale used to determine the severity level, only one scale should be used as standard for the whole analysis. The members have to know the ranking well too.

"Occurrence is the chance that one of the specific causes/mechanisms will occur." (Dale, Carol, Glen, Mary, 1999)

The following occurrence scale is used by Laosrimongkol (Laosrimongkol, 2004), provided by QS 16949.

Ranking	Description	Criteria
1	Remote : Failure is unlikely	<= 0.01 per thousand pieces; Ppk => 1.67.
2	Low : Relatively few failures	0.1 per thousand pieces; Ppk => 1.30.
3	Low : Relatively few failures	0.5 per thousand pieces; Ppk => 1.20.
4	Moderate : Occasional failures	1 per thousand pieces; Ppk => 1.10.
5	Moderate : Occasional failures	2 per thousand pieces; Ppk => 1.00.
6	Moderate : Occasional failures	5 per thousand pieces; Ppk => 0.94.
7	High : Frequent failures	10 per thousand pieces; Ppk => 0.86.
8	High : Frequent failures	20 per thousand pieces; Ppk => 0.78.
9	Very High : Persistent failures	50 per thousand pieces; Ppk => 0.55.
10	Very High : Persistent failures	'=> 100 per thousand pieces; Ppk => 0.55.

Table 2.2 : Scale of Occurrence level (O), (Laosrimongkol , 2004)

The researcher then has to evaluate the current process control of the failure mode. The current process controls have to be identified for every failure modes. This information will allow the researcher to learn about the existing process control and their lack of ability to control the failure mode. This information has to be recorded in the FMEA sheet.

The researcher will then have to determine the detection (D) level of the failure modes. The scale of the detection level is between 1 to 10 with 1 being the easiest to detect and 10 being almost impossible to detect. Again, the researcher can check for the detection level by looking at the table of detection level.

"Detection is an assessment of the probability that the proposed current process control will detect a potential weakness or subsequent failure mode before the part or component leaves the manufacturing operation or assembly location." (Dale, Carol, Glen, Mary, 1999)

The following detection scale is obtained by Laosrimongkol (Laosrimongkol, 2004), provided by QS 16949.

Ranking	Description	Criteria
1	Very High	Discrepant parts cannot be made because item has been error proofed by process/product design.
2	Very High	Error Proofed or Gauging Inspection. Error detection in-station (automatic gauging with automatic stop feature). Cannot pass discrepant part.
3	High	Error Proofed or Gauging Inspection. Error detection in-station, OR in subsequent operations by multiple layers of acceptance: supply, select, install, verify. Cannot accept discrepant part.
4	Moderately High	Error Proofed or Gauging Inspection. Error detection in subsequent operations, OR gauging performed on setup and first-piece check (for setup causes only).
5	Moderate	Gauging Inspection. Control is based on variable gauging after parts have left the station, OR Go/No Go gauging performed on 100% of the parts after parts have left the station.
6	Low Gauging or Manual inspection	Control is achieved with charting methods, such as SPC (Statistical Process Control)
7	Very low Manual Inspection	Control is achieved with double visual inspection only.
8	Remote Manual Inspection	Control is achieved with visual inspection only.
9	Very Remote	Manual Inspection. Control is achieved with indirect or random checks only.
10	Almost Impossible Manual inspection	Cannot detect or is not checked.

Table 2.3 : Scale of Detection level (D), (Laosrimongkol, 2004)

The severity level, occurrence level and detection level will be used to calculate the Risk Priority Number (RPN).

$$RPN = (S) \times (O) \times (D)$$

RPN is the numerical value which is used to describe the risk of the failure modes. The maximum RPN value is 1000 while the minimum is 1.

Once the RPN of the process are calculated, the researcher must rank the failure modes according to the RPN value. It will help the researcher to list out and prioritize the failure modes. In many cases, a base RPN which will be set as the acceptable value must be discussed and agreed. The failure modes with RPN above this value will be dealt with first and the rest later. The members have to discuss and come up with the recommended action (s) to prevent or solve the failure modes. This must be accompanied by the personal/department responsible and target completion date.

After the completion, the process can be analyzed again to check for the result. If the RPN value is still above the expected level, it has to be re-analyzed again to fine more appropriate solution.

In the thesis, the focus will be on process FMEA as the study will be conducted on existing product manufacturing process. Prior the FMEA the manufacturing process, product flow and manufacturing techniques have to be well studied. Data has to be collected carefully and accurately as to set up a good foundation for the thesis. This can be done with the help of the block diagram. Block diagram will illustrate the process flow and the critical point of the production system.

2.3 Cause and Effect Diagram, Fishbone Diagram

The next important tool is the cause and effect diagram, or fishbone diagram. Cause and effect diagram is also known as Ishikawa Diagram which is named after its inventor, Kaoru Ishikawa. Ishikawa develop this diagram in the 1960s while working in Kawasaki shipyard. The use of Ishikawa diagram became popular and adopted by other industries. It is so widely accepted that it was included among the seven basic tools of quality management. It is later known as fishbone because of its shape. Cause and effect analysis gain its reputation by being simple to understand, easy to use, can be applied to many situation (service, process, product), cheap, providing a clear picture of the analyzed topic, and easy to visualize.

Cause and effect diagram is a graphic tool which is used to investigate the root cause of the problem, display them in the systematical and logical order. In the diagram, the problem or effect to be analyzed will be placed in the box on the right with a long horizontal leading to it. The causes of the problem are located on the diagram with arrows leading to the main horizontal arrow. The causes can be divided into many categories, depending on the situation. In the following diagram, the causes are divided into 4M's, man, machine, material and method. This is the basic category for any process. Other popular category includes the 8 P's (Price, Promotion, People, Processes, Place / Plant, Policies, Procedures & Product (or Service), for administration and service industry) and 4 S's (Surroundings, Suppliers, Systems, Skills, for service industry) (Wikimedia Foundation, Inc, 2007). In each of the category, the causes are written down. Sometime, when the causes are complicated, sub-causes are included into the diagram too.

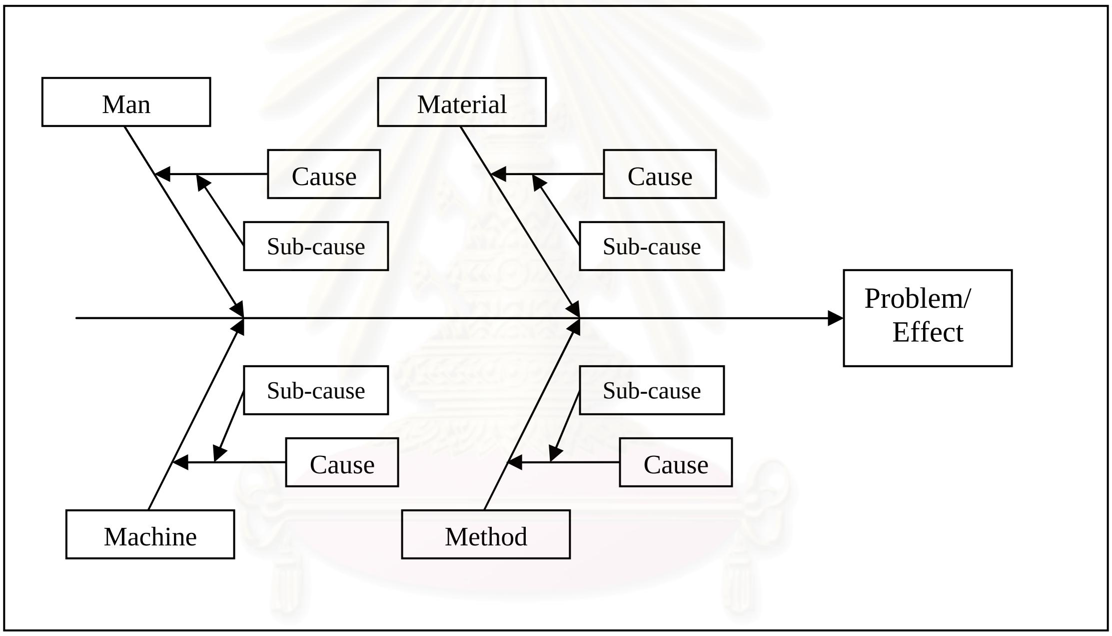


Figure 2.1 : Cause and Effect Diagram

Cause and effect diagram is usually accompanied by brain storming technique, which is a technique where by a group of people who are involved with the project to get-together and share their ideas regarding the topic. Only positive ideas are given and everyone is encourage to voice their though. At the end of the secession, relevant ideas will be selected and discussed. Cause and effect diagram can be done on the board with the help of self-adhesive notes to determine the causes. This will help to provide a better picture of the diagram and allow better understanding. When the cause and effect diagram are completed, it can be used to find the solution to solve the problems.

In this thesis, the 4M's will be used to analyze the critical failure modes that have been found from the FMEA result.

2.4 Pareto Diagram

Pareto diagram is a bar chart which its values are arranged in descending order, showing the order of importance of information. Pareto diagram was invented by Vilfredo Pareto to show the importance of information on the chart.

Basically, a Pareto diagram consists of the frequency on the left axis (occurrence, cost, measuring unit, number of times). On the right axis is the cumulative percentage of the total frequency of the left axis. On the horizontal axis are the bar chart of the variables, arrange in descending order. The horizontal axis can be the types of defect found, the different measurements, different products or processes.

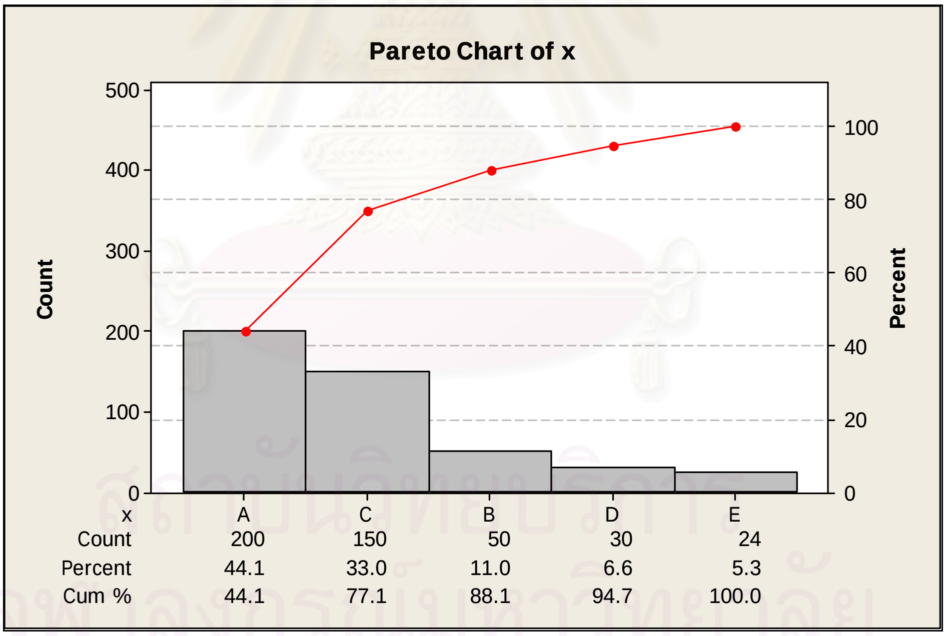


Figure 2.2 : Pareto Diagram

In this research, Pareto diagram will be used to classify process with problems and the type of defective found in each of the process. Pareto diagram will help the research by

- Highlighting the important information from a number of sources.

- Allowing the research to focus on essential topic.
- Save time and resources.
- Providing a systematic documentation of important information.

2.5 Design of Experiment, DOE

In 1920s, Sir Ronald Fisher, an agricultural researcher in England introduced an experimental technique to study the different growth of crops variation. He used a logical and systematic experimental technique to study the growth of crops under different conditions which includes the different controllable and uncontrollable factors. He was able to obtain important information from a small amount of sample size via the analysis of variance. He was able to conduct valid experiment with the method that he had developed. This principle quickly spread to other researchers and other industries. His principle is known as "Design of Experiments".

Design of experiment is a structured, systematical method in studying the relationship between the input variable factors (X's) which will affect the output responses (Y), usually with the help of statistical method.

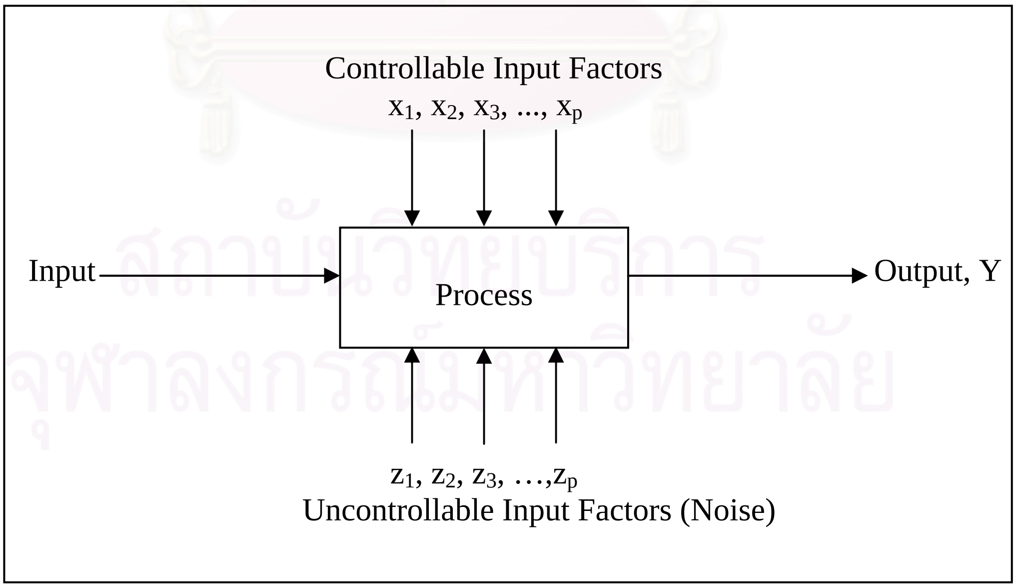


Figure 2.3 : General Model of a Process

From the figure, x_1, x_2, x_3, ..., x_p represent the controllable input factors, such as raw material, man, method and machine. Z_1, z_2, z_3, …,z_p represent the uncontrollable factors that affect the process. Both the controllable factors and uncontrollable factors will combine in the process to produce the output, Y.

The following set of definitions is taken from Warwick Manufacturing Group Module notes: Statistic Process Control (Warwick Manufacturing Group, 2004).

“Experiment – Anything done to test a theory or discover something unknown. The measurement of the effect of changes in operating conditions on the level of one or more responses of a system.

Factor – A characteristic or feature of a system which possibly causes a change in the response. Any circumstance that influences the course of events. A factor may operate at two or more levels and may be quantitative (measurable) or qualitative (classifiable but not measurable) or a mixture of both.

Treatment – A set of experimental conditions which will involve several factors.

Unit or Plot – A relatively uniform quality of material or resources to which one or more treatments are applied. One unit is the smallest division of the experimental material such that any two units may receive different treatments in the actual experiment.”

Design of Experiment (DOE) is widely used in both academic, research and industrial field. It has a universal application whose main purposes are

- To determine the input factors (x) that affects the output most.
- To determine the value of the input factor (x) that produces the desired output value (Y).
- To determine the value of the input factor (x), to reduce the variability in the output value (Y).
- To determine the value of the input factor (x), so that the effect of the uncontrollable variable factors (z) are minimized.

In general, there are 4 main steps involved in performing DOE.

1. Formation of the conjecture, which is the hypothesis of the topic of interest that will lead to the experiment.
2. Conducting the experiment which will be used to study and proof the hypothesis.
3. Analysis of the data obtained from the experiment via the use of statistical method.
4. Concluding the result of the analysis, confirmation of the hypothesis, the important lesson learned, and further recommendation.

There are 3 basic principles in DOE. They are randomization, replication and blocking.

Randomization is a technique where by each treatment is arranged randomly so that they have the same chance of being picked. Randomization is employed to remove any bias of the experimenters, variables, treatments, etc. This is to ensure that each treatment is being treated fairly and there will be no advantage or disadvantage between treatments. Statistical analysis requires that the observation/error be independently distributed, therefore, randomization is required. Randomization will also help to distribute the uncontrollable factor (noise) evenly among the treatments.

Randomization can be sub-divided into 3 categories, complete randomization, simple randomization, and complete randomization with blocks. The type of randomization used depends on factors such as application and data type.

Replication is the repeating of the same treatment/experiment more than once. Replication has 2 main benefits.

Firstly, it will help to determine the experimental error between each treatment. This can be used to check if the experimental error between the same experiment is significant or not.

Secondly, it will increase the precision of the experiment. From the equation,

$$\sigma_{\bar{y}} = \sqrt{\sigma^2 / n}$$

It can be seen that the increase in the number of replicate (n) will reduce the mean standard deviation. This indicates that the increase in the number of replicate will reduce the variability and increase the accuracy of the result.

Blocking is the arrangement of grouping the experiment and collecting the data in group to minimize the effect of variation among the data. It will minimize the effect of the noise on the experiment, increasing the precision of the experiment.

There are several approaches to DOE, completely randomization design, randomized complete block design, and factorial design. The choice of the approach depends on various factors.

Completely randomiz ed design is the method whereby only one factor is being investigated with a number of treatments with several units in each treatment. The number of test unit in each treatment are usually equal, however, a larger number of unit can be used for import treatment. Only one factor is investigated with treatment or level of at least 2 levels. The analysis will only focus on the effect of a single factor. Completely randomized design can tell the experimenter about the difference between the each treatment.

It is the simplest design which is normally used to screen the effect of different factors prior any in-depth analysis. In order for this method to become effective, the units used for the treatment should be homogenous and have very little variation as possible. This is due to the fact that the only controllable factor is the different treatment level of a single factor. Any variation in the treatment unit can cause inaccurate data, thus analysis. Another important parameter that must be considered is the order of the experiment. The experiment must be done in a randomized pattern.

The following diagram and model will illustrate the concept of the complete randomized design.

	Treatment					
	1	2	→	j	→	n
1	y_{11}	y_{21}		y_{1j}		y_{1n}
2	y_{21}	y_{22}		y_{2j}		y_{2n}
↓						
i	y_{i1}	y_{i2}		yij		
↓						
r	y_{r1}	y_{r2}				y_{rn}
	$\bar{y}_1$	$\bar{y}_2$		$\bar{y}_j$		$\bar{y}_n$

Figure 2.4 : Model of Complete Randomized Design

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij}$$

where; Y_{ij} = response output
μ = average yield
τ_i = deviation from treatment i
ε_{ij} = deviation of the experimental unit
i = 1, 2, 3,…, r
j = 1, 2, 3,…, n

Randomized complete block design is an experimental technique whereby the treatment units are grouped into blocks with equal unit in each block. The data in each block is collected and used for the analysis. In some experiment, there is large variation in each treatment unit, causing the completely randomized design to be in effective. The differences in the data might not come from the treatment alone; they might come from the variation in the unit or other uncontrollable factors as well. When these variations are added up, the result of the analysis will be affected. Therefore, the experimenter must try to eliminate the unwanted variation. Randomized complete block design will focus on the treatment effect and reduce the unwanted variables.

In randomized complete block design, the treatment units that are expected to share similar properties are grouped together. For example, the treatment unit can be grouped in time of day, the location of the treatment unit, and the weight of the animal.

As the treatments are grouped together, the variation within the block is reduced and the difference between each block can be clearly shown. It is important to note that the all treatments should be included in the block and they should be the same for every block. The allocation of the treatments to the test unit within the block must be done randomly to minimize the noise of the experiment.

The concept of randomized complete block design will be illustrated in the following model.

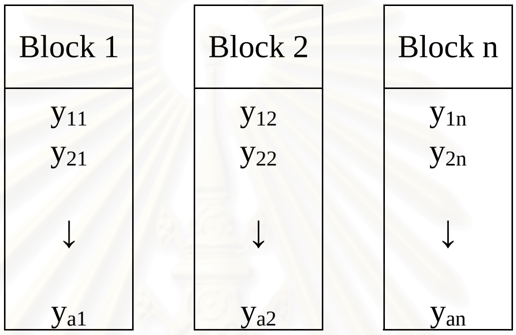


Figure 2.5 : Model of Block Design

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij}$$

where; Y_{ij} = response output
μ = average yield
τ_i = deviation from treatment i
β_j = deviation from block j
ε_{ij} = deviation of the experimental unit
i = 1, 2, 3,…, a
j = 1, 2, 3,…, n

Factorial experiment is the method that allows the experimenter to investigate more than 1 variable factor with a series of treatment level for each factor. Factorial experiment is one of the most useful techniques for the researchers to study the effect of several factors at the same time. Factorial experiment will not only tell the experimenter on the effect of the factors (main effect). It will also reveal the effect between treatments (interaction effect). For example, there are 2 factors in the experiment, A and B, and factor A with a level and factor B with b level. The relationship of the 2 factors can be shown as followed.

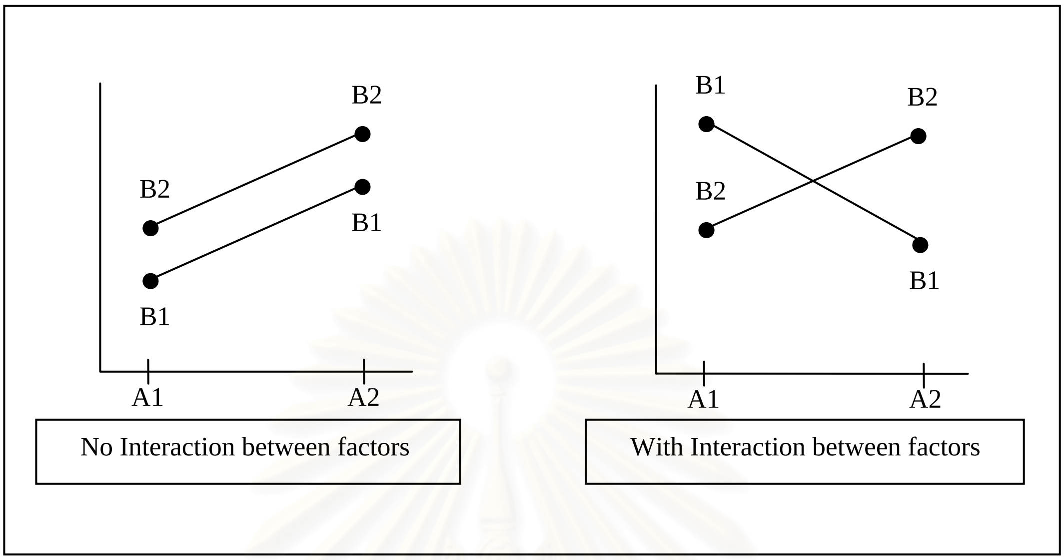


Figure 2.6 : Diagram Showing Interaction and No-Interaction between Factors

Main effect is the effect of the different treatment levels of a single factor on the output response.

Interaction effect is the effect on the output of both factor A and B when they are combined together.

Factorial experiment combines multiple variables into the experiment, making it faster and more effective than method where only 1 factor is tested at a time. Factorial experiment also tells the experimenter about the interaction effect between the factors, making it more accurate and increases its application. However, with the large treatment combinations, the number of replicates might be increase. As a result, more testing unit and resources will be high. The analysis of several factors at once might be complicated and can not be expressed easily.

Factorial design can be formed in several ways, however, the basic concept of the design is

$$A \times B \times C$$

where A = the level in the factor

B = the number of factors

C = the number of replicates in each treatment

2^k factorial is the basic technique in factorial design. It consists of more than 1 factor with 2 levels for each factor. It is used in experiment where the result is likely to be formed in linear model. It is also often used to screen the effect of the input variables before the in-depth analysis of the experiment.

3^k factorial is another technique in factorial design. It can have several factors, but the number of level in each factor is limit to 3. The advantage of 3^k factorial is that it can be used to study non-linear model.

The model for the factorial design is as followed.

		Factor j			
		1	j	b	
Factor i	1	$(y_{111},y_{112},y_{11n})$	$(y_{1j1},y_{1j2},y_{1jn})$	$(y_{1b1},y_{1b2},y_{1bn})$	
	2	$(y_{211},y_{212},y_{21n})$	$(y_{2j1},y_{2j2},y_{2jn})$	$(y_{2b1},y_{2b2},y_{2bn})$	
	↓	:	:	:	$\bar{x}$
	i	:	:	:	
	↓	:	:	:	
	a	$(y_{a11},y_{a12},y_{a1n})$	$(y_{aj1},y_{aj2},y_{ajn})$	$(y_{ab1},y_{ab2},y_{abn})$	
		$\bar{x}_1$	$\bar{x}_j$	$\bar{x}_b$	

Figure 2.7 : Model of Factorial Design

Equation for 2^k factorial design, with 2 factors, A and B.

$$Y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk}$$

where; Y_{ijk} = response output

μ = average yield

τ_i = effect from factor A at i^{th} level

β_j = effect from factor B at j^{th} level

$(\tau\beta)_{ij}$ = effect of interaction between τ_i and β_j

ε_{ijk} = random error experimental unit

i = 1, 2, 3,…, a (level of factor A)

j = 1, 2, 3,…, b (level of factor B)

k = 1, 2, 3,…, n (number of replicates)

Equation for 3^k factorial design, with 3 factors, A, B and C.

$$Y_{ijkl} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \gamma_k + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \varepsilon_{ijkl}$$

where;
Y_{ijkl} = response output
μ = average yield
τ_i = effect from treatment A at i^{th} level
β_j = effect from treatment B at j^{th} level
γ_k = effect from treatment C at k^{th} level
$(\tau\beta)_{ij}$ = effect of interaction between τ_i and β_j
$(\tau\gamma)_{ik}$ = effect of interaction between τ_i and γ_k
$(\beta\gamma)_{jk}$ = effect of interaction between β_j and γ_k
$(\tau\beta\gamma)_{ijk}$ = effect of interaction between τ_i, β_j, γ_k
ε_{ijk} = random error experimental unit
i = 1, 2, 3,…, a (level of factor A)
j = 1, 2, 3,…, b (level of factor B)
k = 1, 2, 3,…, c (level of factor C)
l = 1, 2, 3,…, n (number of replicates)

Analysis of Variance, ANNOVA

The analysis of variance in DOE is usually used to test for the hypothesis in the main effect and the interaction effect of the input variables. The example shown is for 2^k factorial design with factor A and B.

1.	$H_0 : \tau_1 = \tau_2 = \tau_i = 0$	(no main effect on factor A)
	$H_1 : \tau_i \neq 0$: at least 1	(main effect on factor A)
2.	$H_0 : \beta_1 = \beta_2 = \beta_j = 0$	(no main effect on factor B)
	$H_1 : \beta_j \neq 0$: at least 1	(main effect on factor B)
3.	$H_0 : (\tau\beta)_{11} = (\tau\beta)_{12} = (\tau\beta)_{ij} = 0$	(no interaction between A and B)
	$H_1 : (\tau\beta)_{ij} \neq 0$: at least 1	(interaction between A and B)

The ANNOVA table of the 2^k factorial design is as followed.

Variation	Sum of Square (SS)	Degree of Freedom (DF)	Mean Square (MS)	F_0
Between A treatments	SS_A	a-1	$MS_A = SS_A/(a-1)$	MS_A/MS_E
Between B treatments	SS_B	b-1	$MS_B = SS_B/(b-1)$	MS_B/MS_E
Interaction of A&B	SS_{AB}	(a-1) x (b-1)	$MS_{AB} = SS_{AB}/(a-1)(b-1)$	MS_{AB}/MS_E
Error/ Residue	SS_E	ab x (n-1)	$MS_E = SS_E/ab(n-1)$	
Total	SS_T	abn - 1		

Table 2.4 : ANNOVA table for 2^k factorial design

where:

$$SS_A = \sum_{i=1}^{a}(y_i^2 / bn) - (y^2.. / abn)$$

$$SS_B = \sum_{j=1}^{b}(y_j^2 / bn) - (y^2.. / abn)$$

$$SS_{AB} = \sum_{i=1}^{a}\sum_{j=1}^{b}(y_{ij}^2 / n) - (y^2.. / abn) - SS_A - SS_B$$

$$SS_E = SS_T - SS_{AB} - SS_A - SS_B$$

$$SS_T = \sum_{i=1}^{a}\sum_{k=1}^{n}\sum_{j=1}^{b} y_{ijk}^2 - (y^2.. / abn)$$

$$MS_A = SS_A / (a-1)$$

$$MS_B = SS_B / (b-1)$$

$$MS_{AB} = SS_{AB} / (a-1)(b-1)$$

$$MS_E = SS_E / ab(n-1)$$

For the first hypothesis testing, the main effect of factor A can be calculated as followed.

$H_0 : \tau_1 = \tau_2 = \tau_i = 0$ (no main effect on factor A)

$H_1 : \tau_i \neq 0$: at least 1 (main effect on factor A) where : $F_0 = MS_A / MS_E$

If F_0 of the treatment is more than $F_{\alpha, a-1, ab(n-1)}$, the null hypothesis H_0 will be rejected and the experiment can be concluded that factor A has significant effect to the response output. If F_0 is smaller than $F_{\alpha, a-1, ab(n-1)}$, then the hypothesis H_1 will be accepted and the result can be concluded that factor A has no significant effect on response output. The value of $F_{\alpha, v1, v2}$ can be obtained from the F-distribution table. The level of α (significance level) must be determined by the experimenter, v1 and v2 is the degree of freedom, can be calculated as shown above.

The second hypothesis testing will be done on the effect of factor B.

$H_0 : \beta_1 = \beta_2 = \beta_j = 0$ (no main effect on factor B)

$H_1 : \beta_j \neq 0$: at least 1 (main effect on factor B)

where : $F_0 = MS_A / MS_E$

For factor B, the F_0 must also be compared to the $F_{\alpha, v1, v2}$ from the F-distribution table. $F_{\alpha, v1, v2}$ can be calculated from $F_{\alpha, b-1, ab(n-1)}$. H_0 will be rejected if $F_0$of factor B is more than $F_{\alpha, v1, v2}$. If it is smaller, then the null hypothesis is accepted.

The last hypothesis is the conclusion of the interaction between factor A and B.

$H_0 : (\tau\beta)_{11}=(\tau\beta)_{12}=(\tau\beta)_{ij} = 0$ (no interaction between A and B)

$H_1 : (\tau\beta)_{ij} \neq 0$: at least 1 (interaction between A and B)

where: $F_0 = MS_{AB} / MS_E$

For the case of the interaction between factor A and B, the $F_{\alpha, v1, v2}$ can be calculated from $F_{\alpha, (a-1)(b-1), ab(n-1)}$ and obtaining the value from the F-distribution table. H0 will be rejected if F0 is greater than $F_{\alpha, v1, v2}$. If F_0 is smaller, then the null hypothesis will be accepted.

Model Accuracy Checking

In the analysis of variance, there are some basic conditions in the data collected in order for the calculated result to become more effective. Firstly, the data must come from a normal distribution. Secondly, the variance from each treatment must be equal. Lastly, the order of treatment must be randomized. The data collected must be analyzed to check if it fit into the condition. This can be done by model accuracy checking.

The test for the normal distribution can be done by analyzing the residuals of the data.

$$e_{ijk} = y_{ijk} - \hat{y}_{ijk}$$

where : e_{ijk} = residual

y_{ijk} = actual value of the response output

$\hat{y}_{ijk}$ = calculated value obtained from the least-square fit of the model

The residuals will be then plotted on the probability plot in ascending order. The residue can be then analyzed by checking the residuals plot on the graph.

2.6 Return on Quality Investment, ROQI

In financial perspective, return on investment is the ratio of the money gained/lost in an investment against the amount of money invested. For return on quality investment (ROQI), it is the ratio between the benefit gained from the investment against the investment to improve the quality of the process/product. It would tell if the investment is beneficial or not. If the ROQI is above 1, the investment is worthwhile. If the ROQI is below 1, the investment is a loss.

$$ROQI = \frac{Benefit}{Investment}$$

Apart from ROQI, there are also other measurements to evaluate the financial benefit of the investment, such as the payback period.

The payback period is the amount of time taken for the investment to repay the amount of initial investment.

$$Payback = \frac{Investment}{Benefit(monthly, annualy)}$$

2.7 Metal Cutting Methodology

In this thesis, the focus on the DOE to improve the quality of the product will be based on 2 metal cutting processes, drill and reamer process. The following paragraph will explain the detail and the technology of the 2 processes.

In drilling process, a hole is made in the material with the use of the rotating drill bit. In this case, the drilling process is made by the CNC-milling machine. There are a few cutting parameter that must be carefully considered before the drilling process. This consideration will provide desirable hole quality in term of tolerance and surface finishes. Economically, using the right drill for the right job with proper cutting parameter can increase the tool life of the drill, increasing productivity and reducing cost. Using the drill incorrectly can result in product failure and injury from damaged drill bit.

Firstly, the type of drill used must match the type of material being cut. This can be found from the manufacturer's recommendation. Usually, a single drill can be used to cut a number of different materials with similar properties. However, the cutting parameter must be varied from material to material. In this case, the cutting material is cast iron while the drill bit is being changed from high-speed drill to carbide drill. High-speed drill is commonly used as it has a wide application, easily available with economical price. Carbide drill provides good tolerances with longer tool life, however, it is not easily available and it is more expensive.

The operator then has to determine the rotation speed and the table feed which has to be input into the CNC machine. The rotation speed (s) can be calculated from the following formula.

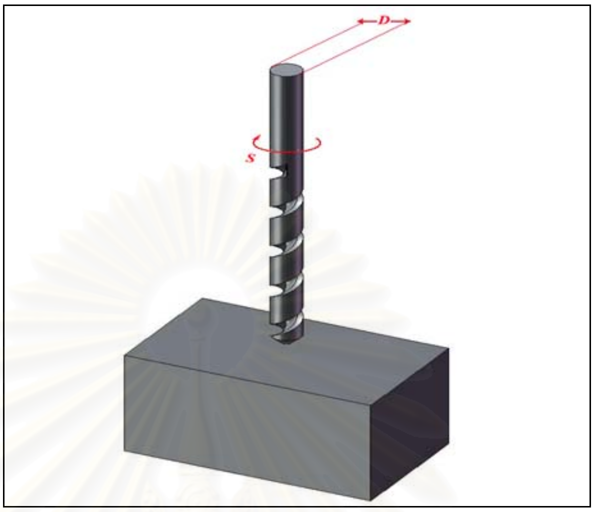


Figure 2.8 : Diagram of Drilling Process (S calculation)

$$s = \frac{1000 \times Vc}{\pi \times D}$$

where: s = rotation speed (round per minute)

Vc = Cutting speed (m/min)

π = 3.142

D = drill diameter (mm)

The cutting speed (Vc) must be chosen from a list of manufacturer's recommendation. Usually, the manufacturer will give a range of recommended cutting speed (Vc) for different material. The operator has to select the range of cutting speed to match the type of material and the cutting preferences. The range of different cutting speed can determine the tolerance, the surface quality, the tool life, and the cutting time. For example, the cutting speed of the tested carbide has a range between 70 – 120 m/min for cast iron. Once the cutting speed is selected, the rotation speed can then be calculated.

The next important parameter is the table feed (Vf). The table feed (Vf) can be calculated from the following formula.

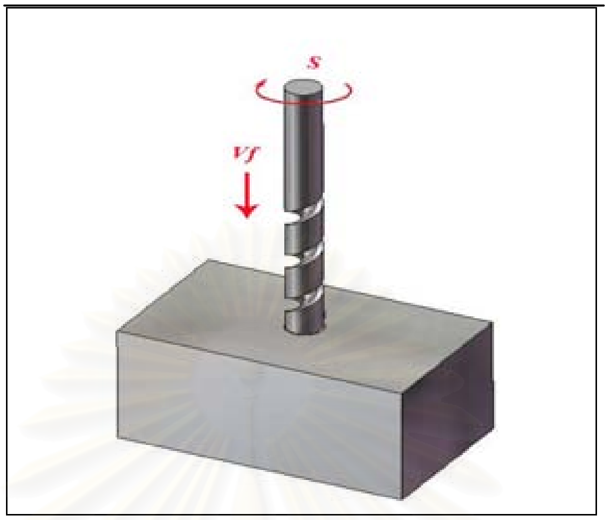


Figure 2.9 : Diagram of Drilling Process (Table Feed calculation)

$$Vf = fz \times z \times s$$

where: Vf = Table feed (mm/min)

fz = Feed rate per tooth (mm/tooth)

z = Number of teeth of cutter

s = rotation speed (round per minute)

The feed rate per tooth (fz) is again given by the manufacturer, the feed rate per tooth is given in a range. The feed rate per tooth is varied from material to material. The operator has to select the fz according to the desired cutting parameter. The feed rate per tooth will effect the cutting time, the surface finish and the tolerances of the hole. The increase in fz will reduce the cutting time, however, the tool life will also reduced. The selection of the feed rate per tooth is also influence by the type of cutting coolant used, the flow rate of the coolant, the condition of the machine, etc. Nevertheless, these factors are less important.

Once the rotation speed and the table feed rate are obtained from the calculation, the operator can program the cutting parameter and the coordinate of the work piece for the CNC-milling machine to perform the work.

Reamer process is used to bore a hole using a reamer in order to obtain a very small tolerances and good surface finish.

For the reamer process, the rotation speed and the table feed are calculated by using similar formula and method as the drill process.

Another useful formula which can be used for the drilling and reamer process is the formula which is used to calculate the cutting time.

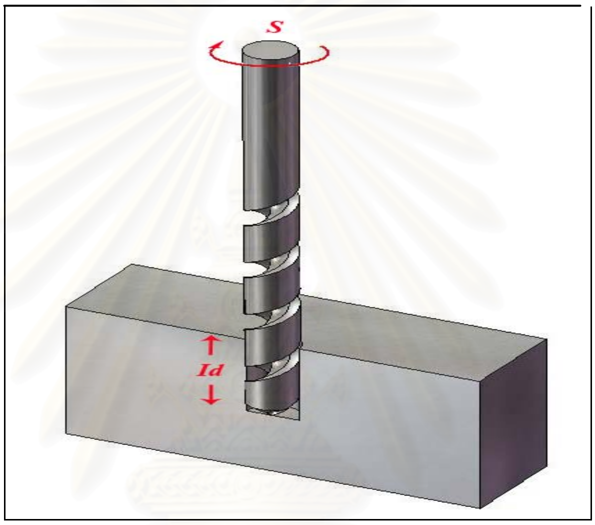


Figure 2.10 : Diagram of Drilling Process (Cutting Time calculation)

$$T = \frac{L}{Vf}$$

where: T = Cutting time (min)

L = The depth of the hole (mm)

Vf = Table feed (mm/min)

In this thesis, the standard of the pin hole is a H7 tolerance hole. The following table will summarize the hole diameter and their H7 hole tolerances.

Diameter Over	To	H7 Hole Tolerance	
		Max	Min
0	3mm	+0.010	+0.000
3mm	6mm	+0.012	+0.000
6mm	10mm	+0.015	+0.000
10mm	18mm	+0.018	+0.000
18mm	30mm	+0.021	+0.000
30mm	50mm	+0.025	+0.000

Table 2.5 : Diameter for H7 Hole Tolerance

2.8 Literature Reviews

Related books, thesis and researches have been studied to obtain useful theories and information. In many similar cases, the research on quality improvement often begin with the study of background information, such as production statistics and the production process (Laosrimongkol, 2004) and (Anruksakul, 2002). Useful technique in this stage includes, using of Pareto diagram to collect production statistics as well as the nature of the defect symptoms. Another technique is to set up block diagram which will help to provide a clearer picture of the production process, enabling the researchers to locate the critical process easily.

Kittisak Anuraksakul, 2002, Analysis and Defect Reduction for Automotive Body Press Part by FMEA Technique

Kittisak Anruksakul (Kittisak, 2002) use FMEA techniques to reduce defects in the formation of the car body arts. Kittisak was determined to improve the quality the body parts as there was a high scrape and rework rate.

After the statistic of the production and defect were collected, the author decided to select a specific part for the case study and choose process FMEA for the case study. The author carefully studied the processes involved in the production, the parameters as well as documents the processes. The author focused into 4 main processes, draw, trim/pierce, separate and flange, and looked into the detail of the defects. The author and the team used brainstorming technique to list out the causes of defect. The author also linked the causes (mould personal, method, and machine) with the defect using fishbone diagram.

Once the causes were clear, the author bring in process FMEA technique to analyze the severity, occurrence and detection of each made. The risk priority number can then be obtained. Further discussion was made with the team and the author came up with ways to reduce defects. These plans were carried out accordingly.

After the first month, the total percentage of defects was reduced from 6.49% down to 2.54%. The processes were analyzed again and those with RPN exceeding 100 had to be improved. One month later, another evaluation was carried out and the total percentage of defects dropped to 0.69%. The same procedure was repeated and the third evaluation resulted in the percentage of 0.64%.

The author developed a good documentation process in FMEA sheet, data collection as well as analyzing the process. The result of the case study had improved the quality significantly.

Intira Laos rimongkol, 2004, Application of Modified FMEA Approach for Iron Foundry's Product Defects Reduction

Intira Laosrimongkol (Laosrimongkol , 2004) applied FMEA to analyze and evaluate the effect of blowholes of pinholes in cast iron products.

The author first studied the casting process as well as determining the parameters that affect the quality of the casting. Next, the author selected a product for the case study, which is the fly wheel ZE1. It was one of the most rejected parts in the production line. The author then had chosen to bench marks the performance of the company to that of the first tier company. Once the FMEA team has been set up, the FMEA process was carried out on the selected part. Though evaluation, discussions and meetings it had been found that the defects could come from 2 main reasons, the difference of the dust and the present of corn starch in the sand mould. From the FMEA the roots of the defect also lay in the higher suppler content in coal and the low permeability of sand mould which was a result of the corn starch.

After the cause had been analyzed, the author used Poka-Yoke or Fool Proof Technique to solve the quality issue. In addition, the author conducted a Design of Experiment of DOE check on the effect of the change in coal dust and the absence of corn starch. The experiment had revealed the change of coal dust and absence of corn starch reduced the defect rarely with 95% confidence. The parts were also evaluated during the actual production; the defect had decreased from 15% down to 1.7% which is highly acceptable. The author went further to illustrate the effect of the change by calculating the Return on Quality Investment. The ROQI would have been paid off in the first 6,381 units. By comparing with the total production, the finding could also be used to improve other similar products.

Shankara Prasad , 1990, Improving Manufacturing Reliability in IC Package Assembly Using FMEA Technique

Prasad (Prasad, 1990) employed FMEA to improve the manufacturing reliability in IC package. In his work, the author explained how FMEA can help in the design of IC packaging and in electrical components. In the electrical component business, especially, IC assembly and packing, there is a high level of accuracy and quality to be achieved. A failure in both design and process could lead to a large amount of loss.

The author identified the benefit of FMEA in designing well as processing. Then the author listed the steps that he took during the FMEA process. His coast benefits of FMEA revealed that the systems cost could be reduced by the rule of ten when the failures were found early, using FMEA.

In the case study a design of an IC power package was chosen. The author and his team investigated the product and process in the design stage with FMEA techniques. In the analysis the author found more than 100 failure modes, however, only about 25% were considered series and had dealt with, Most of the critical failure modes were chosen when the Risk Priority Number (RPN) were higher than 100. During the finding of solution, the author illustrated how team working in FMEA group helped the team to get new ideas from various departments which will benefit the organization as a whole.

The author also concluded that FMEA is a good technique which helps the engineers to solve problems before reaching the customer.

Melinda Kennedy , 1998, Failure Modes & Effects Analysis (FMEA) of Flip Chip Devices Attached to Printed Wiring Boards (PWB)

Kennedy (Kennedy, 1998) had combined the FMEA technique and DOE to help in the design, of and assembly of flip chip devices on printed wiring boards.

Firstly, the author and the design team discuss the design and the manufacturing processes of the part. In initial stage six DOEs (design of experiment) were carried out and there were 3 main areas in concern. They are “solder screening reflow profiles of the filp clip dice and underfill dispense parameters.” The next process is followed by Failure Mode and Effect Analysis of each of the concerned area. The FMEA technique for this case focused on the risk analysis of the process. The FMEA result revealed 3 major failure modes which associated components & fillip chip dice and flip chip dice with very high RPN value. The FMEA also showed the failure effects, failure causes as well as the preventive measures. The author and the engineers the used the failure causes to set up the DOEs. The DOEs were to investigate the parameters of the 3 important concerned factors. There were 4 essentials DOE to be mate regarding the screening, the reflow, the underfill parameters and the underfill placement.

At the end of the DOEs the author was able to determine the best conditions as well as processes for the flip chip devices production. It can be seen that the 4 DOEs used a total of 178 boards for testing and 259 boards for the confirmation run. The amount of investment was very little when compared with the result of the finding and the benefit gained by the organization. The success of the experiment is highly related to the systematic steps provided by the FMEA and DOEs.

Dale H.Bes terfileld, C aro Bester field-Michna, Glen H. Besterfield and Mary Besterfield-Sacre, 1999, Total Quality Management, Second Edition, Prentice-Hall International, INC

In chapter 16 of this book, the authors (Dale, Carol, Glen, Mary, 1999) carefully explain the principle and the introduction to Failure out the important processes involved in FMEA implementation. The importance, procedures and the involvement are described in detail. The author then divided the documentation process into 2 sections, design FMEA and process FMEA of their documents are clearly illustrate and the elements in the document are exhibited. These also include demonstration on how to fill the form. Essential topics such as Severity, Occurrence and Detection are guided with ranking which will help the users to have an idea of what each value should be. Finally, the calculation of the RPN is showed.

In addition the authors also included the samples of actual FMEA documents to provide a cleaver picture for the users. As a result of the combination between the theory and the industry application, the text is a good reference for those who are interested in FMEA.

Nattaka Y okakul, 2003, Quality Cost Optimization for an SME Industry: A Case Study of Dog Chew Company, Chulalongkorn Company.

Yokakul (Yokakul, 2003) imported the application of the quality cost system to reduce the total quality production of the dog chew.

The author interviewed the member and staffs of the company before coming up with the "quality check list" form which was used to calculate the quality cost. The author divided the quality cost into 3 sections, prevention cost, appraisal cost and failure cost. After the quality cost had been collected and analyzed, the result show that the company was in the improvement zone. The author then decided to increase the prevention cost and appraisal cost to reduce the total failure cost. A number of tools such as Pareto diagram, Cause-and-Effect diagram were used to indicate and solve the quality problem. The comparison of quality cost revealed that the quality cost had been reduced by 44.3%, from 4251 Baths per ton to 2367 Baths per ton. The author went further to study the economic model of the production to find out optimum value of quality cost. The author then found out that the total quality cost can be reduced to 2240 Baths per ton to obtain maximum productivity at the production of 60.161 ton per month.

Tossapol Kiatcharoenpol , 1995, Determination of Suitable Condition for the Lacquering Process on Tin Plate by Design of Experiment Method.

The author's objectives (Kiatcharoenpol, 1995) in the research was to study the factors, their effect in the lacquering process of the tin plate and to obtain a good quality lacquering that can be used for production. The study would be done via the help of design of experiment.

The author started by studying the related theories in lacquering and designing of experiment. From the study, he derived at the 4 important factors which affect the quality of the lacquering and will be used for the design of experiment. Then he determined the 6 characteristics which will be tested for the quality of the lacquer. The design selected for the experiment was 3^4 factorial design which is completely randomized with 2 replicates. The result is then analyzed by ANOVA and response plot. The result was obtained and a better lacquering condition was achieved.

The author suggested that the range used in the tempering time can be widen to increase the significance of the effect. Also that the research focus only on the quality of the lacquering, the cost was not considered. In order to obtain a feasible condition, the cost should be included into the design of experiment.

Aik Silavisesrith, 2000, Suitable Conditions for Reactor Process Control in Melamine Compound Process by Using Design of Experiment Tools.

The goal of this research (Silavisesrith, 2000) is to find the suitable condition of the molar ratio of formalin to melamine crystal, the acid-base indicator of melamine crystal, formalin, and water, and volume of sodium hydroxide for the reactor process in the melamine compound process. This is done to reduce the variation of the melamine compound's curling time.

For the design of experiment, the author started by conducting a factor screening experiment to study the effect and the relationship of various factors. The 2^k factorial design was chosen for factor screening process because of its effectiveness. Then the preliminary experiment is used to confirm the result of the factor screening experiment with only those factors of interest conducted, again 2^k factorial design was employed. With specific factors and range, the experiment for finding suitable condition for the melamine compound's curling time is conducted via two-factor factorial design. 2 levels of melamine crystal pH and 3 levels of F/M ratio were used for the two-factor factorial design.

With the suitable solution, the author did a confirmation experiment by carrying out the confirmation experiment which compares laboratory results against that of the actual production process.

Apart from the success of the experiment, the author illustrated the importance of selecting the range for factors in DOE. The result from the DOE might be different from the actual production. As a result, a confirmation experiment is essential is the solution is to be used in the actual production.

Pornthep Laptuvasiri , 2001, Application of Experimental Design for Defect Reduction: Case Study of Shaft Propeller Line Production Process.

In this thesis, the author (Laptuvasiri, 2001) aims to study the factors which influence the balance of propeller shaft and to find the optimum operating condition to improve the quality as well as minimizing waste.

From the combination of experience and production statistics, cause and effect diagram is used to find the cause that might affect the shaft's quality. After the likely causes have been found, failure mode and effect analysis was carried out to find the failure mode, the cause, the affect as well as ranking them according to the RPN. The author found that the supply voltage of the welding machine, the welding speed, the concentricity and the torque affect the quality of the shaft. The author decided to look into his factors as they will not increase any production cost in the modification. DOE is then carried out to study the effect of each of the effect. The author set the present value in the middle and set 1 smaller and 1 larger value for every factor. A factor screening experiment with the maximum and minimum value was carried out to study on the effect of the change. For factor screening, 2^k factorial design was used, ending up with 2^4 factorial design. Then a 3^k factorial design is used for the experiment to find the optimal condition. The 3^k factorial experiment was done and ANOVA was used to analyze the result. The optimal condition was found by using the regression equation with the help of computer software. A confirmation experiment was carried out and the results were compared with the old condition. The balance of the shaft had been improved.

Watcharasak Thaw eesuk, 2003, The Study of Factors Effecting the Crown Inducement of Write/Read Head Assembly of Hard Disk Drive by Using the Design of Experiment.

The author's objective (Thaweesuk, 2003) is to access the factors in the write/read head assembly process which affect the crown inducement of the write/read head as well as searching for more optimum condition. The aim is to reduce the standard deviation to be 0.033 micro-inch.

In the initial stage, the author gathered production data and use cause and effect diagram to find the possible caused which might have affected the crown inducement. From the analysis, 6 potential factors were located. DOE was then used to study the effect of the 6 factors. Due to limited resources, the author selected one-half fractional of the 2^6 design (2^5 design). Complete randomization is used to reduce bias. Anova is used to calculate the result. The DOE resulted in a change in the position of glue and conducting glue while the rest are kept as usual. This had reduced the standard deviation to under 0.033 micro-inch.

The author suggested that the number of replicates can be increased to study the effect in greater detail and making the DOE more accurate. The result from the experiment might differ from that in the actual production, therefore the process must be carefully monitored when applying in the actual production line.

CHAPTER III

SITUATION ANALYSIS

3.1 Company Background

Company T was established 28 years ago as a local machine shop, repairing and over-hauling all kind of engines. The company also repaired and reproduced machine parts and tools. It started off in the center of the town in Saraburi province. As time passed by, industries in Saraburi have grown rapidly in many areas such as ceramic industries, cement industries, food industries and machine tool industries. Soon, company T joined in the industrial revolution. The company supported the ceramic industries by repairing and creating ceramic mould for tiles companies. For the cement industries, the company repaired and replaced their ball mill, grinder and other machine parts. The company quickly expanded through the year.

From the work force of 15 people at a single plant 28 years ago, currently, the company has 5 plants located in Saraburi, involving in many kinds of engineering business. There are around 150 employees working in the office and factory. The founder of the company now holds the position of the director. There are 2 general managers working directly with the director. The general managers supervise the other department of the company, they are Production Department, Technical advisor, Financial Department, Human Resources Department and Purchase Department. Each department has a manager and assistants. For the Production Department, it is further sub-divided into 5 departments. They are Quality Control department, Manual Machining department, CNC Machining department, Grinding Department and Welding Department. Each of this department has a head and an assistant. The machines in the production lines includes manual milling & lathe machine, CNC milling and lathe machine, bridge type machining center, welding machine, press machine, surface grinding machine, etc.

The headquarter of the company still holds its tradition, repair and over-hauling of engines, while the new business is separated into 5 major manufacturing groups, Automobile Mould & Die, Jig & Fixture, Metal Fabrication, Machine Tools and Tire mould. The production of the company is now working round the clock on a 2 shifts basis. Most of the work force of the company is operator of the machines.

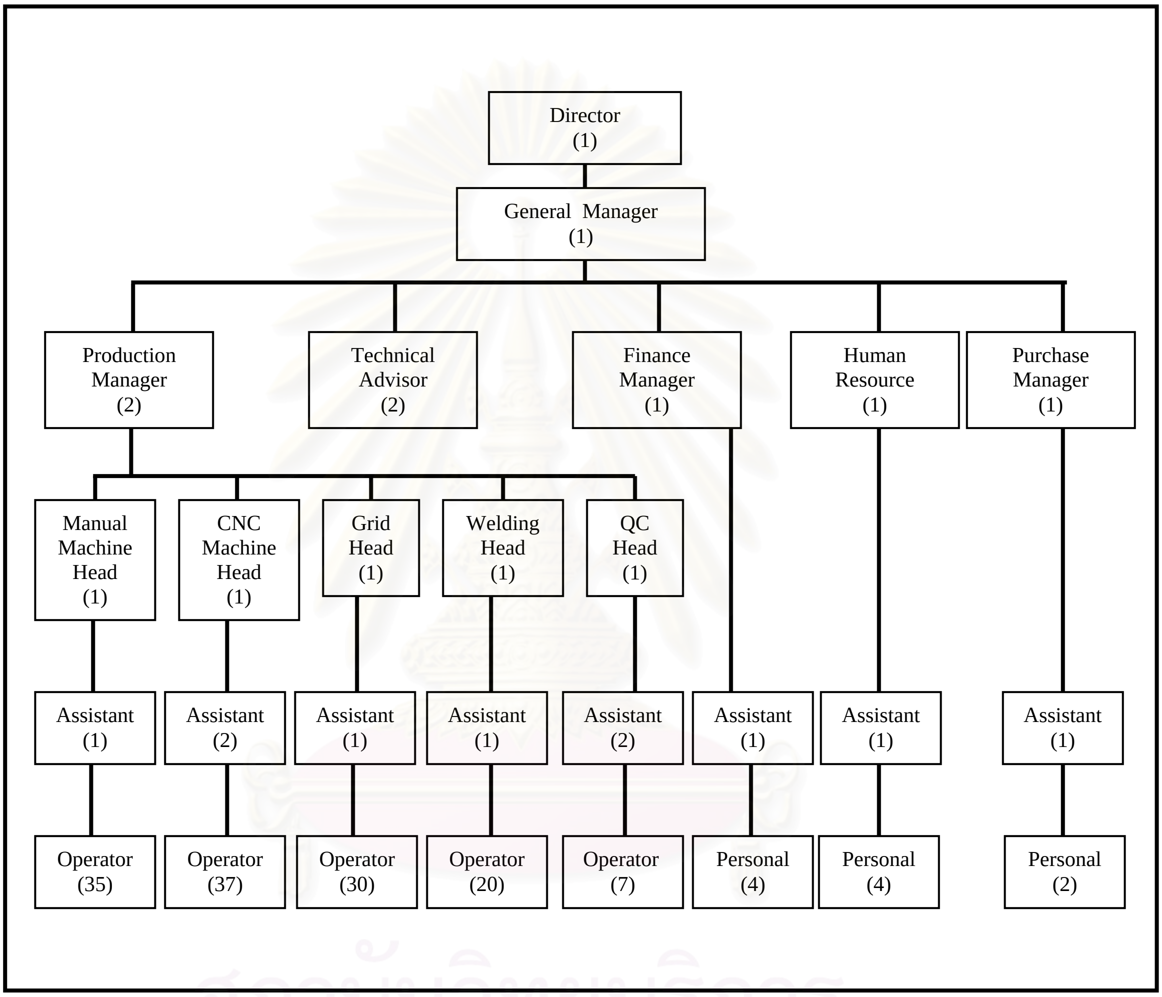


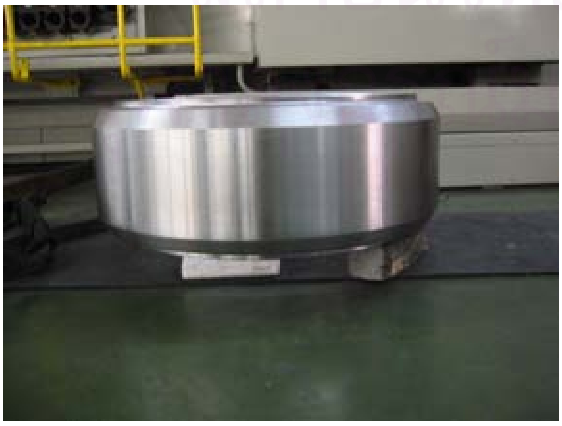
Figure 3.1: Organization Chart

3.2 Tire Mould Production Processes

For this case study, the focus will be on the production of the tire mould of company A. The part is a cylindrical casting which has to be cut according to the customer specifications. The shape and size of the mould varies, however, the general manufacturing procedures are similar. The following process will illustrate the processes involved in the production of the tire mould.

The raw material for the tire-mould is a round iron casting with an external-diameter of 700mm. to 800mm. and a height of 300mm. to 400mm. The raw materials are supplied by the customer along with the drawing and specifications. The receiving representative will check the dimension and condition of the raw materials before accepting them.

The raw material will be mounted on the CNC vertical turning machine where it will be cut to its shape and size. The machine operator will program the code required by machine to cut according to the drawing.



The work piece will then be packed on the rack and sent to the machining department for further work.

Figure 3.2 : Tire Mould Production Process

The machine that will be used for the next process is the CNC horizontal milling machine.

The operator will draw the part using CAD/CAM software and will then generate the computer code which will be transferred to the machine.

The processes in this stage involve drilling, tapping, cutting and chamfering.

The part will then be sent for gas cutting. The cut will be done according to the profile of the drawing.

Figure 3.2 : Tire Mould Production Process (continue)

The gas cut will make several vents on the mould. The mould will be separated into small sectors by the saw.

The mould will then returned to the CNC horizontal milling machine where it is cut into several small sectors.

The mould is separated into several sectors.

The sectors will have to be cut by the CNC vertical milling machine to obtain a flat side.

Figure 3.2 : Tire Mould Production Process (continue)

The sectors have to be fitted together in the jig before it is sent to the turning machine.

The sectors are turned again to the desired profile.

The mould sectors are then sent for numbering.

The rings are fitted to the top and bottom of the sectors to hold them together.

Figure 3.2 : Tire Mould Production Process (continue)

The assembled mould will be inspected by the QC personal. The approved mould will be packed and sent to customer.

Figure 3.2 : Tire Mould Production Process (continue)

3.3 Team Set Up

In the study and analysis, the processes will be supported by the members of the organization. They are selected based on the involvement with the selected product. Each of the team members has been involved with the tire mould production from the start. They will be able to provide useful information and share their experiences. Most of the participants has been working in company for more than 1 year. The participants come from the management field as well as the shop floor operators. The following paragraph will provide detail of the participants.

Team Chief	Author
Team Advisor	Senior Advisor from Japan, responsible for advising and analyzing the technical detail of the tire mould, highly experienced in machine tool industry.
Team Member	General Manager, deals with the customers and internal production. He communicates between the customers and the production.
Team Member	Product Engineer, responsible for analyzing the drawing and the detail of the tire mould drawing. He plans the production method, selecting tools and generating CAD/CAM code.
Team Member	Process Engineer, responsible for the monitoring of the production processes of the tire mould in the shop floor.

Team Member	Manufacturing Staff (CNC Department), responsible for machining the tire mould in various processes with CNC vertical and horizontal milling machine.
Team Member	Manufacturing Staff (Manual Department), responsible for all turning processes of the tire mould on both CNC vertical and horizontal lathe.
Team Member	Manufacturing Staff (Welding Department), responsible for cutting the mould into sectors (via gas cutting machine), and repairing the tire mould (by welding and sent for re-cutting).
Team Member	QC leader is responsible for the final inspection prior the delivery, and recheck the tire mould during production upon request.
Team Coordinator	Tire mould project leader, responsible for following on the progress of the tire mound production in the shop floor, as well as reporting to the head of department.

3.4 Block Diagram

In order to understand the manufacturing processes and narrow the scope down, the author decided to form the block diagram. The diagram will include the manufacturing steps as well as the department that is responsible for each process.

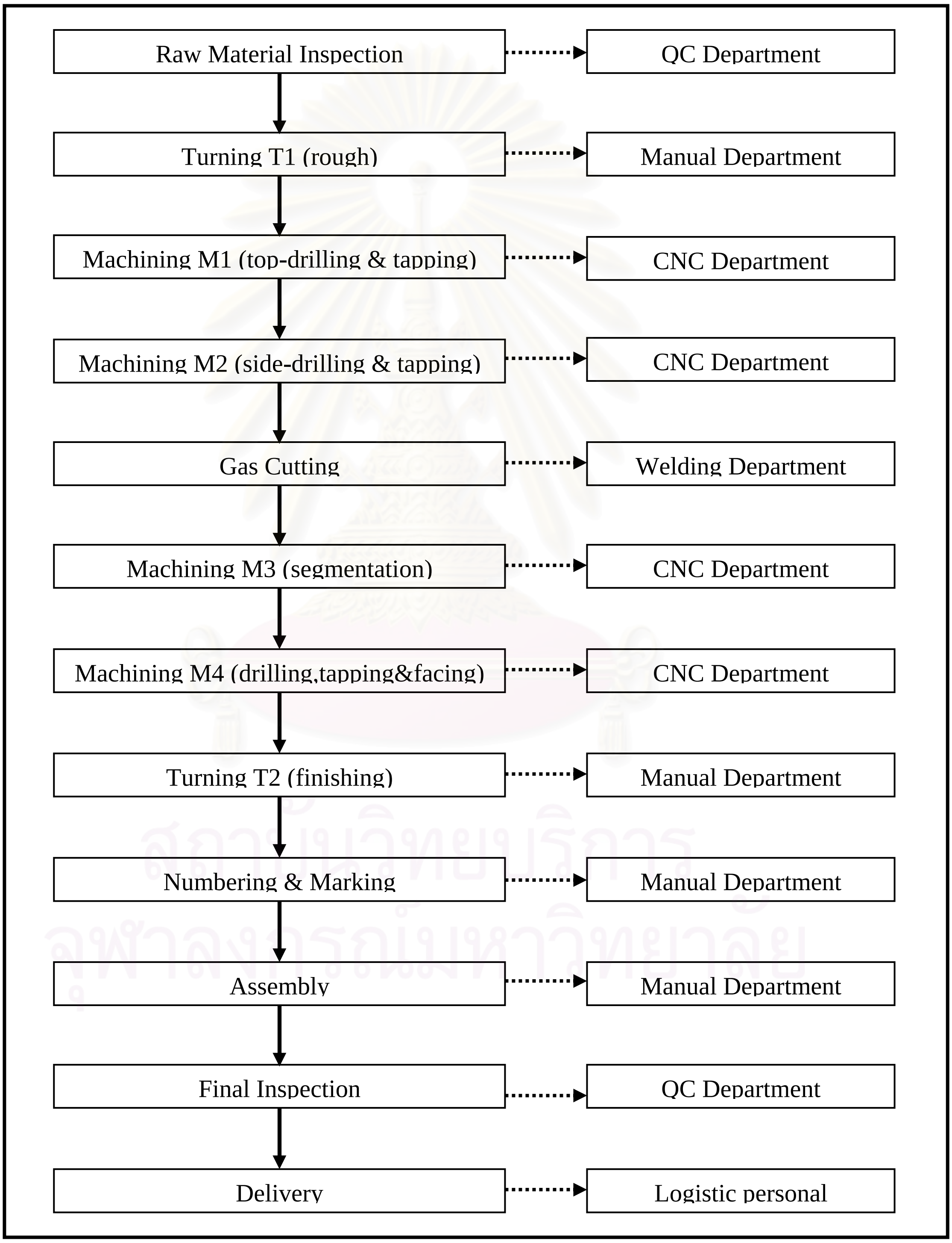


Figure 3.3 : Block Diagram of Tire Mould Production Process

3.5 Process Boundary Definition

In this thesis, the processes involved in the calculation of the cost of quality will come from non-conformance products (tire mould) which have been found by the customers and internal QC department.

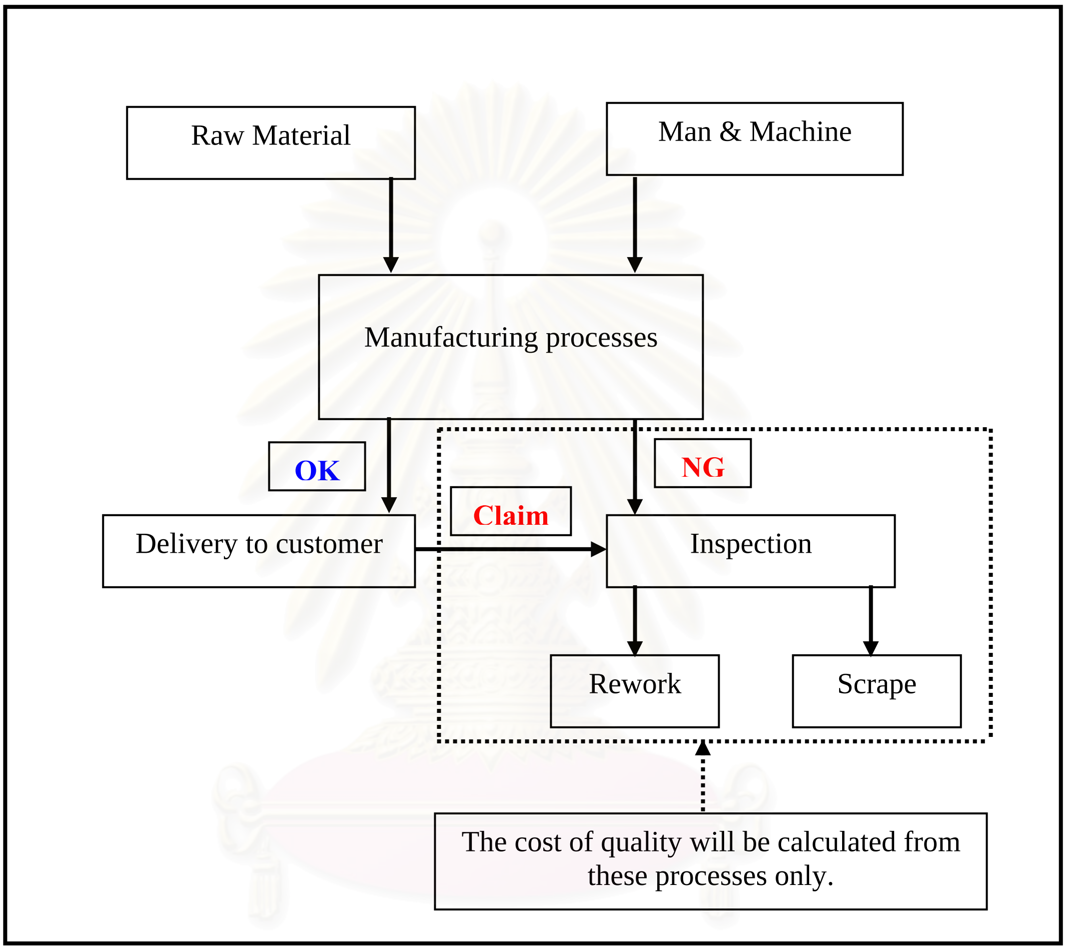


Figure 3.4 : Process Boundary Diagram

3.6 Development of Cost of Quality collection

In this chapter, the focus will be on setting up the cost collection system. These include data and useful information which will be analyzed in the later part of the thesis. The first process will be started by selecting the costs of quality that are related to the research in the case study. Then the calculation method for each of the selected costs, and locating the data sources must be decided. The existing cost collection and calculation system will be analyzed. This is to ensure that the existing information and invent the necessary document is used wisely.

Costs of Quality

First, it is very important to study the elements of the costs of quality. In this thesis, it is mentioned earlier that the costs considered come from the defective parts. Therefore, the costs of quality will be mainly failure costs. Research had been made on the type of failure costs. The author decided to follow the guideline of BS6143: Part 2: 1990.

The author selected these failure costs from BS6143: Part2 guideline. The costs have been discussed and agreed that these costs are directly related to the case study of the thesis. There are other failure costs which are not directly related or negligible. These costs are left out and not included in the calculation.

Preliminary study on the cost report and data collection system

The company in the case study is a medium size local company with very little information on the costs of quality. It is very important that the team and staff must be educated on the costs of quality and each type of failure costs. Therefore, the author held a session to educate them. The topic of the tutorial include introduction on the cost of quality, the importance of cost of quality and failure cost, the types of failure costs, data collection, report and application, and the benefits of study.

The author plans to investigate on the existing data collection system and report of the company. The investigation is done by interviewing the top managements, departmental leader as well as the operators in the shop floor. This is done to locate the required information and to check if they are available. The author also has to see if the existing reports have to be modified and if they need to invent new report sheet. The following tables will indicate the type of failure cost and the personal responsible for recording the data.

No.	Failure category	Responsible personal
	Internal failure	
1	Scrape	QC
2	Replacement, rework, repair	QC
3	Troubleshooting or defect/failure analysis	QC
4	Re-inspection and testing	QC
	External failure	
1	Product reject and return	QC

Table 3.1 : Failure Category and Responsible Personal

The next table will summarize the detail of the availability of the document and the costs of the failure.

No.	Failure cost	Document Availability	Failure Cost Availability	Relating Document
	Internal Failure Cost			
1	Scrape	QC	Financial	Nc report, Po
2	Replacement, rework, repair	QC	Financial	Nc report, Po
3	Defect/failure analysis	QC	Financial	Nc report,
4	Re-inspection and testing	QC	Financial	Nc report,
	External failure			
1	Product reject and return	QC	Financial	Nc report, Customer's reply

Table 3.2 : Failure Category and Related Documents

3.7 Failure Costs and Calculation

Cost calculation is an essential process towards quality improvement and it needs to be taken seriously. It requires support from the whole organization. In order to obtain accurate cost of quality, the author has discussed the failure costs and their calculation with the top management and the department leaders. The team expects to get useful information from them. The purpose is to make them realize the important of cost calculation as well as gaining their permission and support.

After the discussion, the author set up standard calculation method which will be used to calculate the cost of quality. The calculation methods for each type are listed as followed.

Internal Failure Costs

Scrape

Cost = Labor cost + Machine cost + Overhead cost

Labor cost = Cost of labor per unit time x time used in manufacturing the defective parts
Machine cost = Machine cost per unit time x time used in the manufacturing processes of the item that has been scrapped
Overhead cost = Overhead cost incurred from the production processes

Replacement, rework, repair

Cost = Cost of material + Cost of labor & machine + Overhead cost

Cost of material = Material cost purchased for replacement
Labor cost = Cost of labor per unit time x time used to rework/repair the defective parts
Machine cost = Machine cost per unit time x time used in the manufacturing processes of the item that has been replaced, reworked and repaired

Overhead cost = Overhead cost incurred from the production processes

Defect/failure analysis

Cost = Labor cost + Overhead cost

Labor cost = Cost of labor per unit time x time used in the analysis and investigation when the product fail or defects are found
Overhead cost = Overhead cost incurred from the analysis processes

Re-inspection and testing

Cost = Labor cost + Overhead cost

Labor cost = Cost of labor per unit time x time used in re-inspection and testing
Overhead cost = Overhead cost incurred from re-inspection and testing processes such as consumable materials

External Failure Cost

Reject/return

Cost = Labor cost + Machine cost + Material cost + Overhead cost

Labor cost = Labor cost = Cost of labor per unit time x time used to rework/repair the defective parts rejected or returned by customers
Machine cost = Machine cost per unit time x time used in the manufacturing processes as a result of product failure/defect rejected or returned by customers
Material cost = Material cost purchased for replacement
Overhead cost = Overhead cost incurred from the production processes as a result of product failure/defect rejected or returned by customers

CHAPTER IV

PROBLEM ANALYSIS & QUALITY IMPROVEMENT

4.1 Statistics of the failure parts

The author decided to look deeper into the type of failure as well as the symptoms of the failure. The data is taken from the problem report from customers and the internal NC report issued by QC department. The following table will reveal the monthly defect.

Monthly production statistics			
Month	Production	Defect	Defect %
Sep	20	10	50.00
Oct	22	8	36.36
Nov	22	6	27.27
Dec	20	8	40.00
Total	84	32	38.10

Table 4.1 : Monthly Production and Defect

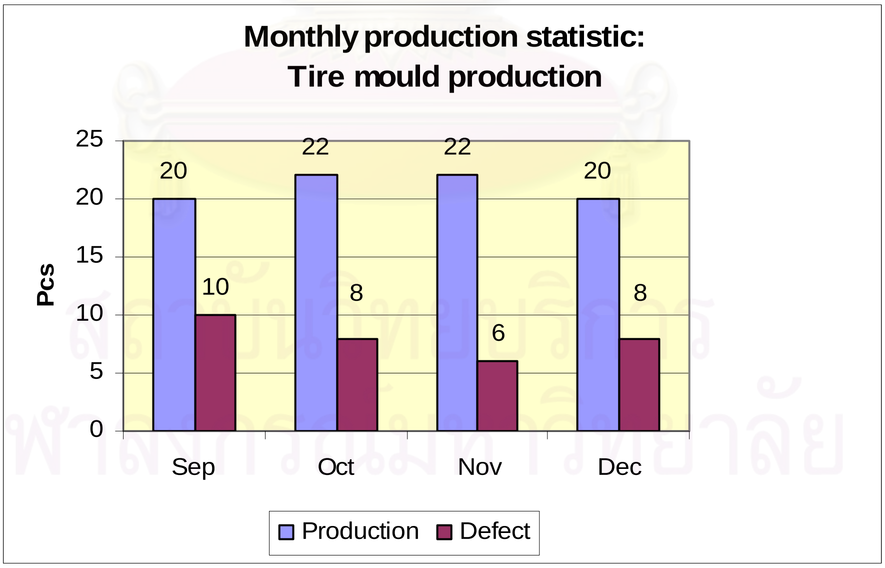


Figure 4.1 : Monthly Production Statistics

From the monthly defects, the scopes of the problem are narrowed down by studying the symptoms of the defect and grouped them into categories. The following graph will illustrate the types of defect that has been found.

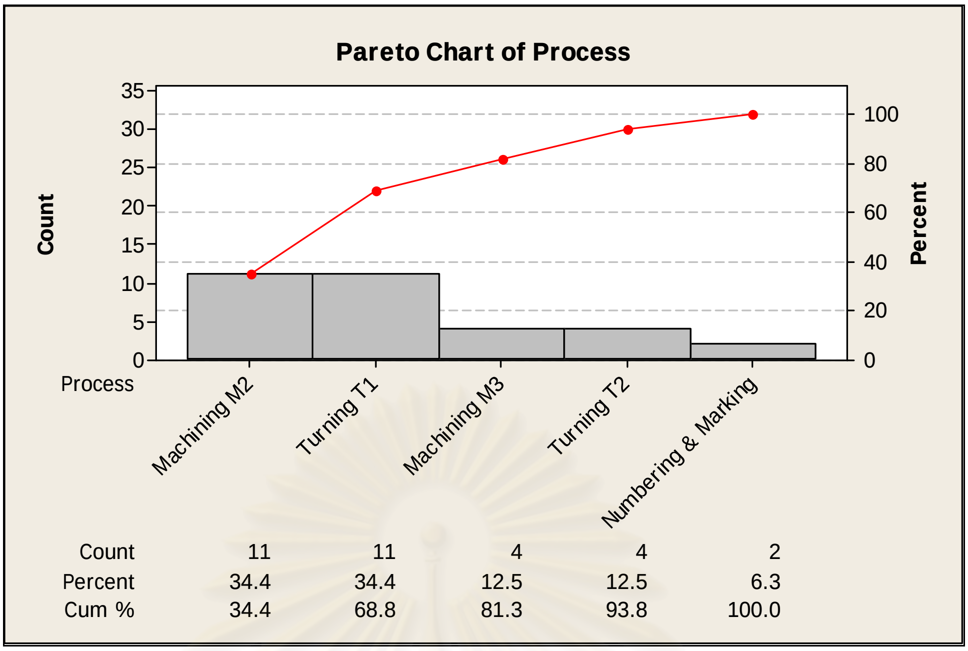


Figure 4.2 : Pareto Diagram of Defect and Production Processes

The Pareto diagram above reveals the relationship between the production processes and the number of defects found in the period of 4 months. It can be seen that machining M2 contributes to 35.5% of the total defect, which is equal to that of the turning 1 process. The amount of defect found in machining M3 process, turning T2 and numbering and marking processes are 12.9%, 12.9% and 6.5% respectively. Out of the total 12 production processes, 3 processes have contributed to 83.9% of the total defect found. Machining M2, Turning T1, and machining M3 are the main causes of the defect, however, turning T2, numbering and marking should not be over looked. All the processes must be investigated.

Next, the defects that frequently occurred during the past 4 months to study the types of defects and their occurrences will be studied. The Pareto diagram of the types of defect and occurrences is as followed.

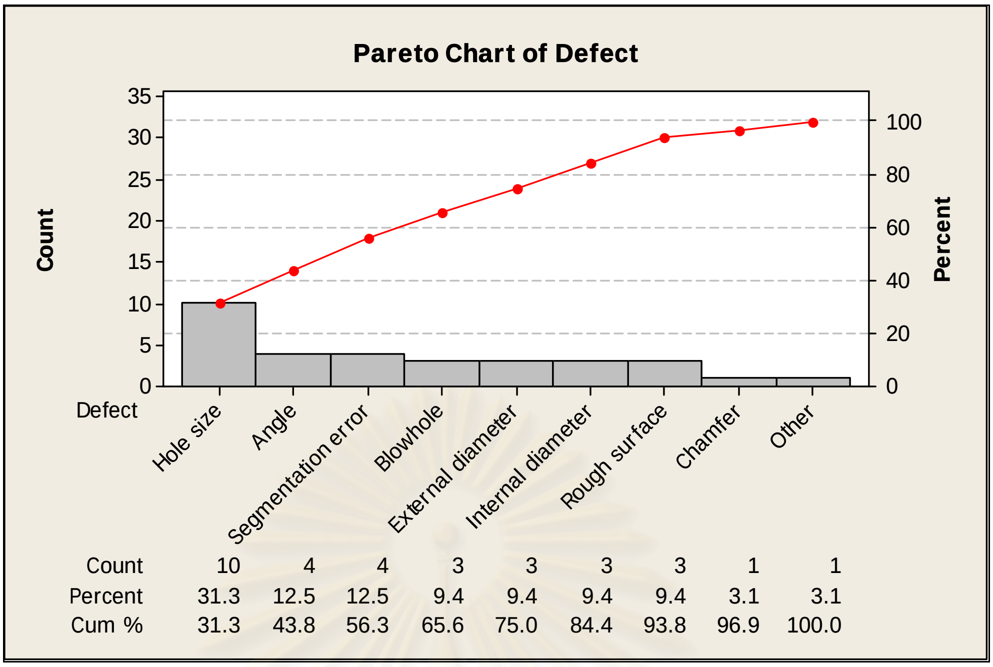


Figure 4.3 : Pareto Diagram of Types of Defects and Occurrences

From the data collected, there are 9 types of defect which have been recorded. Among these defect types, hole size ranked first with 31.3%, followed by angle and segmentation error with 12.5% each. Internal diameter, external diameter, rough surface and blowhole accounted the same defect proportion of 9.4%. Finally, chamfer error and key position contribute to 3.1% for each type.

4.2 Defect Symptoms in Each Process

From the defect statistic, it can be seen that the product failures come from 5 production processes. They are machining M2, turning T1, turning T2, machining M3 and numbering and marking. It can be seen that these processes contribute significantly to the product failure and that they must be analyzed in detail. In the next section, the manufacturing processes will be linked to the types of defect found. The histogram of the defect symptoms will be included, so that they can be arranged according to the ranking. The percentage of each defect symptoms will also be included, so that it can be used for further investigation.

Machining M2

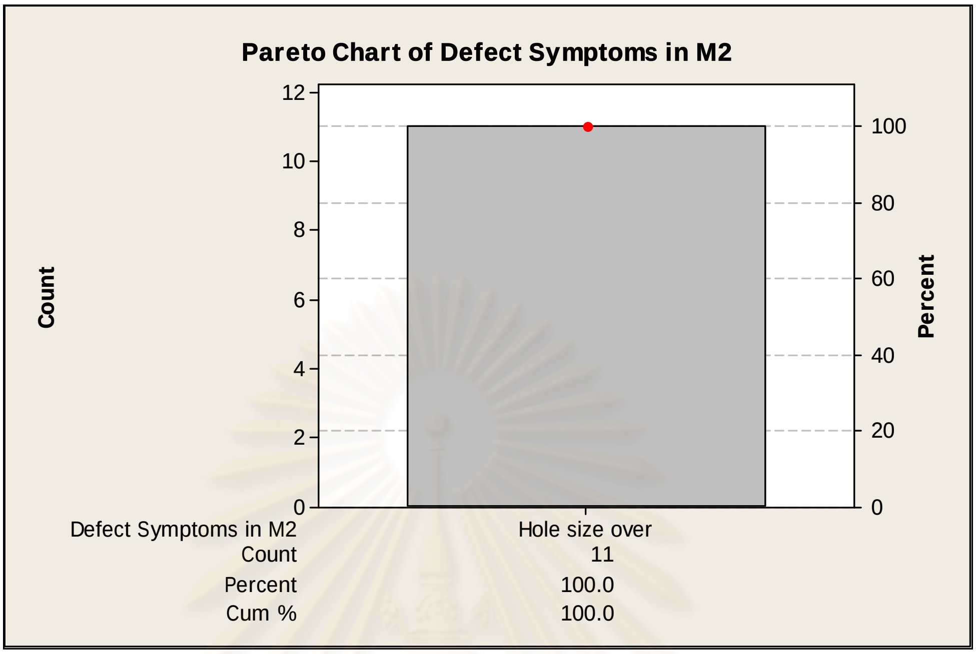


Figure 4.4 : Defects Symptoms & Occurrence in Machining M2

From Figure 4.4 , it can be seen that the defect symptom in the machining M2 is related to hole size. Hole size over is the only defect symptom found in this process, contributing to 100% of the defect symptom.

The close attention must be given to the analysis in this category as machining M2 and defect regarding hole size is accounted for the highest number of defects.

Hole size over – The hole size of the mould exceeds the specification (H7 tolerance) during drilling in the external machining process.

Turning T1

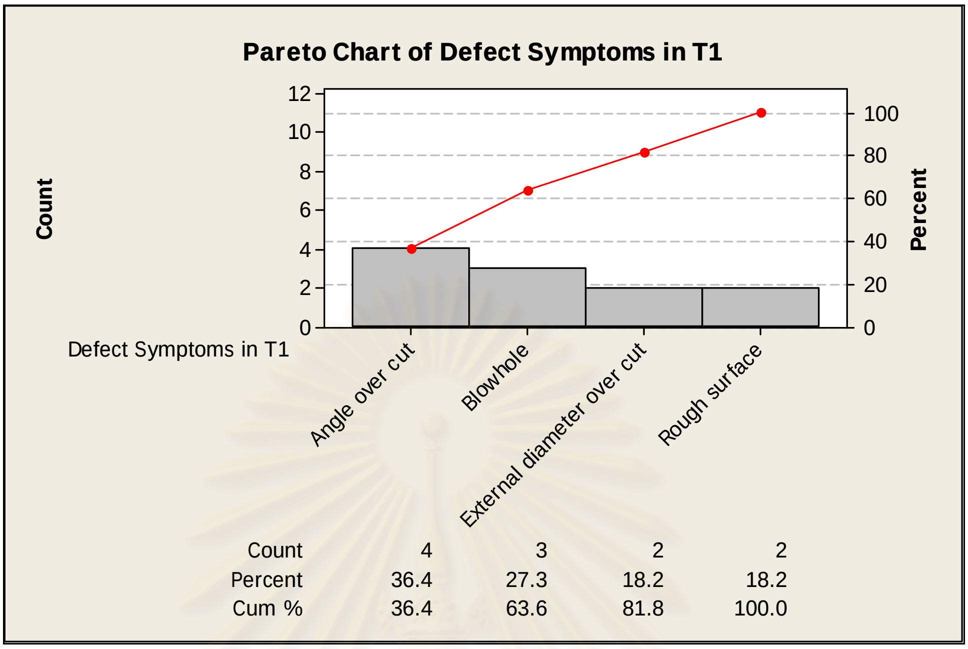


Figure 4.5 : Defects Symptoms & Occurrences in Turning T1

The data from Figure 4.5 reveals that there are 4 defect symptoms found in turning T1. Angle over cut is the main symptom with 36.4%, blowhole is second with 27.3%. Rough surface and external diameter over cut both accounted for 18.2%.

The turning T1 process is also the process which contributes to the highest amount of defect. This indicates that the turning T1 process must be studied closely.

Angle over cut – The slope on the top of the tire mould has been over cut and out from the specification.

Blowhole – The blowhole is found on the surface of the mould during the turning process.

Rough surface – The surface of the mould made by the turning process is too rough and can not be accepted.

External diameter over cut – The external diameter of the mould is smaller than the specification as a result of over cutting of the external diameter.

Machining M3

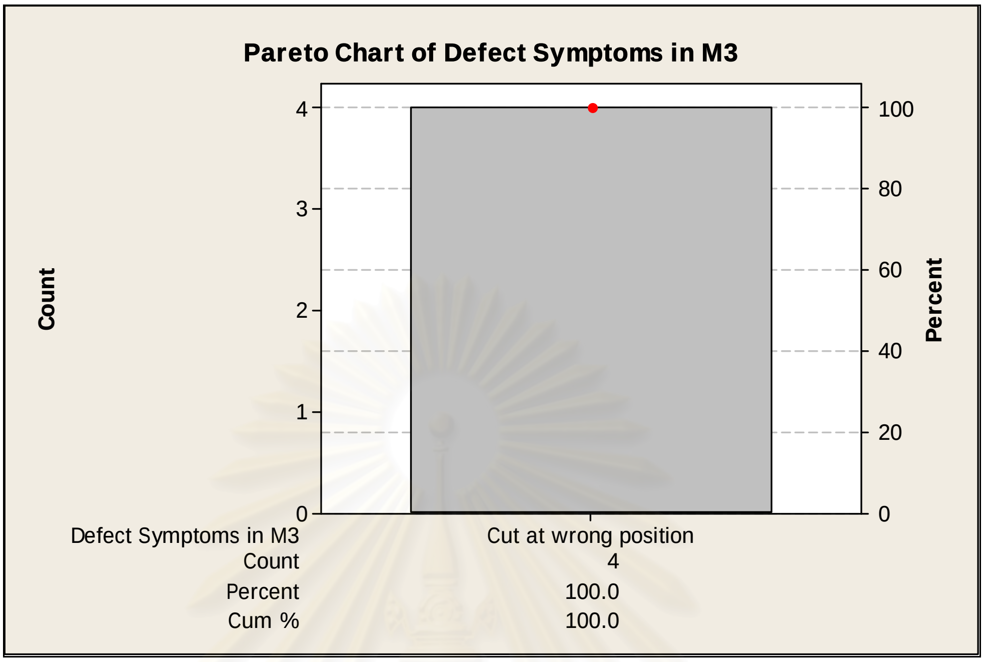


Figure 4.6 : Defect Symptom & Occurrences in Machining M3

Figure: and table: show that there is an only one defect symptom in machining T3, cutting the mould at wrong position. It accounts for 100% of the defect symptom.

Segmentation error – The mould segments are divided in a series of angles. Each piece can sometime have the same or different angles. Each segment must be cut according to the angle given in the drawing. In this case, the segments of the mould are cut at the wrong angles. The angles for each segment are given in the drawing, cutting them at the wrong angle will cause gap in the mould and the position of the holes and key will be wrong.

Turning T2

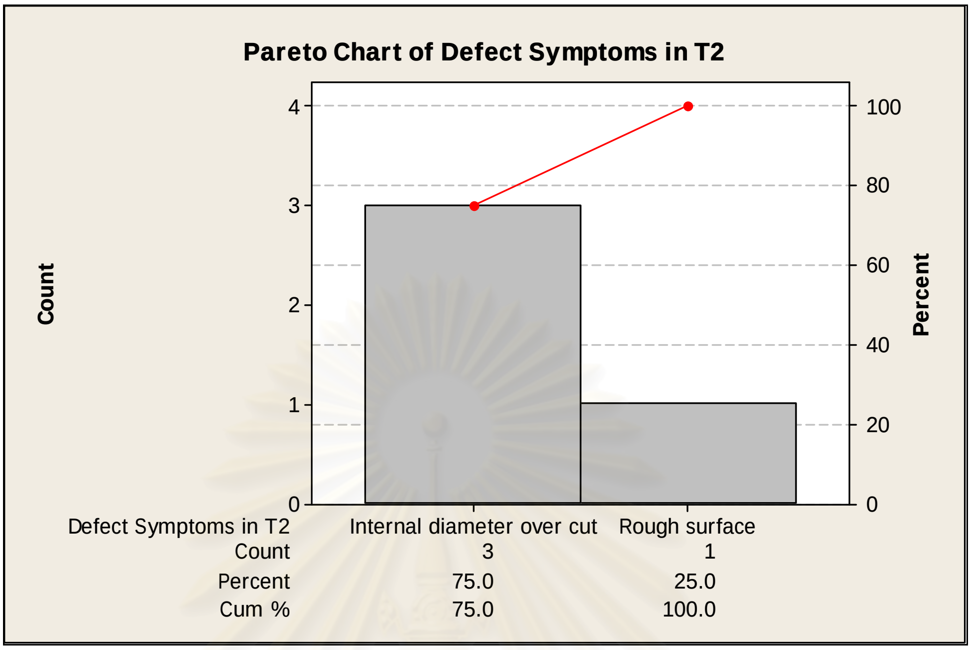


Figure 4.7 : Defects Symptoms & Occurrences in Turning T2

There are 2 defect symptoms which are found in the turning T2, internal diameter over cut (75%) and rough surface (25%).

Internal diameter over cut - The internal diameter of the mould is larger than the specification as a result of over cutting of the internal diameter.

Rough surface - The surface of the mould made by the turning process is too rough and can not be accepted.

Numbering & Marking

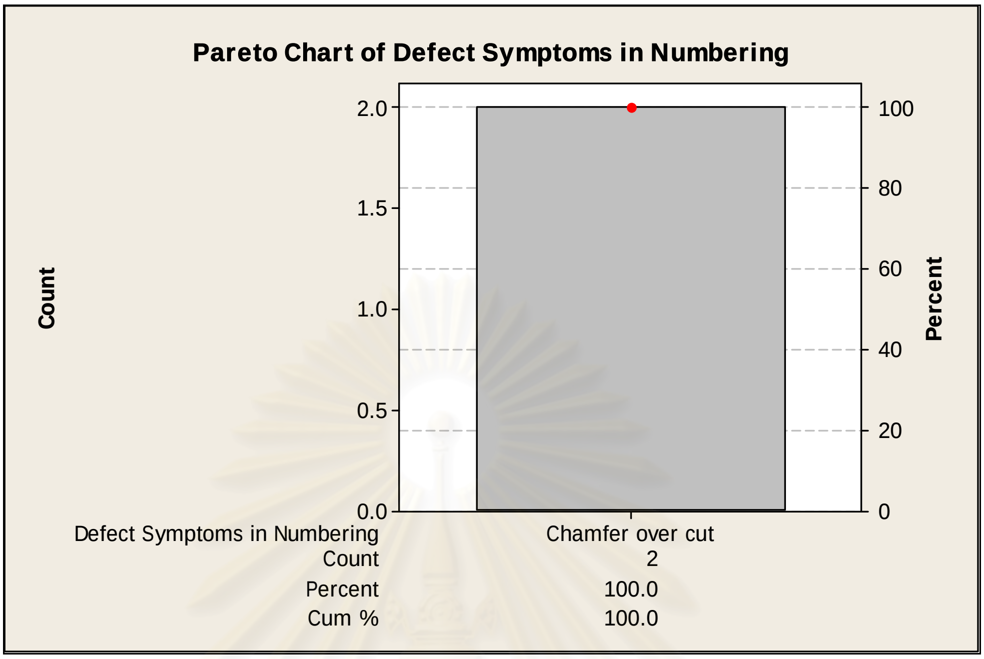


Figure 4.8 : Defects Symptoms & Occurrence in Numbering & Marking Process

In numbering & marking process, there is only one defect symptom, chamfer over cut.

Chamfer over cut – The chamfer at the edge of the mould exceeds the specification.

4.3 Cause Analysis (FMEA)

After the author has collected and study the defect symptom with regards to the production process, the members decided that they will have to analyze the causes of the defects according to the manufacturing process. The first tool to be used is the process FMEA. The author will be analyzing each process with reference to the failure modes that have occurred and also the potential failure modes that might take place in the future. The author will gather and discuss on the level of severity, occurrence, and detection according to the guides that have been mentioned earlier. The values of the 3 items will then be used to calculate the RPN (risk priority number). The process and cause with high RPN will be selected for further investigation to find the solution and improvement.

Process FMEA (Failure Mode and Effect Analysis)																
Process Name	: Machining M2			Documented by		: Arnon (team chief)				FMEA No.	:					
Produce Name	: Tire mould			Responsibility		:				FMEA Date (Org) :						
Core Team	: Team chief, Team advisor, General manager, Product engineer, Process engineer, CNC staff, QC leader, Team coordinator									(Rev)	:					
										Page	: 1/6					
Process Function and Requirement	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recommended Action(s)	Responsibility & Target Completion Date	Expected S	Expected O	Expected D	Expected RPN
Drilling	Hole out of position	Sectors can not be fixed on ring	8	Load work piece on wrong side	4	Marking on work piece	3	96	10						
	Drill through	Hole on mould, leakage	8	Programming mistake	4	Check workpiece with drawing by operator	3	96	10						
	Drill wrong pin position	Sectors can not fit together	8	Programming mistake	5	Operator check drawing & work setting	4	160	6						
	Drill too shallow	Sector can not be tapped	8	Wrong tooling used	5	Operator check tools during work setting	4	160	6						
	Hole diameter over	Sector can not be reamer	8	Inappropriate drill, vibration	7	Operator check drill before start	3	168	5						
	Drill wrong pin height	Sectors can not fit together	8	Programming mistake	4	Operator check drawing & program	5	160	6						
	Missing hole	Sector can not be tapped	7	Programming mistake	4	Operator check drawing & program	3	84	11						
Tapping	Thread depth too shallow	Screw can not be fixed	6	Programming mistake	4	Operator check drawing & program	4	96	10						
	Missing tapping	Screw can not be fixed	6	Programming mistake	4	Operator check drawing & program	4	96	10						

Table 4.2 : FMEA of Machining M2

Process FMEA (Failure Mode and Effect Analysis)					
Process Name	: Machining M2	Documented by	: Arnon (team chief)	FMEA No.	:
Produce Name	: Tire mould	Responsibility	:	FMEA Date (Org) :	
Core Team	: Team chief, Team advisor, General manager, Product engineer, Process engineer, CNC staff, QC leader, Team coordinator			(Rev)	:
				Page	: 2/6

Process Function and Requirement	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recommended Action(s)	Responsibility & Target Completion Date	Expected S	Expected O	Expected D	Expected RPN
Tapping	Deform thread	Screw can not be fixed	6	Tool wear out	4	Operator check tools during work setting	4	96	10						
Milling of key position	Steps in key slot	Sectors do not fit properly	4	Tool wear	5	Operator check tools during work setting	3	60	13						
	Wrong key position	Sectors can not fix on jig	8	Programming mistake	3	Operator check drawing & program	4	96	10						
Boring	Over boring diameter	Sectors can not fix on jig	8	Inappropriate reamer	7	Operator check Reamer before Start work	4	224	2						
	Boring and screw are not centered	Sectors can not fix on jig	8	Programming mistake	5	Operator check drawing & program	4	160	6						
	20mm hole out of position	Sectors can not fit together	8	Work piece slant ,dirty working jig	4	Operator check tools & jigs	4	128	8						

Table 4.2 : FMEA of Machining M2 (continue)

Process FMEA (Failure Mode and Effect Analysis)

Process Name	: Turning T1	Documented by	: Arnon (team chief)	FMEA No.	:
Produce Name	: Tire mould	Responsibility	:	FMEA Date (Org):	
Core Team	: Team chief, Team advisor, General manager, Product engineer, Process engineer, Manual staff, QC leader, Team coordinator			(Rev)	:
				Page	: 3/6

Process Function and Requirement	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recommended Action(s)	Responsibility & Target Completion Date	Expected S	Expected O	Expected D	Expected RPN
Cut external diameter	Dimensional error (upper diameter too small)	Sectors can not fix on jig	8	Programming mistake	4	Operator check drawing & program	4	128	7						
	Dimensional error (height too small)	Sectors can not fix on jig	6	Programming mistake	4	Operator check drawing & program	4	96	9						
	Rough surface	Bad appearance	4	Tool wear	7	Operator check tools	3	84	10						
	Angle out of specification	Sectors can not fit together	8	Programming mistake	6	Operator check drawing & program	4	192	4						
	Blowhole	Bad appearance	5	Casting defect	7	No process control	3	105	8						

Table 4.3 : FMEA of turning T1

Process FMEA (Failure Mode and Effect Analysis)																
Process Name	: Machining M3			Documented by		: Arnon (team chief)				FMEA No.	:					
Produce Name	: Tire mould			Responsibility		:				FMEA Date (Org) :						
Core Team	: Team chief, Team advisor, General manager, Product engineer, Process engineer, CNC staff, QC leader, Team coordinator									(Rev)	:					
										Page	: 4/6					
Process Function and Requirement	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recommended Action(s)	Responsibility & Target Completion Date	Expected				
												S	O	D	RPN	
Cut mould segments	Mould segments slant	Sectors can not fit together	7	Set work in wrong position	5	Operator check Work piece during work setting	3	105	8							
	Wrong segment angles	Sectors can not fit together	8	Programming mistake	5	Operator check drawing & program	5	200	3							

Table 4.4 : FMEA of Machining M3

Process FMEA (Failure Mode and Effect Analysis)																
Process Name	: Turning T2			Documented by		: Arnon (team chief)				FMEA No.	:					
Produce Name	: Tire mould			Responsibility		:				FMEA Date (Org) :						
Core Team	: Team chief, Team advisor, General manager, Product engineer, Process engineer, Manual staff, QC leader, Team coordinator									(Rev)	:					
										Page	: 5/6					
Process Function and Requirement	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recommended Action(s)	Responsibility & Target Completion Date	Expected				
												S	O	D	RPN	
Cut internal diameter	Dimensional error (internal upper diameter too large)	Sectors do not fit properly	3	Improper measuring instrument	4	Check by carbon shaft	5	60	12							
	Internal angle error	Parts can not be fixed on sectors	8	Tool wear, Programming mistake	7	Operator check drawing, tools & program	4	224	2							
	Dimensional error (internal middle diameter too large)	Parts can not be fixed on sectors	7	Improper measuring instrument	8	Check by carbon shaft	5	280	1							
	Dimensional error (internal height too large)	Parts can not be fixed on sectors	8	Programming mistake	4	Check by internal micrometer	5	160	5							
Finish surface	Blowhole	Leakage	8	Casting defect	6	No process control	3	144	6							
	Rough surface	Bad appearance	5	Tool wear	4	Operator check tools	3	60	12							
	Step	Bad appearance	5	Tool wear	3	Operator check tools	3	45	13							

Table 4.5 : FMEA of Turning T2

Process FMEA (Failure Mode and Effect Analysis)																
Process Name	: Numbering & marking			Documented by		: Arnon (team chief)				FMEA No.	:					
Produce Name	: Tire mould			Responsibility		:				FMEA Date (Org) :						
Core Team	: Team chief, Team advisor, General manager, Product engineer, Process engineer, QC leader,									(Rev)	:					
	Team coordinator									Page	: 6/6					
Process Function and Requirement	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking	Recommended Action(s)	Responsibility & Target Completion Date	Expected S	Expected O	Expected D	Expected RPN
Marking product code	Punch number on wrong side	Bad appearance	3	Operator does not check drawing	5	No process control	3	45	13						
	Punch wrong number	Bad appearance	3	Operator does not check drawing	4	No process control	3	36	14						
Chamfering mould edge	Over chamfer	Sectors do not fit properly	3	Operator does not check drawing	5	No process control	3	45	13						
	Grinding mark on pin hole	Bad appearance	3	Operator does not check drawing	7	No process control	3	63	11						

Table 4.6 : FMEA of Numbering & Marking

4.4 FMEA Result

The result of the FMEA has provided the basic information on the effects of the failures, the causes of failure and the RPN. Before analyzing further, a base line for the risk priority value that will be used for selection must be calculated. The calculation of the risk priority value will be as followed.

The author decided to select the severity value should be rated at 5, which will give low severity level. 100% of product in this category may have to be reworked offline, but does not need to be sent to repair department. This level will suit the condition of the company best.

The average value for occurrence is agreed at 6. It is a moderate value. The occurrence rate for this category is around 1/100. This is appropriate for the production level of the company.

For the detection level, the value selected is 5. This is the value for moderately high detection level. It is selected based on the company's criteria, as most of the parts are checked by instruments or gauge in most of the production processes.

From the value selected, the base for the RPN can then be calculated.

$$RPN : 5 \times 6 \times 5 = 150$$

Therefore, the failure modes with RPN higher than 150 will be selected and used for further process improvement.

The following table will summarize the failure modes with RPN higher than 150. The failures are also ranked according to the RPN.

Process Function and Requirement	Potential Failure Mode	Potential Effect(s) of Failure	S	Potential Cause(s) / Mechanism(s) of Failure	O	Current Process Controls	D	RPN	Ranking
Cut internal diameter	Dimensional error (internal middle diameter too large) B	Parts can not be fixed on sectors	7	Improper measuring instrument	8	Check by carbon shaft	5	280	1
Boring	Hole diameter over	Sector can not fix on jig	8	Inappropriate reamer	7	Operator check reamer before start	4	224	2
Cut internal diameter	Internal angle error	Parts can not be fixed on sectors	8	Tool wear, Programming	7	Operator check drawing, tools & program	4	224	2
Cut mould segments	Wrong segment angles	Sectors can not fit together	8	Programming mistake	5	Operator check drawing & program	5	200	3
Cut external diameter	Angle out of specification	Sectors can not fit together	8	Programming mistake	6	Operator check drawing & program	4	192	4
Drilling	Hole diameter over	Sector can not reamer	8	Inappropriate drill	7	Operator check drill before start	3	168	5
Drilling	Drill wrong pin position	Sectors can not fit together	8	Programming mistake	5	Operator check drawing & work setting	4	160	6
Drilling	Drill too shallow	Sector can not be tapped	8	Wrong tooling used	5	Operator check tools during work setting	4	160	6
Drilling	Drill wrong pin height	Sectors can not fit together	8	Programming mistake	4	Operator check drawing & program	5	160	6
Boring	Boring and screw are not centered	Sectors can not fix on jig	8	Programming mistake	5	Operator check drawing & program	4	160	6
Cut internal diameter	Dimensional error (internal height too large)	Parts can not be fixed on sectors	8	Programming mistake	4	Check by internal micrometer	5	160	6

Table 4.7 : Failure modes with RPN more than 150

From the result of the FMEA, it can be seen that there are 11 failure modes with RPN higher than 150. They are

1. Dimensional error from T2
2. Hole diameter over from M2 (reamer)
3. Internal angle error from T2
4. Segmentation error from M3
5. Angle out of specification from T1
6. Hole diameter from M2 (drill)
7. Drill wrong pin position from M2
8. Drill too shallow from M2
9. Drill wrong pin height from M2
10. Bore holes & screw not centered from M2
11. Internal height too large from turning T2

Apart from the RPN, the FMEA also provide other useful information. The following paragraphs will illustrate the interesting findings that has been discovered from the FMEA.

Firstly, it is found that programming error is the biggest potential cause behind the failures associated with CNC machines. These failure modes come from turning T1 and T2, and machining M2. Even thought there are existing process controls, it is clearly visible that they are not working well. The working methods and the controlling processes require immediate improvement. At this point, it is noticed that the failure modes come from similar failure causes and their solutions might be able to use for different processes which involve CNC machines. The author foresees that the solutions to reduce failures and enhance process control would help to reduce a significant amount of failures. This will in turn increase the productivity of the tire mould production.

Secondly, the FMEA reveal that tool wear and using of wrong tools are contributing to many failure modes. Although the failure modes associated with these causes do not have RPN above 150, the author is concerned with the potential of the outcome. When tools ware out, they can brake, causing injury to the operators. Broken tools can also damage the mould and machines. Replacing the damaged casting and repairing CNC machines can be costly. For this case, the author decided to find preventive measures to reduce failures that relate to tools wear.

Next, a number of failure modes in turning T2 process are caused by improper measuring instruments. It seems that the measuring instruments and the techniques used are not appropriate and they must be corrected. The improper instrument and incorrect technique could also affect other processes too. It also affects the confidence of the operators and the image of the company.

After the failure modes are collected, it is clear that there are many problems to be solved. The failure modes must be prioritized. The solving should start with the bigger problem first, before continuing to the smaller ones. However, some small problems can be solved or prevented easily and immediately. These failure modes will be attended too.

4.5 Fish-bone Analysis

For more detailed analysis, the author will investigate the failure modes with fish-bone analysis. The analysis will be based on the 4Ms, man, method, machine and material. The analysis will be based on the 5 working processes which produce the highest amount of defects. They are machining M2, turning T1, machining M3, and turning T2.

The fish-bone analysis include meeting of staffs who are involved in each process. Members will brainstorm their ideas and thoughts on the factors that would have contributed to the nonconformity products. This will be done with regards to man, method, machine and material. The author will be attending all meetings to record the finding.

Machining M2

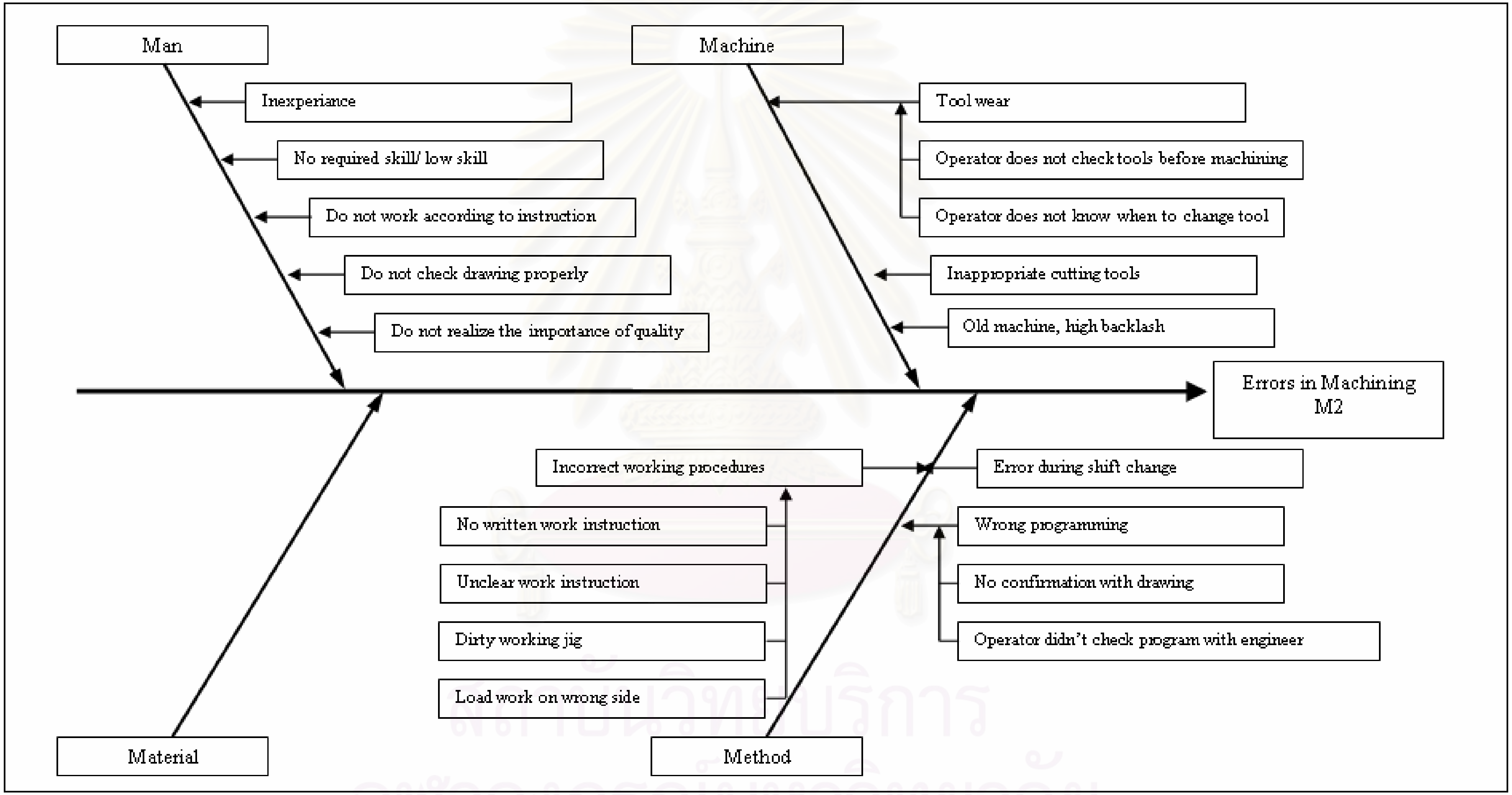


Figure 4.9 : Fish-bone diagram of Errors in Machining M2

Turning T1 & T2

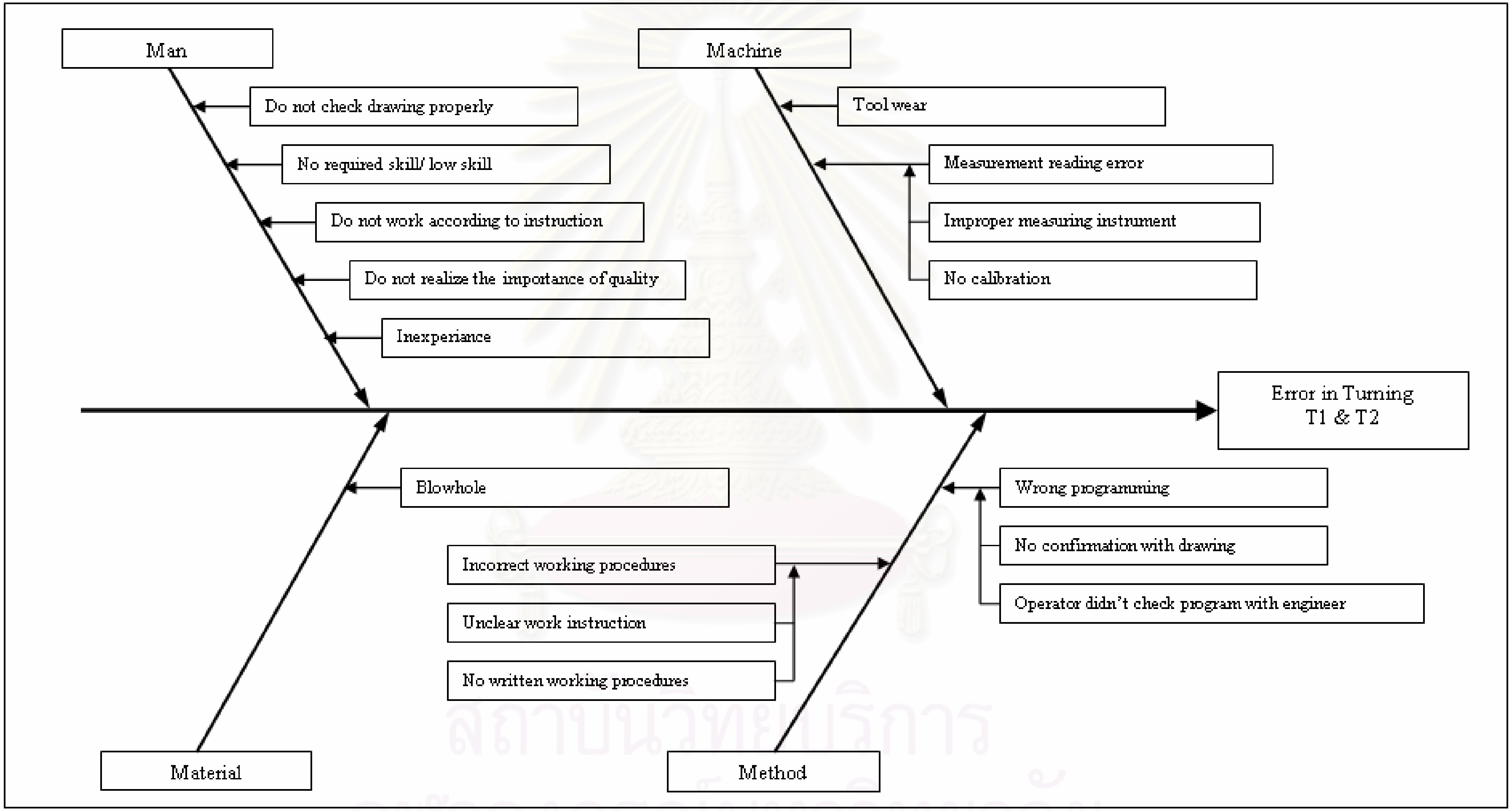


Figure 4.10 : Fish-bone diagram of Errors in Turning T1 & T2

Machining M3

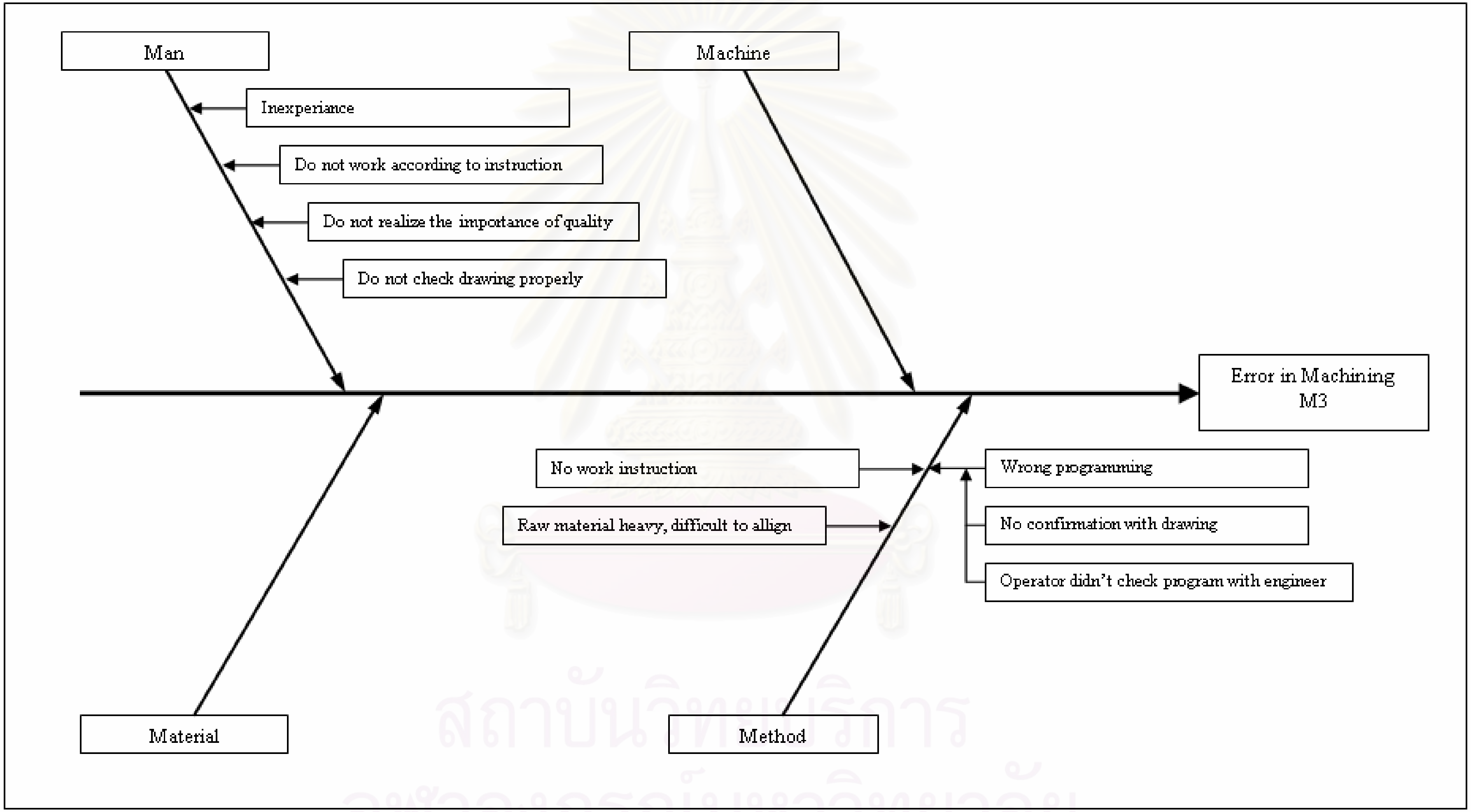


Figure 4.11 : Fish-bone diagram of Errors in Machining M3

4.6 Fish-bone Analysis Result

Machining M2

Man

1. Some operators are new to the machines and/or the tire mould production. As a result, they are prone to make mistakes.

2. The operators do not have sufficient skill to do the required job. CNC machines require training and education before the operators can operate the machines. There are also a large number of functions and parameters that the operators have to remember for individual machine. Without required skill and knowledge, CNC machines can be very difficult to operate.

3. The operators do not work according to instruction given to them. They prefer to choose the easier way out and take short cut in programming. This can lead to programming error and other failure modes.

4. The operators will receive drawing for every piece of mould, as individual mould has its own detail. The operators will use this drawing to program the codes for their CNC machines. However, the operator does not check the drawing properly and they cut on the wrong piece of raw material. This also results in cutting, drilling and tapping in the wrong position. Operators also miss important details of the mould, they cut in wrong position, resulting in dimensional error.

5. The operators do not realize the importance of quality. They think that they can rework if anything went wrong with the mould. This is the attitude of some operators as they are not serious about the quality of the mould and do not see the loss of the company.

Machine

1. There is specific tooling to be used differently for different material and cutting types and they come in a variety of sizes. Sometime, wrong tools are used by the operation both because of laziness to change tools or their lack of knowledge. This reduces the tool life of the tools and causes them to wear quickly. Operators also do not know when to change the tools. As a result, the tools do not perform well and the quality of the mould is affected. The drill and reamer used in this process is not suitable for mass production and they cause vibration and wear fast. This will cause the hole diameter to become over size.

2. Operators are given instruction to check the tools before each operation. Sometime, they refuse to check and the wear tools are used in the process.

3. The CNC horizontal machine which is used for this process I was made in 1990. The machine is in normal operating condition and is mechanically functional. However, after more than 17 years of operation, the slide ways, bearings, bushes and guides of the machine has been worn out. This situation is normal for machines that have been working consistently for a long time. Nevertheless, different machines wear at different rate. The effect of the wear will be amplified through the years. As a result of the wear, the accuracy and the rigidity of the machine is significantly affected. The effect in the wear is called "backlash". The backlash caused the accuracy of the machine to decrease. The machine did not perform as programmed. It can be noticed that the tolerance of the work pieces are getting larger. Only jobs with wider tolerance and less precision can be given to the machine. The reduction in machine's rigidity means that the machine can not be used for heavy cutting. When cutting tools wear out or larger tools are used, the accuracy of the machine is lost. This leads to a wider tolerance in the worker piece.

Method

1. The procedure for marking and locating of position is not appropriate. Every department should mark the important detail on the mould with permanent marker before sending to the next department. However, the operators sometime forget to mark, causing confusion and lead to machining error if the proceeding department do not checked carefully.

2. Wrong programming or programming error is one of the major causes for many failure modes. There are a few factors from the method used in the machining process which contribute to the failures.

   The operators have to program the cutting path of the CNC machine in the computer or at the control panel of the machine. After the programming has been done, the operators did not check the numerical value with the drawing, they let the machine run. The operators make mistakes in keying in the number from time to time and cause error during machining. The operators should have confirmed the drawing against the program to avoid error.

   Very often, the programs for the CNC machine are kept by the engineer and are given to the operators to use when the same mould is being done for the second time. The designs of the mould are similar and the old program can be used with minor modification. When the programs are given to the operators, they did not check the program before running the machine. As a result, the operator made programming error and machine out of specification.

   There is no written working instruction given to the operators regarding the programming method. The operators work by following the practice which has been done in the company. The departmental head and the engineer advise them from time to time, but sooner or later those advices will be forgotten. This results in unclear work instruction.

3. In the tire mould production, the operators work on 2 shifts basis. The operators have to leave their work while the mould is still being machined frequently during the shift change. Without proper communication between the operators, the operators are prone to make mistake in programming, work setting and machining.

4. The chips from the cutting process are not removed from the jigs, causing the mould to be out of position. When the machine cut the mould, the holes and dimension will be out of specification. This is because the operators did not clean the jig properly.

Turning T1 & T2

Man

Some causes of the failure modes in this category are similar with those machining M2. The detailed descriptions of similar causes can be found in the Man section of machining M2.

1. Operators do not check the drawing and the dimensions of the mould properly

2. Operators do not have the skill required to work with the CNC turning machine.

3. Operators do not realize the importance of quality and not quality-minded.

4. Operators do not work according to the instruction given to them.

5. Some operators are new to the machine and to the job. They do not know how to operate the machine or set up the casting well. This increase the chance of making error in the process.

Machine

Some causes of the failure modes in this category are similar with those external machining M2. The detailed descriptions of similar causes can be found in the Machine section machining M2.

1. Tool wear is the result of wrong usage of tools such as use to cut wrong material, wrong cutting speed, or exceed the tool life of the specification. For the turning process, it is the cause for rough surface and steps on both the inner and outer surface of the mould. It can also affect the tolerance of the turning work, causing the angle and the dimension of the mould to be out of specification.

2. In turning process, measuring the dimension of the mould is one of the most difficult tasks. Very often, the operators have different values when compared to the QC department or the customers. The management's concern towards this quality problem is growing. The fishbone diagram has found a variety of potential causes which contribute to these phenomena.

   The diameter of the tire mould is relatively large. The measuring instruments used are large and heavy too. Measuring the mould with these instruments can be a difficult task, requiring both strength and technique. A little slant in the micrometer screw gauge or other measuring instrument will give incorrect reading. The tolerances given in the critical part of the mould is very small, in microns. To get the correct reading, the operators have to be well trained and measure the mould in the correct position.

Some of the measuring instruments used by the company and the customers are different. The company is using a carbon shaft with dial gauge attached to the end and another fixed end. It has to be calibrated against the linear scale first before measurement. It can be used to measure both internal and external diameter of the tire mould. On the other hand, the customers are using internal micrometer and external micrometer. The author suspects that the difference in the measuring instrument might be the cause of the failure modes.

There is no calibration of measuring instrument against external sources. This is very important especially with the linear scale as it is used to calibrate other measuring instruments in the company.

Method

Some causes of the failure modes in this category are similar with those machining M2. The detailed descriptions of similar causes can be found in the Method section of machining M2.

1. The operators do not double check the program given by the engineer. Sometime, the program has mistakes or the operators machine on the wrong piece of work.

2. After the program has been done, the operators do not check the program against the drawing. They sometime make error in keying the dimension value or inputting wrong decimal points. The mould might be over-cut or the tools might crash into the work piece.

3. After programming, the operators do not check and confirmed the program with the engineer, leading to programming error.

4. There is no written work instruction given to the operator. As a result, the operators do not know what to do and sometime follow the wrong

practice. Verbal instruction given by the engineers and managers are not clear and easily forgotten. Without clear, written work instruction, the operators do not have a standard to follow.

Material

1. There is only one failure mode in material category, blowhole. The raw material is supplied by the customer, the company has no responsible toward it. Even thought it is creating problem to the tire mould. The company can not do anything about the quality of casting as it is supplied by the customer. The management and engineers have discussed this problem with the customers on several occasions, but there seems to be very little improvement. This is beyond the company's control. The customers agreed to pay for the machining cost incurred when the blowhole is found and must be scrapped. This also includes the repair cost of the tire mould, should there be any.

Machining M3

Man

Some causes of the failure modes in this category are similar with those machining M2. The detailed descriptions of similar causes can be found in the Man section of machining M2.

1. The operators do not know how to operate the machine well. They are not familiar with the machine and the job, increasing the risk of making error.

2. Even though instruction are given to the operator, they sometime refuse to follow or forgotten the instruction.

3. The operators are not quality-minded, they do not realize the importance of quality.

4. The operators don not check the drawing carefully during programming.

Machine

1. In the segmentation process with the CNC horizontal machine, the process is taking a lot of time as the operators have difficulty setting up the reference point of the mould. The operators can not see the reference point clearly as they can not go into the working table of the machine. This increase the chance of cutting on the wrong position. The author is looking into this problem as the machine used for this process is in appropriate. The machine needs to be change to increase the productivity.

Method

Some causes of the failure modes in this category are similar with those machining M2. The detailed descriptions of similar causes can be found in the Method section of machining M2.

1. Just like the machining M2, there is no work instruction for the operators.

2. Setting the mould onto the table of the CNC machine is very difficult as the machine is enclosed in the protection cover. The mould is heavy, and adjusting the position during setting manually can be a time consuming task. The operators also can not set the position properly. Investigation is made and a new cutting method is planned, so that the CNC machine can be used for other more productive job. It is aimed to reduce the process time as well as increase the quality of the mould.

4.7 Defect Reduction

The process FMEA and Fish-bone analysis have provided useful information to study the failure modes, their effect, their causes and also their priorities. The author gathers this information and uses it to find the solutions as well as the prevention methods to control the production process which will aims to solve those with higher RPN first, however after discussion, the team discovered that the natures of the failure modes within the same process are similar. Some solutions can be universal and could solve more than 1 failure modes. As a result, the team will find solution for the failure modes according to the process. And the main goal is to reduce the number of defects found in the production process as fast as possible.

Machining M2

Machining M2 contributes to a large amount of defect. There are 6 failure modes in this process with RPN above 150, they are hole diameter over size, drilling of wrong pin position, drilled hole too shallow, drill wrong pin height, and bore hole and screw not centered. Three of these failure modes are caused by programming error. Majority of the failure modes in this process are also caused by programming error. In the analysis, it was found that there are many factors which lead to programming error. They come mainly from man, machine and method.

The operators do not know how to operate the machine well, they do not follow instruction, they do not check drawing and program carefully, and they do not realize the importance of quality. For this cause, it is decided that the following action must be taken.

1. A check sheet must be introduced and used by both operator and the engineer. The engineer will have to check the important dimension with high tolerances, filled in the value into the form and highlight these values on the drawing. The operators will have to double check the dimension against the drawing and the check sheet before programming. Then the operator will have to measure these dimensions again after the work have been done to make sure that the dimensions are correct

before signing and sending it to the next process. The check sheet will also include the major design changes and/or critical areas that the operators have to look out for.

2. Programming knowledge is very important to the operators. Arrangement will be made for the process engineer and CNC head of department to give basic programming lesson to the operators. The engineer and the CNC head of department are well educated and highly experienced in programming. They will be able to give the operators the correct programming method, programming sequence, tool selection, cutting speed, and other important parameters. The operators will be given basic command code sheet so that they can use it with their machines. It is intended that with basic skill, the operators will take around 8 hours to attend the class. This will be done during working time with half of the operators attending the class at a time, taking 2 days in total. In addition, the engineer and the head of department will be moving around and checking on the operators after the class to advice them personally.

3. The operators must realize the importance of quality and they should have a goal to reduce the defects. The process engineer will record the defects every month and paste the graph and detail on the CNC department's notice board. This is to make the operators aware of the amount of loss that the company is facing. The statistics will also be discussed at the weekly meeting to find improvement.

4. The operators do not know how to select the tools for the specific job. The tools selection and usage will be included in the programming class. The operators will learn how to select and use the right tool for the right job. The process engineer and the head of department will give a list of basic tools that are necessary for the tire mould production. This list must be checked for the correct tool and tool condition by the operators before each production.

5. For end mill and drill, the engineer with calculate their tool life and the operators are ordered to change the tool once the tools has completed a certain piece of mould. These tools can be sent to regrind and can be used again. For taps, the tool life till be calculated and they will be replaces after the calculated tool life has been reached. They will be sent to the manual department to be used for other jobs which require less accuracy.

6. In order to solve the problem regarding the reamer hole, the accuracy of the machine must be improved. There are several ways which can be done to solve the problem. They are acquiring new machine, overhauling the existing machine and change the cutting tools. The detail of each alternative is as followed.

   A new machine with better accuracy and rigidity can be used to replace the old machine. This will be the best solution as the new machine will be stronger and more precision. The operators do not have to worry during programming and cutting. Less monitoring and tool checking will be required. However, the cost of the new machine is relatively high and the feasibility of the purchase has to be carefully considered.

   The second alternative is to overhaul the old machine. This means that professional machine builder will have to disassemble the machine into parts, repair and replace the worn out parts. The slide ways and the tables of the machine have to regrind to remove the scratches and get rid of the rough surface. When the worn out parts are repair and replaced, they will be assembled and installed. The accuracy of the machine will be better, but not as good as new.

   The third alternative is to change the cutting tools of the drill and reamer process. The engineer has calculated the tool life of the tools and collects the data on the diameter size. It is found that the tool life is much shorter than expected, and there is a wide variation in the diameter size of the hole. The vibration of the machine as a result of the backlash causes the cutting tools to vibrate, giving a wide range of diameter sizes. A stronger and harder drill and reamer such as those made from carbide can be used to replace the old cutting tools. These tools provide sharper cutting edge which last longer. However, the tools must be carefully selected to match the raw material.

The 3 alternatives must be analyzed in greater detail via ROQI, so that the most feasible alternative can be chosen.

7. In order to standardize the production method, the work instruction must be made. Involved personals to help to compose the work instruction which will be used in the CNC department for the tire mould production. This work instruction will include the process that the operators have to follow, the techniques, the useful tips, the defects that have been found in the past and the critical area that the operators must look out for. This work instruction will be checked and approved by the senior management before given to the operators. This work instruction is believed to be able to solve many issues regarding the method of working. The head of department will then be ordered to strictly monitor the operators to make sure that they follow the work instruction.

8. For the error during shift change, the operators are told to come 10 minute before the work start to meet with the other operators to study the work and pass the work. The head of department and the assistant must meet and discuss the day-to-day work planning before they start their work.

9. The operators in the upstream department are told to mark the reference position of the mould with marker and fill in the check sheet. The head of department will check and confirm before sending to the next department. If the check sheet is not filled or the reference position is not marked, the mould will be returned for correction.

Turning T1 & T2

The next process is the turning process. In this process, the solution will be for the turning T1 and T2 process as the types of failure found in these processes are relatively similar to one another. The turning processes also produce a large amount of defect every month. The failures need to be reduced and stop fast. The processes with high RPN in turning includes, internal dimensional errors, internal and external angle errors. These failures will be dealt with accordingly.

1. The measuring instruments that the company used to measure the outer diameter and inner diameter of the mould is different from the customers. The customers use large micrometer screw gauge and internal micrometer screw gauge, whereas the company uses a carbon shaft measuring instrument with dial gauge fixed at the end. It is suspected that the expansion of the mould in the machine shop is more than that of the carbon shaft. The measuring instruments and the linear scale are kept in air conditioned room, while the moulds are being manufactured outside. The difference in temperatures might causes error in the value obtained. The operators did not compensate for the expansion. The conservation of values is a time consuming task and might be a potential failure modes. To reduce the defects and make measuring more accurate, it is suggested that the company should invest on the new set of micrometer screw gauge. The micrometer screw gauge is made of metal with similar expansion rate. It is also more ergonomic to use these instruments as it can measure a wide range of diameter and do not need to be set every time.

2. Just like other manufacturing processes, there is no work instruction. The author will join with the operators, the engineer and the head of department to discuss the work procedures and the detail of the worn. Then the work instruction will be formed and given to the operators. The work instruction is believed to solve quality issues related to man and method. The work instruction will provide a guide line for the operators to follow. With correct working method and systematic

procedures, the operators will be able to improve the quality of the mould.

3. The author plans to provide a basic CNC programming class for the operators. This class will provide the operators with programming technique, the tool selection and usage, how to read drawing and proper working sequences. The class will be hosted by the process engineer and the head of department. The class will be a 4 hours class with only 1 session as turning process is not difficult to learn.

4. Check sheet will be issued with every piece of drawing and casting. The engineer will check and marked the important dimensions on the drawing before filling in the check sheet. The operators will have to check and fill in the dimensional values again before programming. After the casting has been machined, the operators will have to measure and record the values onto the check sheet. Only when the mould have been checked and approved by the head of department, it can be sent to the next department.

5. The author found that calibrating the linear bench is necessary. The linear bench is used to calibrate other measuring instrument in the factory. It has not been calibrated for more than one year. The calibration will allow the engineer to set the accuracy of linear bench. This will in turn increase the accuracy of other measuring instruments. The linear bench will be calibrated yearly to check and keep it accurate.

6. For the problem regarding the blowhole, the engineers and the manager have contacted the customer and the casting supplier for discussion. The casting supplier is now trying to improve the method and the components to obtain better casting.

Machining M3

There is only one failure in this process with RPN higher than 150. This failure mode is cutting wrong segments. This is very costly mistakes as the sectors have to be scrapped only. Defects from this process can not be repair. Each piece of material can cost between 50,000 to 70,000 Bath. Any mistake made in this process has a high price.

1. The author will provide check sheet which has to be filled by the engineer and the operators when they received the drawing. The operators will then use the check sheet to help them programmed the cutting parameters. This check sheet will follow the sectors to the other departments. It will be finally used to check by the QC department.

2. Again, the operators in this process do not follow instruction and there is no work instruction in the process. The author will discuss the working procedures with the head of department and come up with the working procedures for the machining segmentation process and the gas cutting process. This will allow the operators to work easier with well written work procedures.

4.8 ROQI for Machining M3 Process

In the earlier section, the alternatives to solve the problem in the drill and reamer process of M3 are introduced. There are 3 alternatives, buying new machine, overhauling the old machine, and getting new cutting tools. These alternatives will be discussed and analyze. The ROQI of each alternative will be discussed.

Acquiring New Machine

By acquiring the new machine, it is believed that the defect in the drill and reamer process can be eliminated. The strength and precision of the new machine will be able to produce hole with H7 tolerance. The cost of the new machine will include the machine and the installation cost. From the quotation of the supplier, the CNC horizontal machine with a table size of 800 x 800 mm. with similar specification would cost 15,500,000 bath, including installation. The maintenance cost and operation cost would be the same as the existing machine; therefore, it will not be included. The life of the machine is expected to serve without the accuracy being significantly affected for 15 years. The lead time for the delivery is 2 years. The net present value of the investment will be calculated based on the 6% long-term interest rate for bond and the time period is 15 years.

At present, the cost of defect resulted from this process is 25,000 bath. These cost came from the amount of rework, reject and the overhead cost incurred in the between September to December 2006. The calculation method can be found in the earlier chapter. The ROQI will be calculated on a monthly basis.

Net Value	=	15,500,000 (A/P, 6%, 15)
	=	15,500,000 x 0.1030
	=	1,545,000 bath
Life of machine	=	12 (month/year) x 15 (year)
	=	180 month
Monthly cost	=	1,545,000 (bath) / 12 (month)
	=	128,750 bath/month
Monthly saving/benefit	=	Expected defect reduction

	=	25,000 bath/ month
ROQI	=	Monthly benefit / Monthly cost
	=	25,000/128,750
	=	0.194

Overhaul Existing Machine

The second alternative is overhauling the existing machine. The overhaul is believed to improve the condition and the accuracy of the machine. From past experiences in overhauling other machines, it is suggested that the CNC horizontal machine will be able to perform within the H7 tolerance, even though the overhauled machine might not be as accurate as the new machine. The quotation of overhauling given by the service provider is 2,000,000 baths. The net present value of the investment will be calculated based on the 6% long-term interest rate for bond and the time period is 6 years. The machine is expected to perform at the acceptable accuracy for the next 6 years. The operation cost and maintenance cost will be the same. The lead time to overhaul the machine will be 6 months.

Net Annual Value	=	2,000,000 (A/P, 6%, 6)
	=	2,000,000 x 0.2034
	=	406,800 bath
Life of machine	=	12 (month/year) x 6 (year)
	=	72 month
Monthly cost	=	406,800 (bath) / 12 (month)
	=	33,900 bath/month
Monthly saving/benefit	=	Expected defect reduction
	=	25,000 bath/month
ROQI	=	Monthly benefit /Monthly cost
	=	25,000/33,900
	=	0.737

Change Drill and Reamer

The third alternative is changing the drill and reamer in the M3 process. At present, the high-speed drill and high-speed reamer is used for the M3 process. High speed tools lose their edge quickly as a result of machine’s vibration. The blunt tools cause the hole to become larger than usual. The data from the production statistics have shown that in all cases regarding the diameter, the holes exceed the upper limit. The vibration also causes rough surface. The actual tool lives are much shorter than the calculated value. It is concluded that the high-speed drill and reamer do not mach the machine and the raw material. The switch in the cutting tools from high-speed drill and reamer to carbide drill and reamer is expected to reduce or eliminate the problem in the reamer holes. For the tooling cost, the cost of the carbide tools will be minus by the high-speed tools to find the difference in price. This is based on the calculated tool life with the average production of 22 moulds per month. The carbide tools do not require any special holders, so the old holders can be used. The ordering time of the tool is 1 week.

Cost of high-speed drill for 22 moulds	=	8,226 bath
Cost of high-speed reamer for 22 moulds	=	28,680 bath
Cost of carbide drill for 22 moulds	=	24,408 bath
Cost of inserted reamer for 22 moulds	=	14,550 bath
Difference between carbide	=	38,958 – 36,906
tools and high-speed tools	=	2,052 bath

For this alternative, the ROQI will be done on the scenario basis. The ROQI will be calculated with 30%, 50% and 70% defect reduction. This is to check for the best possible case, worst possible case and to see if the alternative is acceptable.

Scenario	Defect reduction	Saving	ROQI
1	30%	7500	3.65
2	50%	12500	6.09
3	70%	17500	8.53
4	8.20%	2052	1.00

Table 4.8 : Scenario for Defect Reduction

From the scenario, it can be seen that only 8.2% in defect reduction would have the ROQI value of 1. It is forecasted that the defect would have a minimum reduction of 30%, which was seen as the worst case scenario. This would provide the ROQI value of 3.65 which is enough to cover the cost.

From the ROQI results of the 3 alternatives, changing drill and reamer of the process is the only alternative whose ROQI value is more than 1. For acquiring new machine and overhauling existing machine, their ROQI values are 0.194 and 0.737 respectively. As a result, switching from high-speed drill and reamer to carbide drill and reamer is selected. The details for selecting this alternative are summarized in the following paragraph.

1. Changing drill and reamer provide the best ROQI.
2. The investment cost is the lowest when compared with other alternatives.
3. The lead time to order the drill is shorter than those of the other alternatives. It takes only 1 week to order the tools when compared with 2 years to order new machine and 6 months to overhaul the machine.
4. Testing of the new tools can be done internally with some recommendation from the tools supplier, this will help to reduce the development time and cost.
5. The company does not want to put a lot of investment to solve this problem.

As a result, new carbide drill and inserted reamer will be tested via DOE to find the suitable condition as well as checking on the diameter of the hole. The summary of the failure modes and their solution are presented in the following tables.

Failure mode	Failure Cause(s)	RPN	Defect Reduction			RPN
			Action	Purpose	Document	
Drill wrong pin position	Programming mistake	160	Basic CNC class Issue work instruction Check sheet	To educate operators on the correct programming method To give proper instruction for every one to follow To make operators aware of important dimensions and to check during operation		
Drill too shallow	Programming mistake	160	Basic CNC class Issue work instruction Check sheet	To educate operators on the correct programming method To give proper instruction for every one to follow To make operators aware of important dimensions and to check during operation		
Drill wrong pin height	Programming mistake	160	Basic CNC class Issue work instruction Check sheet	To educate operators on the correct programming method To give proper instruction for every one to follow To make operators aware of important dimensions and to check during operation		
Boring & screw position	Programming mistake	160	Basic CNC class Issue work instruction Check sheet	To educate operators on the correct programming method To give proper instruction for every one to follow To make operators aware of important dimensions and to check during operation		

Table 4.9 : Defect Reduction and Activity in M2

Failure mode	Failure Cause(s)	RPN	Defect Reduction: Action	Defect Reduction: Purpose	Defect Reduction: Document	RPN
Hole diameter Exceed limit	Inappropriate Drill, causes vibration	168	Test carbide drill Use DOE to find Suitable cutting condition	To make the drill more rigid To increase tool life To find optimal drill condition		
Hole diameter Exceed limit	Inappropriate reamer, causes vibration	168	Test insert reamer Use DOE to find Suitable cutting condition	To make the reamer more rigid To increase tool life To find optimal reamer condition		

Table 4.9 : Defect Reduction and Activity in M2 (continue)

Failure mode	Failure Cause(s)	RPN	Defect Reduction: Action	Defect Reduction: Purpose	Defect Reduction: Document	RPN
Wrong angle segment	Programming mistake	200	Basic CNC class Issue work instruction Check sheet	To educate operators on the correct programming method To give proper instruction for every one to follow To make operators aware of important dimensions and to check during operation		

Table 4.10 : Defect Reduction and Activity in M3

Failure mode	Failure Cause(s)	RPN	Defect Reduction			RPN
			Action	Purpose	Document	
Dimensional error (internal middle diameter too large) B	Improper measuring instrument	280	Buy new internal micrometer Calibrate linear bench	To make measuring easier and more accurate To make the measuring instrument more accurate		
Internal angle error	Tool wear Programming mistake	224	Limit tool cycle Operators check tools before operation Basic CNC class Issue work instruction Check sheet	To reduce tool wear & breakage during operation To make sure that tools are in good condition To educate operators on the correct programming method To give proper instruction for every one to follow To make operators aware of important dimensions and to check during operation		
Dimensional error (internal height too large)	Programming mistake	160	Basic CNC class Issue work instruction Check sheet	To educate operators on the correct programming method To give proper instruction for every one to follow To make operators aware of important dimensions and to check during operation		
Angle out of specification	Programming mistake	192	Basic CNC class Issue work instruction Check sheet	To educate operators on the correct programming method To give proper instruction for every one to follow To make operators aware of important dimensions and to check during operation		

Table 4.11 : Defect Reduction and Activity in T1 & T2

Chapter V

Design of Experiment

5.1 DOE

From the analysis in the previous chapter, the author decided that the drill and reamer in the drilling process in Machining M2 must be changed. The change will be done to improve the quality of the hole. The result from the past experience has revealed that the regular high-speed drill and reamer loses its edge quickly. This will cause the hole to deform and the diameter will exceed the given tolerances. This had been one of the most frequent complaints from the customer and the QC department. After several discussions, the production engineer and the CNC head of department proposed the idea of switching from high-speed drill & high-speed reamer to carbide drill and inserted reamer. These carbide drill and reamer are believed to perform better than the high-speed tools.

Figure 5.1 : High-speed drill (left), Carbide drill (right)

Figure 5.2 : High-speed reamer (left), Carbide reamer (right)

Nevertheless, the application of these tools must be carefully considered as they require more investment as the unit costs of these instruments are higher than the high-speed tool. There are a number of parameters to be considered when using these tools, in order to optimize their performance. As mentioned in earlier, there are two important parameters to be considered are the cutting speed (Vc) and the feed rate per tooth (fz). These parameters will be used to calculate the tool speed(s) and the table feed rate (Vf) which will be programmed in the cutting sequences for the CNC machine.

The manufacturer usually recommends a range of the cutting speed and the feed rate per tooth to be used with their tools. However, these are only recommended values, the operators or user has to fine tune these parameter according to their job and cutting preferences. The fine tuning process can take very long time and can often damage the cutting tools and the job under study. In this case, the author will combine the experience with application of DOE to find the acceptable cutting parameters for both carbide drill and inserted reamer.

The DOE will be separated into 2 parts. The first part will be focus on the drilling process to obtain the optimal cutting parameters. The result from the first part will then be used to prepare the hole to be tested by the reamer in the second DOE. The second part of the DOE will be based on finding the optimal cutting parameters for the reamer.

The sequence of the experiment will be carried our randomly on the same machine and the same experienced operator. It will be done on the same day to reduce the effect of sudden temperature chance. The drilling process and reamer process will be carried out on the same piece of work to ensure that the material does not vary. Only a single piece of new drill and reamer will be used for the whole experiment. Only one measuring instrument will be used in this experiment, which will be calibrated and measured by the QC head of department. The work piece will be left at room temperature for 24 hour before it is measured to reduce the effect of expansion and contraction of the hole.

5.2 Factor Screening (Drill)

In the drilling process, apart from the cutting speed and feed rate per tooth, the cutting depth of the drill may affect the quality, tolerance and appearance of the hole. In order to know which factors are significant enough to determine the quality in this case study, a factor screening DOE will be required. During factor screening, several factors will be tested at different levels (usually 2), to check for their response as well as the interaction between several factors. The analysis of the result can be done by ANOVA. For this case, 3 factors will be tested, cutting speed (Vc), feed rate per tooth (fz) and cutting depth (z). Each factor will be tested at 2 levels, the lowest and highest values which are recommended from the manufacturers. 2^k factorial technique with randomization will be employed to ensure that the each combination is treated fairly. The following table will summarize the condition of the DOE.

For factor screening experiment, the number of replicate must be calculated. The power level will be set at 0.9 and level of significance (α) will be set at 0.05. The number of replicates will be calculated using MiniTab.

From the calculation, 6 replicates are needed for each combination and the total run of the experiment will be 48 runs. The actual power level is 0.92. This setting is used as it is well above acceptable level. The detail of the factor screening experiment is as followed.

Factor screening Experimental Detail

1. Purpose of the factor screening experiment, 2^k factorial design will be used to investigate the effect of the factors at different level on the response output. The factors with little effect will be omitted from the next experiment.

2. In order to obtain accurate pin holes which are within the customer's tolerances, the pre-reamer hole must have good accuracy with little variation. The acceptable diameter of the pre-reamer hole is between 19.80 ± 0.1mm. However, the specification of the tested drill is 19.80 + 0.05mm. With variation in machine and other environmental from the manufacturer and the company in the case study, the target value of the hole should be set between 19.80 to 19.86mm.

3. Experimental parameter

The response variable for this experiment is the diameter of the hole with target value between 19.85 to 19.86mm.

There are 3 factors in this experiment with 2 levels each.

	Low	High
Cutting depth (z)	3 mm.	5 mm.
Cutting speed (Vc)	80 m/min	110 m/min
Feed rate per tooth (fz)	0.05 mm/rev	0.15 mm/rev

Other factors which might influence the experiment will have to be controlled to make sure that the biases of the factors are minimized.

Machine	Toyoda
Machine operator	Vitool
QC personal	Amornrat
Measuring Instrument	Bore gauge (Number 1)
Raw material	Cast iron
Cutting tool(drill)	Carbide drill
Coolant (external)	Synthetic
Measuring temperature	28-30°C

4. For this experiment, complete randomization will be used to reduce bias in the experimental result, the experimental order is shown in Table 5.1.

5. Total of 6 replicates will be used for all 8 factors combinations, resulting in 48 setups.

6. Result analysis

The result of the experiment will be analyzed by ANOVA.

The result will be checked for its model accuracy. This will be done by the normality test via normal probability plot.

Residual plots

The table for data collection, experimental combinations and experimental sequence generated by Minitab is shown in Table 5.1.

StdOrder	RunOrder	PtType	Blocks	z (mm.)	Vc (m/min)	fz (mm/rev)	Dia (mm.)
40	1	1	1	5	110	0.15	
11	2	1	1	3	110	0.05	
43	3	1	1	3	110	0.05	
22	4	1	1	5	80	0.15	
10	5	1	1	5	80	0.05	
36	6	1	1	5	110	0.05	
38	7	1	1	5	80	0.15	
14	8	1	1	5	80	0.15	
4	9	1	1	5	110	0.05	
1	10	1	1	3	80	0.05	
39	11	1	1	3	110	0.15	
27	12	1	1	3	110	0.05	
20	13	1	1	5	110	0.05	
28	14	1	1	5	110	0.05	
45	15	1	1	3	80	0.15	
48	16	1	1	5	110	0.15	
42	17	1	1	5	80	0.05	
2	18	1	1	5	80	0.05	
47	19	1	1	3	110	0.15	
41	20	1	1	3	80	0.05	
32	21	1	1	5	110	0.15	
9	22	1	1	3	80	0.05	
23	23	1	1	3	110	0.15	
13	24	1	1	3	80	0.15	
18	25	1	1	5	80	0.05	
44	26	1	1	5	110	0.05	
12	27	1	1	5	110	0.05	
25	28	1	1	3	80	0.05	
7	29	1	1	3	110	0.15	
5	30	1	1	3	80	0.15	
24	31	1	1	5	110	0.15	
8	32	1	1	5	110	0.15	
35	33	1	1	3	110	0.05	
16	34	1	1	5	110	0.15	
33	35	1	1	3	80	0.05	
26	36	1	1	5	80	0.05	
34	37	1	1	5	80	0.05	
15	38	1	1	3	110	0.15	
31	39	1	1	3	110	0.15	
29	40	1	1	3	80	0.15	
37	41	1	1	3	80	0.15	
3	42	1	1	3	110	0.05	
19	43	1	1	3	110	0.05	
30	44	1	1	5	80	0.15	
21	45	1	1	3	80	0.15	
46	46	1	1	5	80	0.15	
17	47	1	1	3	80	0.05	
6	48	1	1	5	80	0.15	

Table 5.1 : Data collection table for factor screening (drilling process)

The ANOVA analysis of the factor screening experiment can be summarized as followed.

Source of Variation	Sum of Square (SS)	Degree of Freedom (DF)	Mean Square (MS)	F
A	SS_A	a-1	MS_A	MS_A/MS_E
B	SS_B	b-1	MS_B	MS_B / MS_E
C	SS_C	c-1	MS_C	MS_C / MS_E
AB	SS_{AB}	(a-1)(b-1)	MS_{AB}	MS_{AB} MS_E
AC	SS_{AC}	(a-1)(c-1)	MS_{AC}	MS_{AC} / MS_E
BC	SS_{BC}	(b-1)(c-1)	MS_{BC}	MS_{BC} / MS_E
ABC	SS_{ABC}	(a-1)(b-1)(c-1)	MS_{ABC}	MS_{ABC} / MS_E
Error	SS_E	abc(n-1)	MS_E	
Total	SS_T	abcn-1		

Table 5.2 : ANOVA Table for 2^k Factorial

If the F-value obtained from the experiment is greater than that of the common value at the α level, then the factor can be concluded it has significant effect on the size of the holes. If the F-value obtained from the experiment is smaller than that of the common value at the α level, then factor can then be concluded that it does have significant effect on the size of the holes.

The factor screening experiment has been carried out and the data are as summarized in Table 5.3.

StdOrder	RunOrder	PtType	Blocks	z (mm.)	Vc (m/min)	fz (mm/rev)	Dia (mm.)
40	1	1	1	5	110	0.15	19.840
11	2	1	1	3	110	0.05	19.850
43	3	1	1	3	110	0.05	19.842
22	4	1	1	5	80	0.15	19.851
10	5	1	1	5	80	0.05	19.873
36	6	1	1	5	110	0.05	19.846
38	7	1	1	5	80	0.15	19.845
14	8	1	1	5	80	0.15	19.852
4	9	1	1	5	110	0.05	19.842
1	10	1	1	3	80	0.05	19.868
39	11	1	1	3	110	0.15	19.850
27	12	1	1	3	110	0.05	19.846
20	13	1	1	5	110	0.05	19.845
28	14	1	1	5	110	0.05	19.845
45	15	1	1	3	80	0.15	19.854
48	16	1	1	5	110	0.15	19.845
42	17	1	1	5	80	0.05	19.866
2	18	1	1	5	80	0.05	19.873
47	19	1	1	3	110	0.15	19.842
41	20	1	1	3	80	0.05	19.870
32	21	1	1	5	110	0.15	19.849
9	22	1	1	3	80	0.05	19.868
23	23	1	1	3	110	0.15	19.848
13	24	1	1	3	80	0.15	19.846
18	25	1	1	5	80	0.05	19.870
44	26	1	1	5	110	0.05	19.842
12	27	1	1	5	110	0.05	19.846
25	28	1	1	3	80	0.05	19.866
7	29	1	1	3	110	0.15	19.843
5	30	1	1	3	80	0.15	19.850
24	31	1	1	5	110	0.15	19.844
8	32	1	1	5	110	0.15	19.845
35	33	1	1	3	110	0.05	19.844
16	34	1	1	5	110	0.15	19.843
33	35	1	1	3	80	0.05	19.860
26	36	1	1	5	80	0.05	19.866
34	37	1	1	5	80	0.05	19.868
15	38	1	1	3	110	0.15	19.842
31	39	1	1	3	110	0.15	19.840
29	40	1	1	3	80	0.15	19.845
37	41	1	1	3	80	0.15	19.844
3	42	1	1	3	110	0.05	19.845
19	43	1	1	3	110	0.05	19.843
30	44	1	1	5	80	0.15	19.846
21	45	1	1	3	80	0.15	19.844
46	46	1	1	5	80	0.15	19.847
17	47	1	1	3	80	0.05	19.867
6	48	1	1	5	80	0.15	19.845

Table 5.3 : Experimental Data for Factor Screening (Drilling Process)

5.3 Data Analysis for Factor Screening Experiment

The data from the DOE is analyzed via the help of the computer program, Minitab. The following table will summarized the result from the analysis of variance.

Factor	Type	Levels	Values
z	fixed	2	3, 5
Vc	fixed	2	80, 110
fz	fixed	2	0.05, 0.15

Analysis of Variance for Dia, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
z	1	0.0000060	0.0000060	0.0000060	0.58	0.451
Vc	1	0.0020935	0.0020935	0.0020935	201.06	0.000
fz	1	0.0013125	0.0013125	0.0013125	126.05	0.000
z*Vc	1	0.0000110	0.0000110	0.0000110	1.06	0.310
z*fz	1	0.0000017	0.0000017	0.0000017	0.16	0.689
Vc*fz	1	0.0012100	0.0012100	0.0012100	116.21	0.000
z*Vc*fz	1	0.0000075	0.0000075	0.0000075	0.72	0.400
Error	40	0.0004165	0.0004165	0.0000104		
Total	47	0.0050588				

Table 5.4 : The Analysis of Variance for Factor Screening Experiment

From the F-distribution table, $F_{0.05, 1, 46}$ is equal to 4.056. The F-values from the analysis are then compared with the common value obtained from the distribution table.

Cutting Depth (z)

The cutting depth (z) has the F-value of 0.58 which is less than the 4.056. This indicates that the cutting depth (z) does not have significant effect on the quality of the hole.

Cutting Speed (Vc)

Cutting speed (Vc) has the F-value of 201.06 which is higher than that from the table. Cutting speed does have significant effect on the quality of the hole.

Feed Rate per Tooth (fz)

The F-value for feed rate per tooth (fz) is 126.05, which is also higher than that from the table, indicating that it has a significant effect on the quality of the hole.

Cutting Speed and Feed Rate per Tooth (Vc*fz interaction)

The only interaction effect which has F-value of 116.21, higher value than 4.056 is the interaction between cutting speed and feed rate per tooth (Vc*fz interaction). Interaction between z and Vc, z and fz, z and Vc and fz do not have significant on the hole's quality.

In addition, the Pareto Chart of the Standardized Effect from Figure 5.1 also revealed that there are 3 factors which contribute significantly to the effect of the response. These factors have standardized effect more than 2.02, putting them on the right-side of the graph. They are cutting speed (Vc), feed rate per tooth (fz), and the interaction between the cutting speed (Vc), feed rate per tooth (fz). This information helped to confirm the result from the ANOVA table.

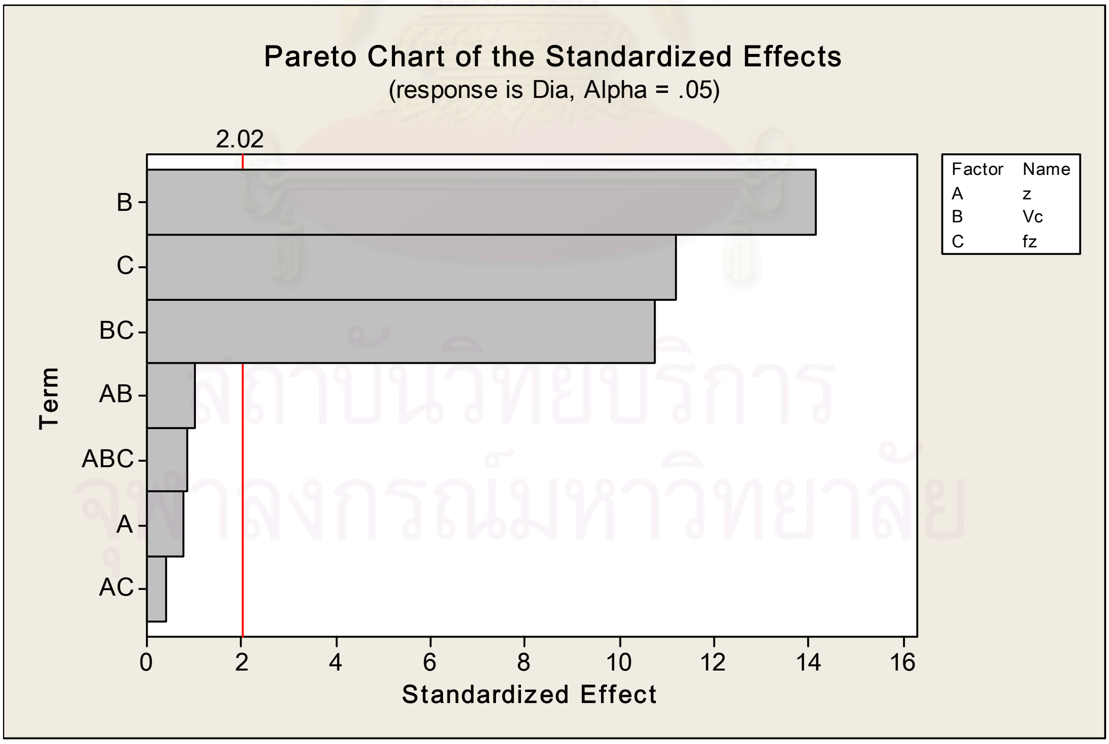


Figure 5.3 : Pareto Chart of the Standardized Effects (Factor Screening)

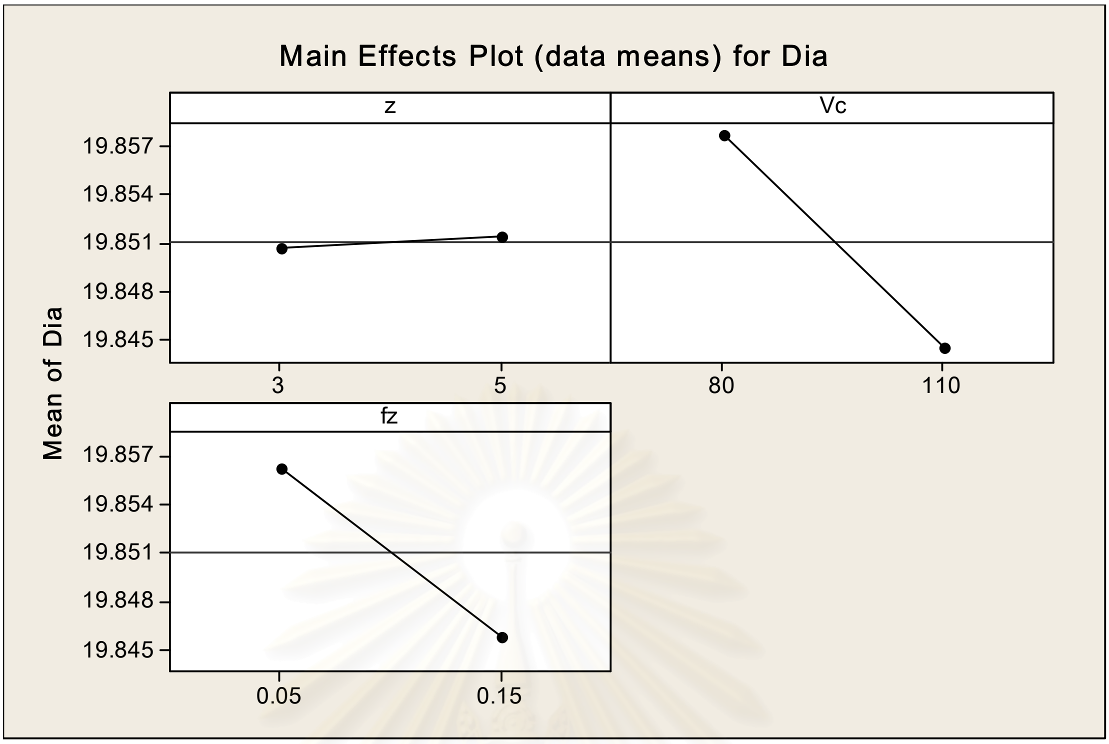


Figure 5.4 : Main Effect Plot (z, Vc and fz) for Diameter (Factor Screening)

Figure 5.2 shows the main effect of each of the 3 factors at different level. The graph is plotted with the mean diameter on the y-axis and the different factor level on the x-axis. These graphs will illustrate the main effect of each factor at different levels.

The gentle slope of the first graph indicates that there is very little change in the mean diameter when the cutting depth (z) is switched from 3 mm. to 5mm. The slope of the graph also reveals the relationship between the mean diameter and the cutting depth. The diameter increases with the raise in the cutting depth, however, the effect of the change is not significant.

The second graph is relationship of the cutting speed (Vc) and the mean diameter. This graph has the steepest gradient compared to the other graph, indicating that the change in cutting speed would affect the response diameter significantly. It also shows that the increase in cutting speed decreases the diameter of the hole.

The last graph explains the relationship between the feed rate per tooth fz and the mean diameter. The feed rate per tooth also has significant effect on the diameter as shown by the steep gradient of the line. As the feed rate per tooth increases, the mean diameter decreases.

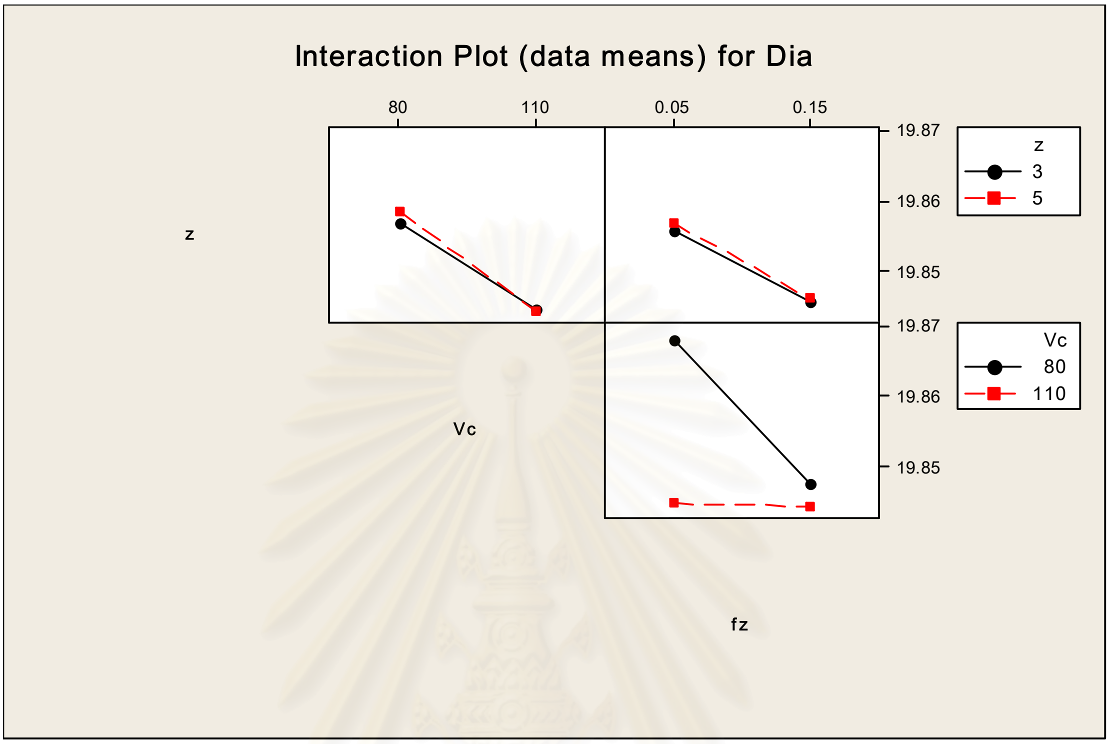


Figure 5.5 : Interaction Effect Plot (z, Vc and fz) for Diameter (Factor Screening)

Figure 5.3 is the interaction effect plot of each factor combinations. It show the effect of the diameter when each of the 2 effect are combined together. This is very important and these factors are combined during experiment.

The interaction between cutting speed and cutting depth has the characteristic similar to that of the main effect of cutting speed (Vc). It can be clearly seen that the cutting speed is the major influence in this combination. This combination result in a smaller diameter as the cutting speed and cutting depth increases.

The interaction between the cutting depth and the feed rate per tooth represent that of the main effect of the feed rate per tooth (fz). The cutting depth has very little role in determining the shape of the graph. The feed rate per tooth is the main cause for this combination.

The interaction between the cutting speed (Vc) and the feed rate per tooth (fz) has the steepest gradient when the cutting speed is at 80mm/min. At this speed, the diameter reduces with the increase of feed rate per tooth. However, it is very interesting to find out that at the cutting speed of 110 mm/min, the mean diameter does not change with the increase in feed rate per tooth. The diameter reduces slightly, almost becoming constant.

Model Adequacy Checking

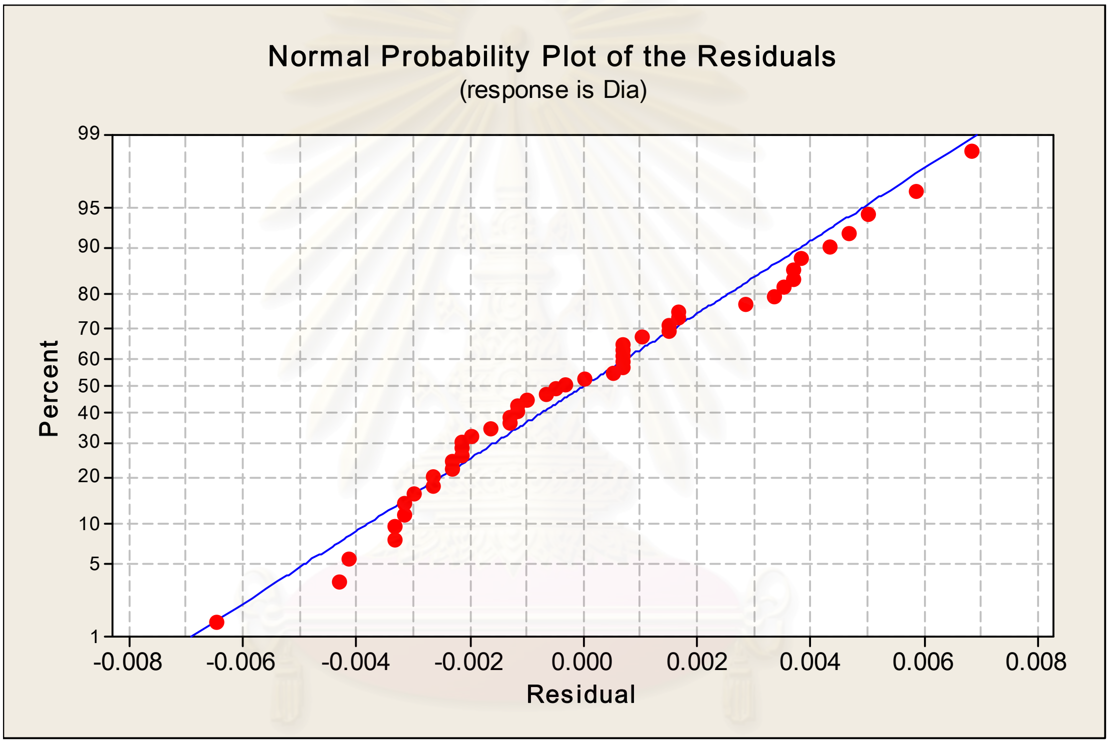


Figure 5.6 : Normal Probability Plot of the Residual (Factor Screening)

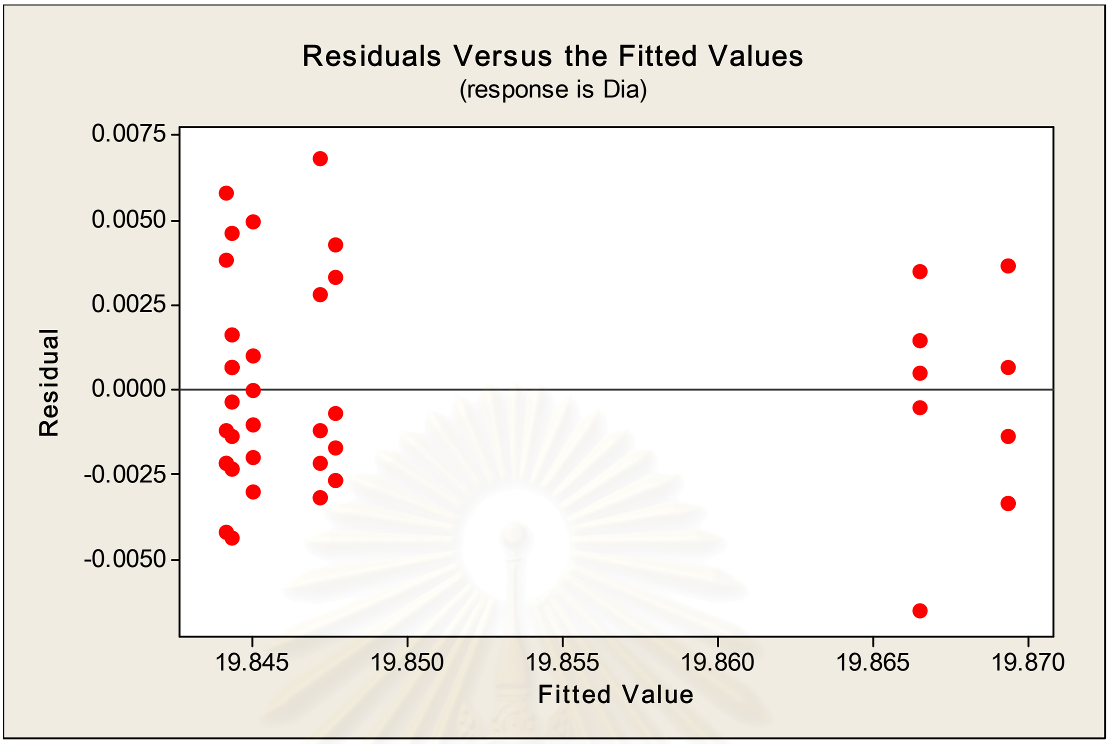


Figure 5.7 : Residual Plot against Fitted Values for Factor Screening Experiment

From the Figure 5.4 and 5.5, there is no evidence of any model inadequacy. From Figure 5.4, the normal probability plot of the residual of the factor screening experiment form a straight line, representing that of a population with normal distribution.

By looking at Figure 5.5, the residual plot against fitted value, the plot are widely spread and does not show any evidence of model inadequacy.

From the factor screening experiment, it can be concluded that the cutting speed (Vc) and feed rate per tooth (fz) have significant effect on the quality of the holes. The interaction between cutting speed (Vc) and feed rate per tooth (fz) ia also a significant factor. This is not surprising as the calculation of the feed rate per tooth require the cutting speed value, as shown in the formula. The model adequacy checking also confirms that the data come from normal population.

In the next section, the cutting speed (Vc) and feed rate per tooth (fz) will be studied to find the suitable cutting condition.

5.4 Finding Suitable Drilling Condition

In finding suitable drilling condition for this case, the 2 factors will be tested, cutting speed (Vc) and feed rate per tooth (fz). In this case, full factorial design will be employed to find the optimal values for the cutting speed and feed rate per tooth. In order to get a more accurate result, 12 replicates are used. The factors, the levels and other information are input into the Minitab. Minitab will generate the experimental procedures and the structure of the experiment. The detail and the experimental procedure will be explained in the next section.

Finding Suitable Drilling Condition Experiment Detail

1. Purpose of the finding suitable drilling condition experiment is to use the DOE technique combine with full factorial design to investigate the effect of the factors that will provide suitable drilling condition that will provide the desirable response output. The 2 factors which will be investigated are the cutting speed (Vc) and the feed rate per tooth (fz).

2. In order to obtain accurate pin holes which are within the customer's tolerances, the pre-reamer hole must have good accuracy with little variation. The acceptable diameter of the pre-reamer hole is between 19.80 ± 0.1mm. However, the specification of the tested drill is 19.80 + 0.05mm. With variation in machine and other environmental from the manufacturer and the company in the case study, the target value of the hole should be set between 19.80 to 19.86mm.

3. Experimental parameter

The response variable for this experiment is the diameter of the hole with target value between 19.85 to 19.86mm. There are 2 factors in this experiment with 3 levels each.

Cutting speed (Vc, m/min)	80	95	110
Feed rate per tooth (fz,mm/rev)	0.05	0.1	0.15

Other factors which might influence the experiment will have to be controlled to make sure that the biases of the factors are minimized.

Machine	Toyoda
Machine operator	Vitool
QC personal	Amornrat
Measuring Instrument	Bore gauge (Number 1)
Raw material	Cast iron
Cutting tool(drill)	Carbide drill
Coolant (external)	Synthetic
Measuring temperature	28-30°C
Cutting Depth (z)	3 mm.

4. For this experiment, complete randomization will be used to reduce bias in the experimental result, the experimental order is shown in Table 5.5.

5. Total of 12 replicates will be used for all factor combinations, resulting in 108 set ups.

6. Result analysis

The result of the experiment will be analyzed by ANOVA.

The result will be checked for its model accuracy. This will be done by the normality test via normal probability plot.

Residual plots

Data Collection Table

StdOrder	RunOrder	PtType	Blocks	Vc	fz	dia
33	1	1.00	1.000	95	0.15	
103	2	1.00	1.000	95	0.05	
8	3	1.00	1.000	110	0.1	
106	4	1.00	1.000	110	0.05	
20	5	1.00	1.000	80	0.1	
16	6	1.00	1.000	110	0.05	
89	7	1.00	1.000	110	0.1	
3	8	1.00	1.000	80	0.15	
63	9	1.00	1.000	110	0.15	
23	10	1.00	1.000	95	0.1	
91	11	1.00	1.000	80	0.05	
57	12	1.00	1.000	80	0.15	
5	13	1.00	1.000	95	0.1	
53	14	1.00	1.000	110	0.1	
59	15	1.00	1.000	95	0.1	
65	16	1.00	1.000	80	0.1	
46	17	1.00	1.000	80	0.05	
54	18	1.00	1.000	110	0.15	
26	19	1.00	1.000	110	0.1	
78	20	1.00	1.000	95	0.15	
12	21	1.00	1.000	80	0.15	
74	22	1.00	1.000	80	0.1	
66	23	1.00	1.000	80	0.15	
97	24	1.00	1.000	110	0.05	
35	25	1.00	1.000	110	0.1	
32	26	1.00	1.000	95	0.1	
73	27	1.00	1.000	80	0.05	
45	28	1.00	1.000	110	0.15	
43	29	1.00	1.000	110	0.05	
102	30	1.00	1.000	80	0.15	
85	31	1.00	1.000	95	0.05	
42	32	1.00	1.000	95	0.15	
58	33	1.00	1.000	95	0.05	
17	34	1.00	1.000	110	0.1	
87	35	1.00	1.000	95	0.15	
56	36	1.00	1.000	80	0.1	

Table 5.5 : Data Collection Table for Finding Suitable Drilling Condition

Data Collection Table

StdOrder	RunOrder	PtType	Blocks	Vc	fz	dia
99	37	1.00	1.000	110	0.15	
37	38	1.00	1.000	80	0.05	
1	39	1.00	1.000	80	0.05	
30	40	1.00	1.000	80	0.15	
64	41	1.00	1.000	80	0.05	
47	42	1.00	1.000	80	0.1	
83	43	1.00	1.000	80	0.1	
10	44	1.00	1.000	80	0.05	
13	45	1.00	1.000	95	0.05	
11	46	1.00	1.000	80	0.1	
81	47	1.00	1.000	110	0.15	
41	48	1.00	1.000	95	0.1	
14	49	1.00	1.000	95	0.1	
69	50	1.00	1.000	95	0.15	
25	51	1.00	1.000	110	0.05	
15	52	1.00	1.000	95	0.15	
50	53	1.00	1.000	95	0.1	
60	54	1.00	1.000	95	0.15	
86	55	1.00	1.000	95	0.1	
70	56	1.00	1.000	110	0.05	
36	57	1.00	1.000	110	0.15	
2	58	1.00	1.000	80	0.1	
24	59	1.00	1.000	95	0.15	
90	60	1.00	1.000	110	0.15	
38	61	1.00	1.000	80	0.1	
7	62	1.00	1.000	110	0.05	
44	63	1.00	1.000	110	0.1	
100	64	1.00	1.000	80	0.05	
93	65	1.00	1.000	80	0.15	
77	66	1.00	1.000	95	0.1	
31	67	1.00	1.000	95	0.05	
101	68	1.00	1.000	80	0.1	
108	69	1.00	1.000	110	0.15	
55	70	1.00	1.000	80	0.05	
96	71	1.00	1.000	95	0.15	
76	72	1.00	1.000	95	0.05	

Table 5.5 : Data Collection Table for Finding Suitable Drilling Condition (continue)

Data Collection Table

StdOrder	RunOrder	PtType	Blocks	Vc	fz	dia
21	73	1.00	1.000	80	0.15	
82	74	1.00	1.000	80	0.05	
68	75	1.00	1.000	95	0.1	
48	76	1.00	1.000	80	0.15	
51	77	1.00	1.000	95	0.15	
98	78	1.00	1.000	110	0.1	
22	79	1.00	1.000	95	0.05	
67	80	1.00	1.000	95	0.05	
92	81	1.00	1.000	80	0.1	
72	82	1.00	1.000	110	0.15	
18	83	1.00	1.000	110	0.15	
4	84	1.00	1.000	95	0.05	
52	85	1.00	1.000	110	0.05	
49	86	1.00	1.000	95	0.05	
88	87	1.00	1.000	110	0.05	
94	88	1.00	1.000	95	0.05	
84	89	1.00	1.000	80	0.15	
79	90	1.00	1.000	110	0.05	
105	91	1.00	1.000	95	0.15	
39	92	1.00	1.000	80	0.15	
104	93	1.00	1.000	95	0.1	
61	94	1.00	1.000	110	0.05	
29	95	1.00	1.000	80	0.1	
28	96	1.00	1.000	80	0.05	
62	97	1.00	1.000	110	0.1	
9	98	1.00	1.000	110	0.15	
19	99	1.00	1.000	80	0.05	
40	100	1.00	1.000	95	0.05	
27	101	1.00	1.000	110	0.15	
95	102	1.00	1.000	95	0.1	
71	103	1.00	1.000	110	0.1	
6	104	1.00	1.000	95	0.15	
80	105	1.00	1.000	110	0.1	
107	106	1.00	1.000	110	0.1	
75	107	1.00	1.000	80	0.15	
34	108	1.00	1.000	110	0.05	

Table 5.5 : Data Collection Table for Finding Suitable Drilling Condition (continue)

The experiments are carried out according to the sequence generated by Minitab. The data is collected and summarized in the following table.

Experimental Result

Order	Vc	fz	dia		Order	Vc	fz	dia		Order	Vc	fz	dia
1	80	0.05	19.874		37	95	0.05	19.854		73	110	0.05	19.853
2	80	0.05	19.868		38	95	0.05	19.860		74	110	0.05	19.854
3	80	0.05	19.876		39	95	0.05	19.866		75	110	0.05	19.848
4	80	0.05	19.874		40	95	0.05	19.862		76	110	0.05	19.854
5	80	0.05	19.870		41	95	0.05	19.863		77	110	0.05	19.852
6	80	0.05	19.868		42	95	0.05	19.858		78	110	0.05	19.851
7	80	0.05	19.875		43	95	0.05	19.873		79	110	0.05	19.852
8	80	0.05	19.878		44	95	0.05	19.867		80	110	0.05	19.850
9	80	0.05	19.868		45	95	0.05	19.870		81	110	0.05	19.848
10	80	0.05	19.873		46	95	0.05	19.856		82	110	0.05	19.853
11	80	0.05	19.866		47	95	0.05	19.857		83	110	0.05	19.852
12	80	0.05	19.873		48	95	0.05	19.853		84	110	0.05	19.850
13	80	0.10	19.858		49	95	0.10	19.857		85	110	0.10	19.851
14	80	0.10	19.854		50	95	0.10	19.847		86	110	0.10	19.852
15	80	0.10	19.856		51	95	0.10	19.853		87	110	0.10	19.852
16	80	0.10	19.853		52	95	0.10	19.850		88	110	0.10	19.853
17	80	0.10	19.852		53	95	0.10	19.848		89	110	0.10	19.852
18	80	0.10	19.852		54	95	0.10	19.850		90	110	0.10	19.847
19	80	0.10	19.855		55	95	0.10	19.850		91	110	0.10	19.847
20	80	0.10	19.857		56	95	0.10	19.850		92	110	0.10	19.851
21	80	0.10	19.852		57	95	0.10	19.847		93	110	0.10	19.852
22	80	0.10	19.850		58	95	0.10	19.850		94	110	0.10	19.852
23	80	0.10	19.863		59	95	0.10	19.848		95	110	0.10	19.852
24	80	0.10	19.856		60	95	0.10	19.848		96	110	0.10	19.850
25	80	0.15	19.849		61	95	0.15	19.857		97	110	0.15	19.858
26	80	0.15	19.853		62	95	0.15	19.854		98	110	0.15	19.850
27	80	0.15	19.855		63	95	0.15	19.852		99	110	0.15	19.851
28	80	0.15	19.856		64	95	0.15	19.848		100	110	0.15	19.850
29	80	0.15	19.850		65	95	0.15	19.850		101	110	0.15	19.849
30	80	0.15	19.847		66	95	0.15	19.848		102	110	0.15	19.848
31	80	0.15	19.852		67	95	0.15	19.852		103	110	0.15	19.848
32	80	0.15	19.852		68	95	0.15	19.850		104	110	0.15	19.850
33	80	0.15	19.848		69	95	0.15	19.850		105	110	0.15	19.851
34	80	0.15	19.848		70	95	0.15	19.851		106	110	0.15	19.847
35	80	0.15	19.849		71	95	0.15	19.850		107	110	0.15	19.850
36	80	0.15	19.845		72	95	0.15	19.847		108	110	0.15	19.845

Table 5.6 : Experimental Data for Finding Suitable Drilling Condition

General Linear Model: dia versus Vc, fz

Factor	Type	Levels	Values
Vc	fixed	3	80, 95, 110
fz	fixed	3	0.05, 0.10, 0.15

Analysis of Variance for dia, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Vc	2	0.0012656	0.0012656	0.0006328	50.68	0.000
fz	2	0.0027262	0.0027262	0.0013631	109.17	0.000
Vc*fz	4	0.0014281	0.0014281	0.0003570	28.59	0.000
Error	99	0.0012362	0.0012362	0.0000125		
Total	107	0.0066561				

S = 0.00353363   R-Sq = 81.43%   R-Sq(adj) = 79.93%

Estimated Effects and Coefficients for dia (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		19.8546	0.000410	48366.87	0.000
Vc	-0.0083	-0.0042	0.000503	-8.29	0.000
fz	-0.0114	-0.0057	0.000503	-11.30	0.000
Vc*fz	0.0100	0.0050	0.000616	8.09	0.000

S = 0.00426604   R-Sq = 71.56%   R-Sq(adj) = 70.74%

Analysis of Variance for dia (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	0.0035733	0.0035733	0.00178667	98.17	0.000
2-Way Interactions	1	0.0011900	0.0011900	0.00119002	65.39	0.000
Residual Error	104	0.0018927	0.0018927	0.00001820		
Lack of Fit	5	0.0006565	0.0006565	0.00013131	10.52	0.000
Pure Error	99	0.0012362	0.0012362	0.00001249		
Total	107	0.0066561				

Table 5.7 : ANOVA Table for Finding Suitable Drilling Condition

Cutting Speed (Vc)

From the ANOVA table, the analysis of variance show that cutting speed (Vc) has the F-value of 50.68, which is more than the critical value. The P-value of the cutting speed is also less than 0.05. This indicates that the cutting speed have significant effect on the diameter.

Feed Rate per Tooth (fz)

The feed rate per tooth (fz) has the F-value of 109.17, well above the critical value. The P-value is also at 0.000, less than the alpha value used. This confirms that the feed rate per tooth affect the diameter significantly.

Cutting Speed and Feed Rate per Tooth (Vc*fz interaction)

This interaction has the F-value of 28.59 and P-value of 0.000. This shows that the effect of this interaction is significant in determining the diameter.

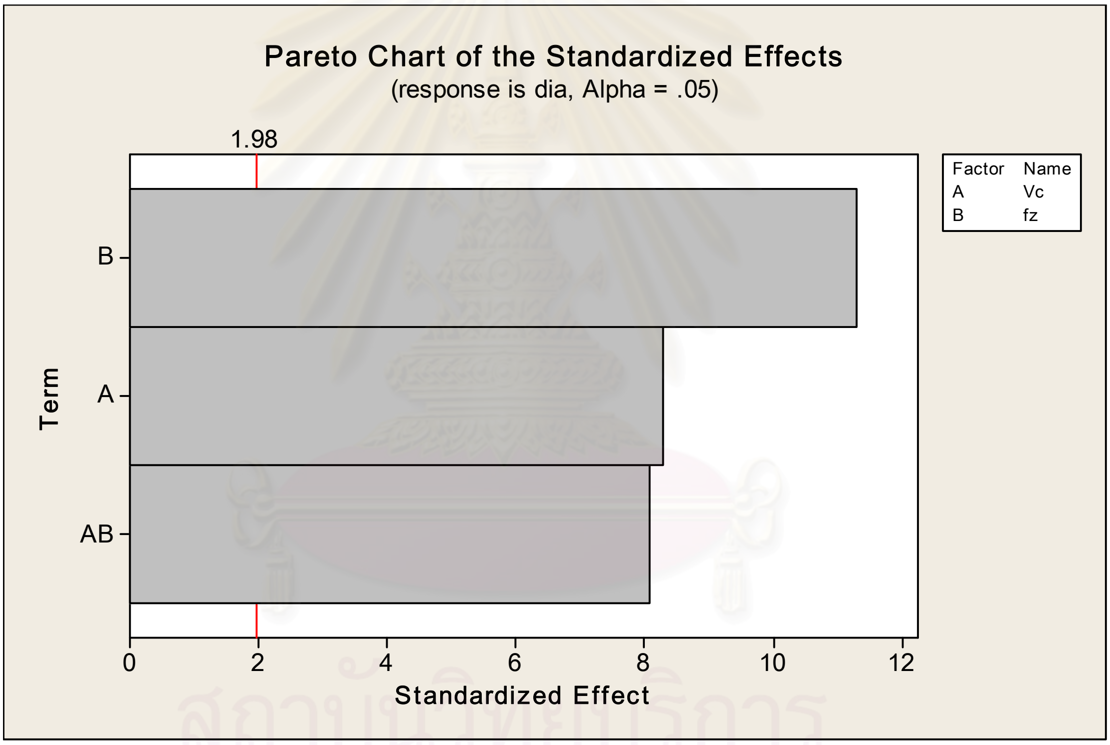


Figure 5.8 : Pareto Chart of the Standardized Effects (Suitable Drilling Condition)

The Pareto Chart of the Standardized Effects reveals that the standardized effect of both factors, cutting speed and feed rate per tooth and their interaction has the standardized effect on the right side of the graph. This also confirms that they have significant effect on the size of the diameter.

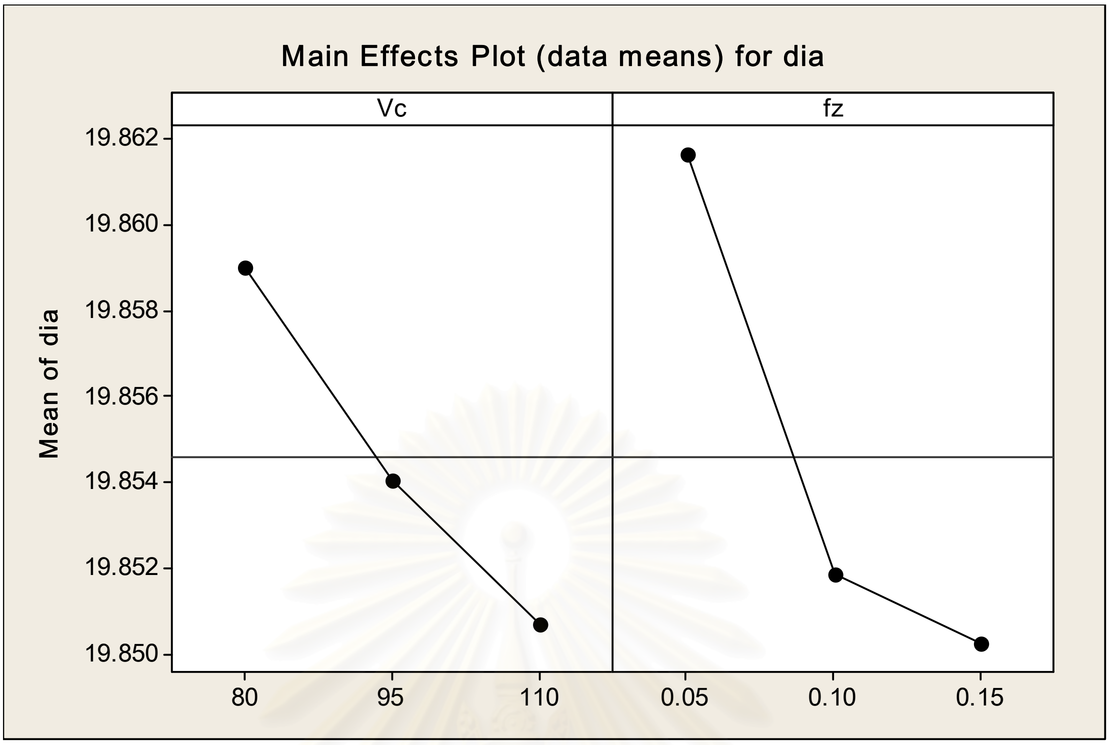


Figure 5.9 : Main Effect Plot (Vc and fz) for Diameter (Suitable Drilling Condition)

Figure 5.7 shows the main effect plot of cutting speed (Vc) and feed rate per tooth (fz). From cutting speed effect plot, the mean diameter reduce with the increase in cutting speed. The range between 80-95 mm/min has steeper gradient than between 95-110 mm/min. This indicates that between 80-95 mm/min has greater effect than between 95-110 mm/min. However, the gradient is not much different.

The graph on feed rate per tooth (fz) shows that the mean diameter decreases with the increase in feed rate per tooth. The change in mean diameter is grate between 0.05-0.10 mm/tooth as it has steeper gradient than that of between 0.10-0.15 mm/tooth.

As compared with the factor screening experiment, the main effect plot draws the same conclusion. The trends of the main effect are the same.

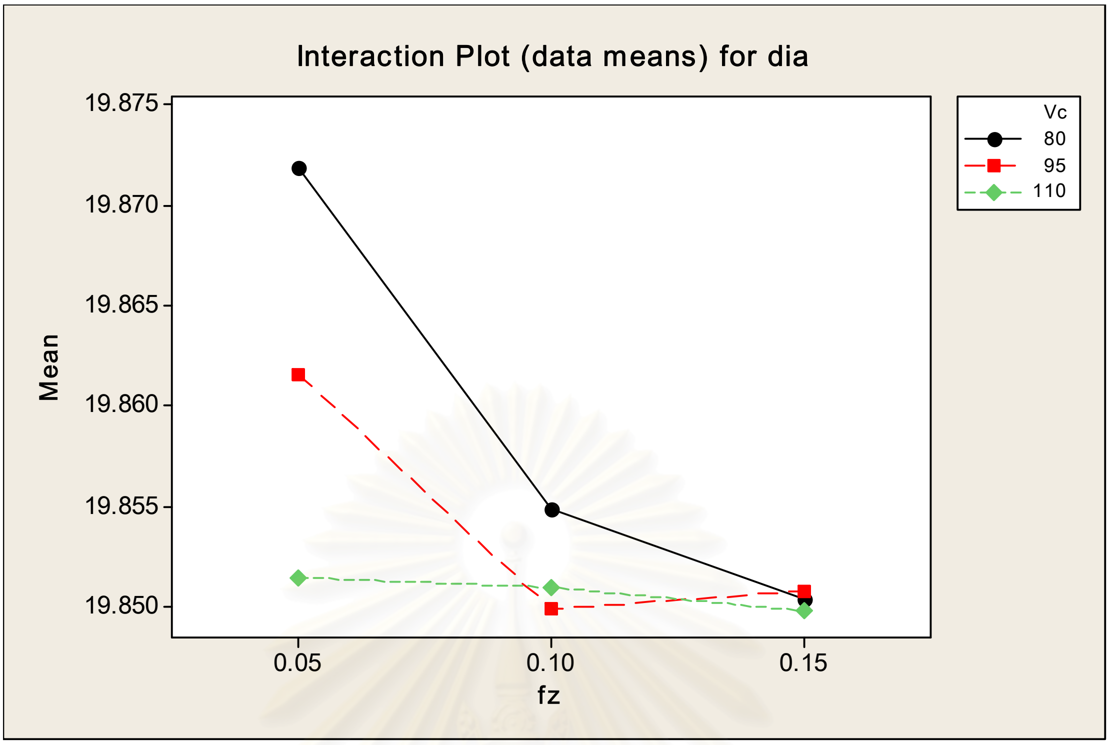


Figure 5.10 : Interaction Effect Plot (Vc and fz) for Diameter (Suitable Drilling Condition)

Figure 5.8 show the relationship between the interaction of cutting speed (Vc) and the feed rate per tooth (fz) at different levels. In general, it can be seen that the increase in cutting speed (Vc) and feed rate per tooth (fz) would reduce the mean diameter. However, the reductions are at different rate.

The reduction in the mean diameter is greatest when the cutting speed (Vc) is at 80 mm/min. At this cutting speed, the gradient of the graph is steepest with the change in feed rate per tooth.

For cutting speed at 95 mm/min, the mean diameter reduces when the feed rate per tooth increases from 0.05 mm/tooth to 0.10 mm/tooth. However, the mean diameter increases slightly when the feed rate per tooth is increased from 0.10 mm/tooth to 0.15 mm/tooth.

At 110 mm/min, there is little reduction in the mean diameter when the feed rate per tooth (fz) is increased. When compared with other graphs, it can be seen that at 110 mm/min, the feed rate per tooth has little influence on the diameter of the hole.

Model Adequacy Checking

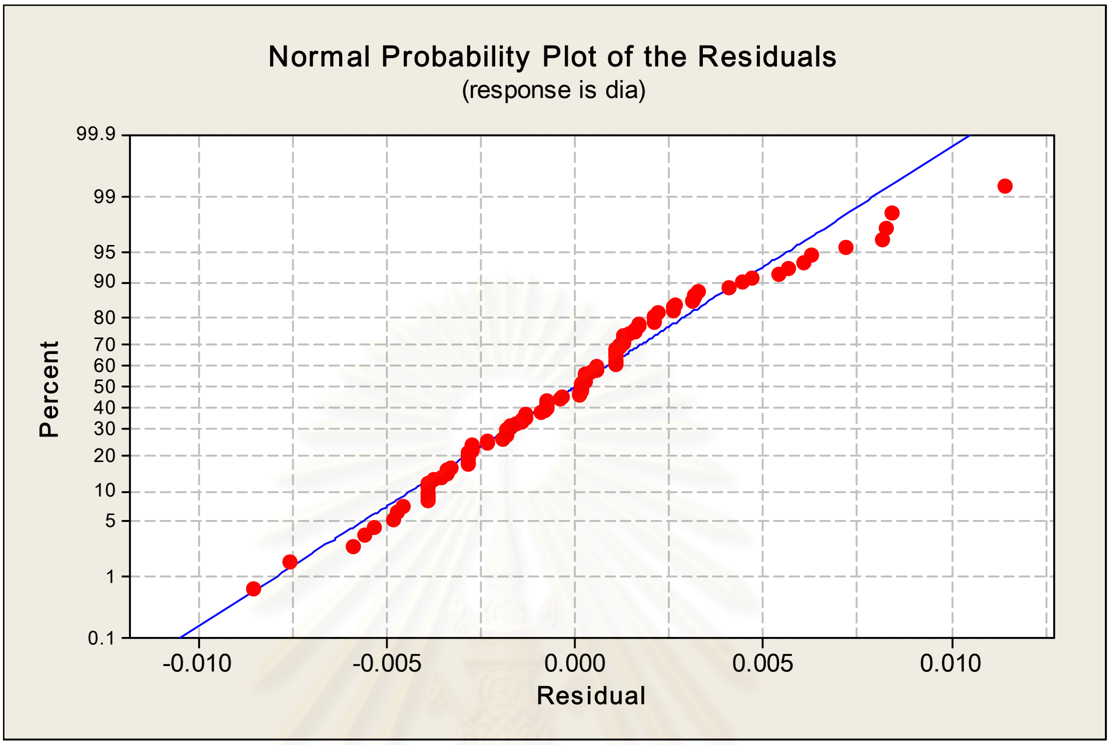


Figure 5.11 : Normal Probability Plot of the Residual(Suitable Drilling Condition)

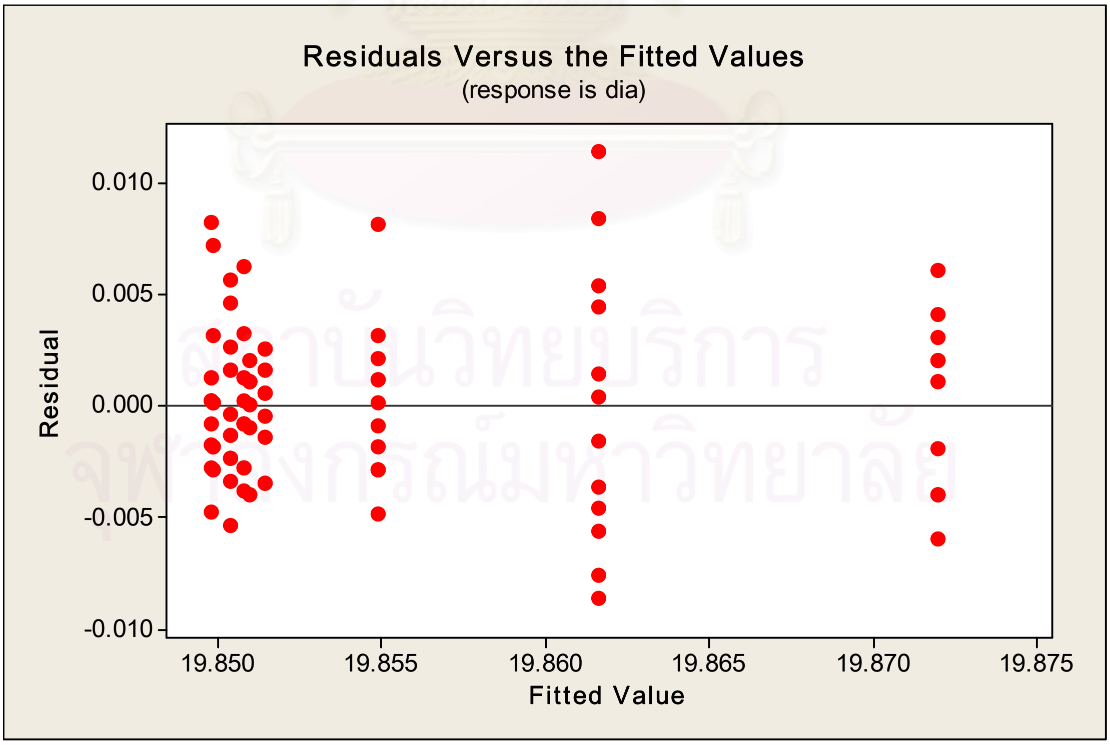


Figure 5.12 : Residual Plot against Fitted Values (Suitable Drilling Condition)

From the figures, there is no evidence of any model inadequacy. From Figure 5.9 , the normal probability plot of the residual of the factor screening experiment form a straight line, representing that of a population with normal distribution. The residual plot against the fitted value shows that the residuals are spread widely and randomly, which is the property of data from normal distribution.

From the evidence mentioned, the data obtained from the experiment can be considered that they come from a normal population.

Response Optimization

From the ANOVA table, the coefficient calculated can be used to input into the regression equation. The regression equation will show the relationship between the 2 factors (cutting speed and feed rate per tooth) and the diameter of the output. The regression equation of the drilling process can be writes as followed.

Regression Equation

Diameter = 19.8546 – 0.0042Vc- 0.0057fz + 0.005Vc*fz

Where : Vc = Cutting Speed (mm/min)

fz = Feed Rate per tooth (mm/tooth)

The optimal drilling condition can be obtained from the use of statistical computer program. The computer will generate the optimal value for cutting speed and feed rate per tooth so that the desired diameter can be achieved. In this case, Minitab will be used to calculate the optimal drilling condition for the process.

The input of the parameter is the diameter which is targeted at 19.85mm. Minitab then calculated the optimal value as shown in the following paragraph.

Response Optimization

Parameters

	Goal	Lower	Target	Upper	Weight	Import
dia	Minimum	19.85	19.85	19.86	1	1

Global Solution

Vc = 95.0000

fz = 0.1404

Predicted Responses

dia = 19.85, desirability = 1

Composite Desirability = 1.00000

Table 5.8 : Response Optimization of Drilling Condition

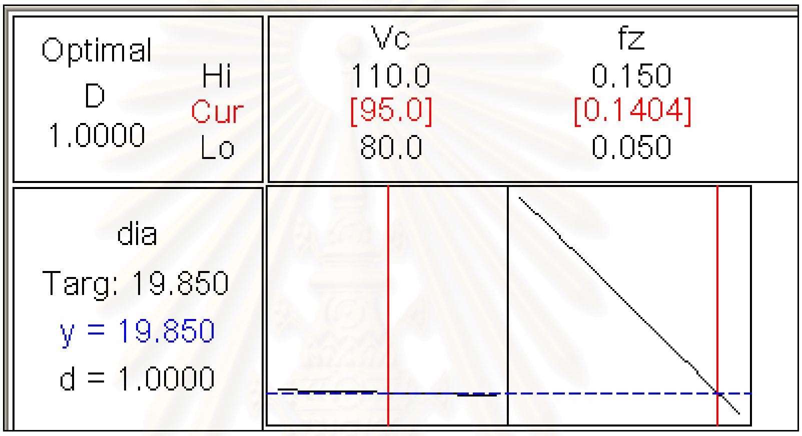


Figure 5.13 : Graph indicating the optimal drilling parameter

From the analysis, it can be seen that the target value is set at 19.85 mm, with the lower value of 19.83 mm. and the upper value of 19.86mm. These values are given by the engineer as the desired diameter. The program then generated the optimal cutting condition in order to obtain the diameter of 19.85 mm.

1. Cutting Speed (Vc) = 95 mm/min
2. Feed Rate per Tooth (fz) = 0.1404 mm/tooth

The cutting parameter will be tested for their accuracy before being used for actual production. If the new drilling parameter is proven to be providing the desired diameter, it will be used to drill hole for the pre-reamer process which will be tested next.

5.5 Finding Suitable Reaming Condition

In finding suitable reaming condition for this case, the 2 factors will be tested, cutting speed (Vc) and feed rate per tooth (fz) as there are only 2 variable factors involved in the reaming process. In this case, full factorial method will be employed to find the optimal values for the cutting speed and feed rate per tooth. 5 replicates will be used to obtain an accurate result. The factors, the levels and other information are input into the Minitab. The experimental procedures, the structure and the sequence of the experiment will be generated by Minitab. The detail and the experimental procedure will be explained in the next section.

Finding Suitable Reaming Condition Experiment Detail

1. Purpose of the finding suitable reaming condition experiment is to use the DOE technique combine with central composite design to investigate the effect of the factors that will provide suitable reaming condition that will provide the desirable response output. The 2 factors which will be investigated are the cutting speed (Vc) and the feed rate per tooth (fz).

2. In order to obtain accurate pin holes which are within the customer's tolerances, the reamer hole must have good accuracy which is within the given tolerances and with little variation. The acceptable diameter of the pin hole is between 20 + 0.02 mm as it is in the H7 class. In order to obtain a reliable product with good quality, the target value of the hole should be between 20.00 mm to 20.015 mm.

3. Experimental parameter

The response variable for this experiment is the diameter of the hole with target value between 20.00 to 20.015 mm. There are 2 factors in this experiment with 3 levels each.

Cutting speed (Vc, m/min)	90	110	130
Feed rate per tooth (fz,mm/rev)	0.05	0.10	0.15

Other factors which might influence the experiment will have to be controlled to make sure that the biases of the factors are minimized.

Machine	Toyoda
Machine operator	Vitool
QC personal	Amornrat
Measuring Instrument	Bore gauge (Number 1)
Raw material	Cast iron
Cutting tool (drill)	Carbide drill
Reamer	Inserted reamer
Coolant (external)	Synthetic
Measuring temperature	28-30°C

4. For this experiment, complete randomization will be used to reduce bias in the experimental result, the experimental order is shown in Table 5.9.

5. Total of 5 replicates will be used for all 9 factors combinations, resulting in 45 setups.

6. Result analysis

The result of the experiment will be analyzed by ANOVA.

The result will be checked for its model accuracy. This will be done by the normality test via normal probability plot.

Residual plots

Data Collection Table

StdOrder	RunOrder	PtType	Blocks	Vc	fz	Dia
1	7	1	1	90	0.05	
2	31	1	1	90	0.10	
3	11	1	1	90	0.15	
4	1	1	1	110	0.05	
5	33	1	1	110	0.10	
6	22	1	1	110	0.15	
7	20	1	1	130	0.05	
8	17	1	1	130	0.10	
9	6	1	1	130	0.15	
10	44	1	1	90	0.05	
11	2	1	1	90	0.10	
12	23	1	1	90	0.15	
13	8	1	1	110	0.05	
14	12	1	1	110	0.10	
15	35	1	1	110	0.15	
16	13	1	1	130	0.05	
17	43	1	1	130	0.10	
18	25	1	1	130	0.15	
19	15	1	1	90	0.05	
20	4	1	1	90	0.10	
21	45	1	1	90	0.15	
22	21	1	1	110	0.05	
23	5	1	1	110	0.10	
24	29	1	1	110	0.15	
25	42	1	1	130	0.05	
26	10	1	1	130	0.10	
27	9	1	1	130	0.15	
28	24	1	1	90	0.05	
29	18	1	1	90	0.10	
30	3	1	1	90	0.15	
31	36	1	1	110	0.05	
32	34	1	1	110	0.10	
33	32	1	1	110	0.15	
34	38	1	1	130	0.05	
35	14	1	1	130	0.10	
36	19	1	1	130	0.15	
37	16	1	1	90	0.05	
38	30	1	1	90	0.10	
39	26	1	1	90	0.15	
40	27	1	1	110	0.05	
41	37	1	1	110	0.10	
42	28	1	1	110	0.15	
43	39	1	1	130	0.05	
44	40	1	1	130	0.10	
45	41	1	1	130	0.15	

Table 5.9 : Data Collection Table for Finding Suitable Reamer Condition

Data Collection Table

StdOrder	RunOrder	PtType	Blocks	Vc	fz	Dia
1	7	1	1	90	0.05	20.009
2	31	1	1	90	0.10	20.012
3	11	1	1	90	0.15	20.012
4	1	1	1	110	0.05	20.010
5	33	1	1	110	0.10	20.011
6	22	1	1	110	0.15	20.012
7	20	1	1	130	0.05	20.010
8	17	1	1	130	0.10	20.011
9	6	1	1	130	0.15	20.013
10	44	1	1	90	0.05	20.009
11	2	1	1	90	0.10	20.010
12	23	1	1	90	0.15	20.011
13	8	1	1	110	0.05	20.010
14	12	1	1	110	0.10	20.011
15	35	1	1	110	0.15	20.010
16	13	1	1	130	0.05	20.011
17	43	1	1	130	0.10	20.011
18	25	1	1	130	0.15	20.011
19	15	1	1	90	0.05	20.010
20	4	1	1	90	0.10	20.008
21	45	1	1	90	0.15	20.011
22	21	1	1	110	0.05	20.010
23	5	1	1	110	0.10	20.010
24	29	1	1	110	0.15	20.011
25	42	1	1	130	0.05	20.010
26	10	1	1	130	0.10	20.011
27	9	1	1	130	0.15	20.012
28	24	1	1	90	0.05	20.010
29	18	1	1	90	0.10	20.010
30	3	1	1	90	0.15	20.012
31	36	1	1	110	0.05	20.009
32	34	1	1	110	0.10	20.010
33	32	1	1	110	0.15	20.011
34	38	1	1	130	0.05	20.010
35	14	1	1	130	0.10	20.011
36	19	1	1	130	0.15	20.012
37	16	1	1	90	0.05	20.009
38	30	1	1	90	0.10	20.010
39	26	1	1	90	0.15	20.012
40	27	1	1	110	0.05	20.011
41	37	1	1	110	0.10	20.010
42	28	1	1	110	0.15	20.012
43	39	1	1	130	0.05	20.011
44	40	1	1	130	0.10	20.010
45	41	1	1	130	0.15	20.011

Table 5.10 : Experimental Data for Finding Suitable Reamer Condition

General Linear Model: Dia versus Vc, fz

Factor	Type	Levels	Values
Vc	fixed	3	90, 110, 130
fz	fixed	3	0.05, 0.10, 0.15

Analysis of Variance for Dia, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Vc	2	0.0000035	0.0000035	0.0000018	2.98	0.063
fz	2	0.0000203	0.0000203	0.0000102	17.25	0.000
Vc*fz	4	0.0000016	0.0000016	0.0000004	0.66	0.624
Error	36	0.0000212	0.0000212	0.0000006		
Total	44	0.0000466				

S = 0.000767391   R-Sq = 54.48%   R-Sq(adj) = 44.37%

Estimated Effects and Coefficients for Dia (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		20.0106	0.000112	178278.59	0.000
Vc	0.0007	0.0003	0.000137	2.42	0.020
fz	0.0016	0.0008	0.000137	5.82	0.000
Vc*fz	-0.0004	-0.0002	0.000168	-1.19	0.242

S = 0.000752953   R-Sq = 50.10%   R-Sq(adj) = 46.44%

Analysis of Variance for Dia (coded units)

Source	D	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	0.00002253	0.00002253	0.00001127	19.87	0.000
2-Way Interactions	1	0.00000080	0.00000080	0.00000080	1.41	0.242
Residual Error	41	0.00002324	0.00002324	0.00000057		
Lack of Fit	5	0.00000204	0.00000204	0.00000041	0.69	0.631
Pure Error	36	0.00002120	0.00002120	0.00000059		
Total	44	0.00004658				

Table 5.11 : ANOVA Table for Finding Suitable Drilling Condition

Cutting Speed (Vc)

By looking at the effect of the cutting speed (Vc), the effect of the cutting speed is not significant. The critical f-value at $F_{0.05, 2, 44}$ is 3.214, while the calculated f-value of the cutting speed (Vc) is at 2.98. Moreover, the p-value of the cutting speed is 0.063 which is more than the α-value of 0.05. However, both the f-value and p-value is only slightly out from the critical values.

Feed rate per tooth (fz)

For the feed rate per tooth (fz), the calculated f-value is 17.25, much above the critical value at $F_{0.05, 2, 44}$, indicating that the feed rate per tooth has significant effect on the diameter of the hole. The p-value also helps to confirm the finding, with the p-value of 0.003, below the α-value of 0.05.

Cutting speed and Feed rate per tooth (Vc*fz interaction)

From the experiment, the result of the calculation shows that the interaction between the cutting speed and the feed rate per tooth does not have significant effect on the diameter of the hole. The calculated f-value of the interaction is 0.66, below the critical f-value at $F_{0.05, 4, 44}$ at 3.182. The p-value of the interaction is 0.624, much higher than the α-value at 0.05.

Effect Plot

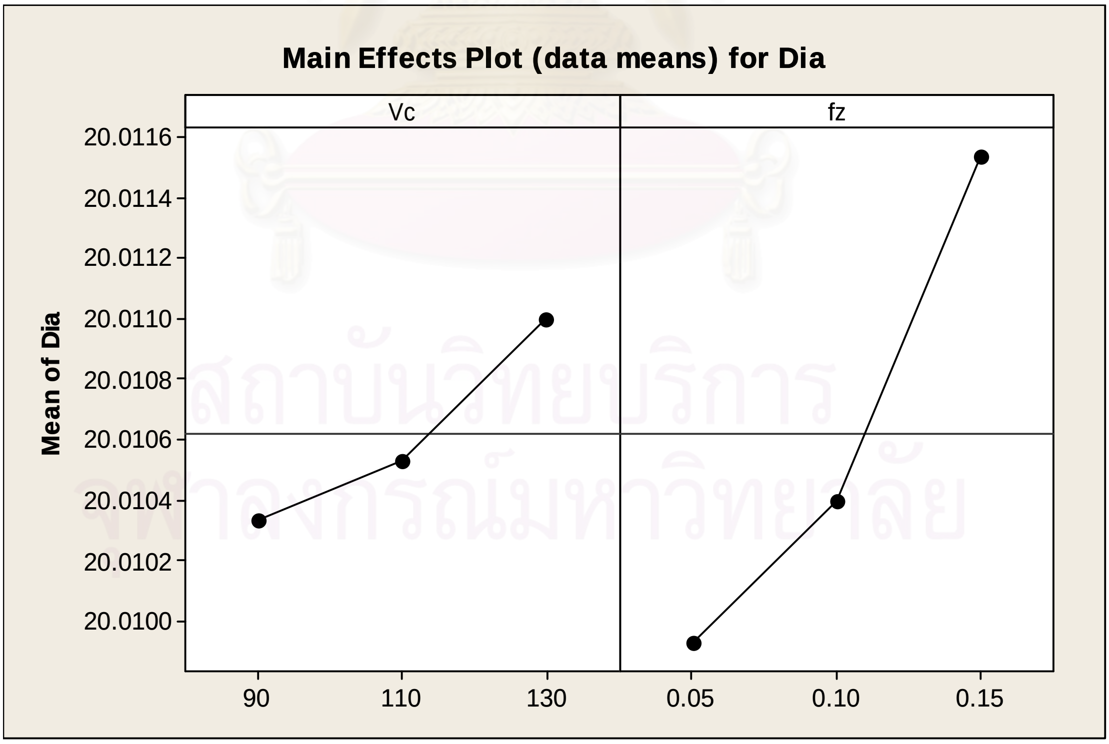


Figure 5.14 : Main Effect Plot (Vc and fz) for Diameter (Reamer)

Figure 5.13 shows the main effect of the cutting speed(Vc) and the feed rate per tooth(fz) at different levels. The graph on the left reveals the effect of the 3 levels of cutting speed against the mean diameter. The 3 different levels of cutting speed (Vc) are 90, 110 and 130 mm/min. It can be seen that the diameter of mean of diameter increases with the rising cutting speed. However, the increase is at different rate. The graph between 110-130 mm/min has steeper gradient than that of the graph between 90-110 mm/min. This means that the change between 110-130 mm/min cause greater effect on the diameter than that between 90-110 mm/min.

The effect of the feed rate per tooth (fz) is shown in the graph at 3 different levels, 0.05, 0.10 and 0.15 mm/tooth. In general, it can be seen that the increase in the feed rate per tooth will cause the mean diameter to increase. The effect of the change is found between 0.10-0.15 mm/tooth as indicated by the steeper gradient of the graph.

From the main effect plot, it can be concluded that the increase in both cutting speed (Vc) and feed rate per tooth (fz) would cause the hole diameter to increase. However, the change made the feed rate per tooth is greater by that of the cutting speed, as indicated by the larger diameter range.

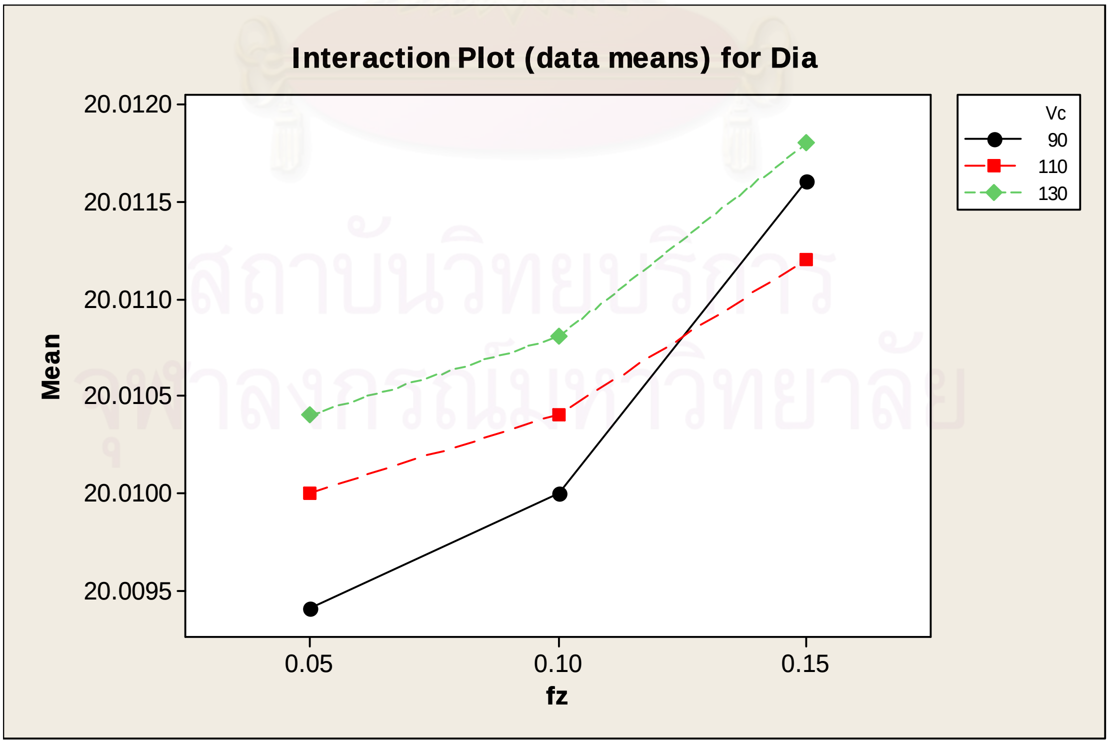


Figure 5.15 : Interaction Plot (Vc and fz) against Diameter (Reamer)

Figure 5.14 shows the interaction plot of the 2 factors, cutting speed (Vc) and feed rate per tooth (fz) against the mean of diameter. The different levels of feed rate per tooth will be shown on the x-axis, the mean diameter will be on the y-axis, while the 3 different lines on graph will be representing the 3 levels of cutting speed. It can be seen that the 3 lines show the same trend. As the cutting speed and the feed rate per tooth increases, the mean diameter will increase.

Between the feed rate per tooth of 0.05-0.10 mm/tooth, the slopes of the 3 lines are similar. However, it can be seen that between 0.10-0.15 mm/tooth, the line of cutting speed at 90 mm/min begin to increase significantly. While the slope of the cutting speed at 110 and 130 mm/min are similar.

Model Adequacy Checking

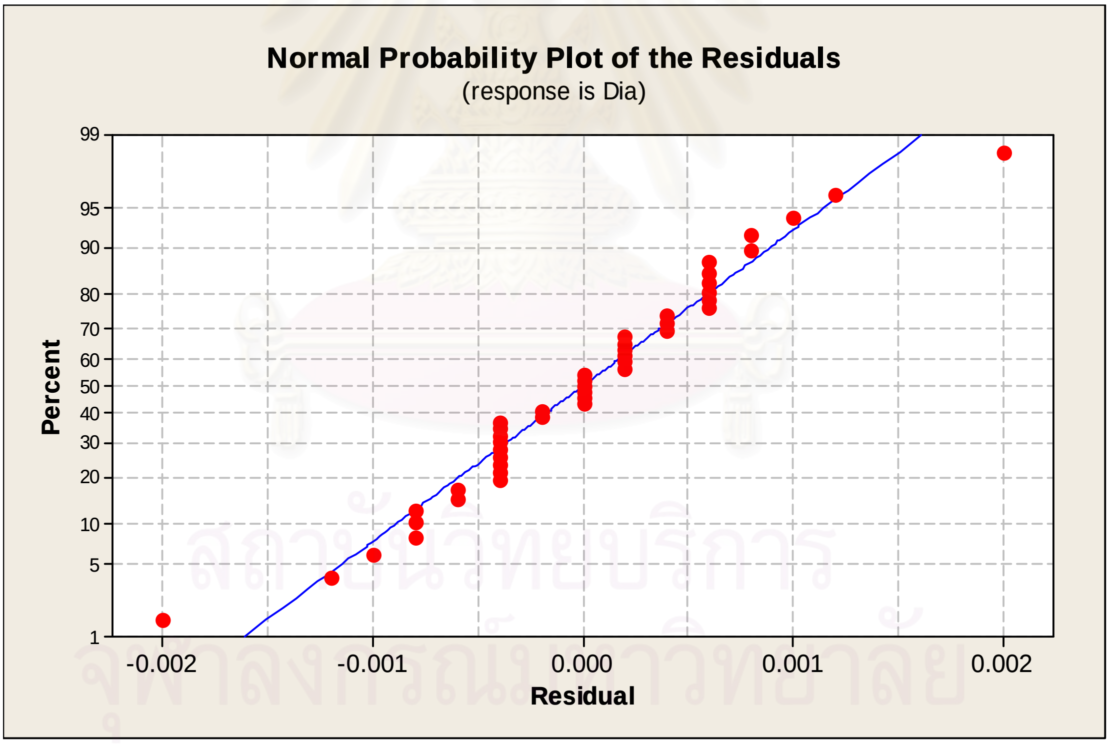


Figure 5.16 : Normal Probability Plot of the Residual (Reamer)

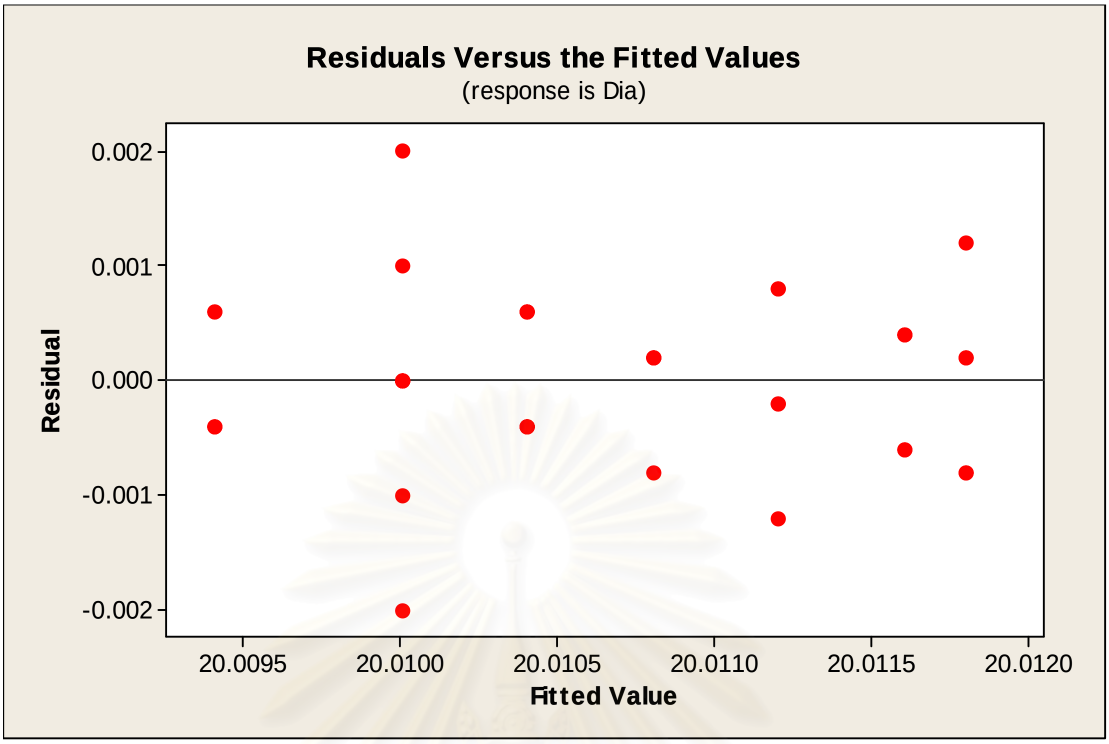


Figure 5.17 : Residual Plot against Fitted Values (Reamer)

Figure 5.15 shows the normal probability plot of the residual from the reamer process. It can be seen that the points are accumulated at certain points. Nevertheless, the trend of the points represents straight line. The accumulation at certain point may result from the little variation of the measured diameters. As reamer process is a process which require high precision, the variation of the diameter at different levels are very small.

From Figure 5.16, the plot reveals that the points are widely spread in random manner.

From the above plots, there is no evidence of model inadequacy. The data from the experiment can be concluded that it come from a normal population.

Response Optimization

From the ANOVA table, the coefficient of the data can be taken to form the regression equation which an be used to find the relationship of the 2 factors, cutting speed (Vc), feed rate per tooth (fz) and the response output, which is the diameter of the hole. With the regression equation, the optimal setting can be found by inputting the variable factors to obtain the desired response output. The regression equation of the reamer process is as followed.

Regression Equation

Diameter = 20.0106 + 0.0007Vc + 0.0016fz – 0.0004Vc*fz

Where : Vc = Cutting Speed (mm/min)

fz = Feed Rate per Tooth (mm/tooth)

As mentioned earlier in the drilling process, the optimal condition can also be found from using statistical program. In this case, Minitab will be employed to calculate the optimal cutting condition for the reamer process. The parameter of the desired diameter is set between 20.010 mm and 20.015 mm. in minimize mode. The minimize mode will help to keep the diameter as close to the target value as possible. The following table will summarized the solution which is obtained from Minitab.

Response Optimization

Parameters

	Goal	Lower	Target	Upper	Weight	Import
Dia	Minimum	20.01	20.01	20.015	1	1

Global Solution

Vc = 110.000

fz = 0.061

Predicted Responses

Dia = 20.01, desirability = 1

Composite Desirability = 1.00000

Table 5.12 : Response Optimization of Reamer Process

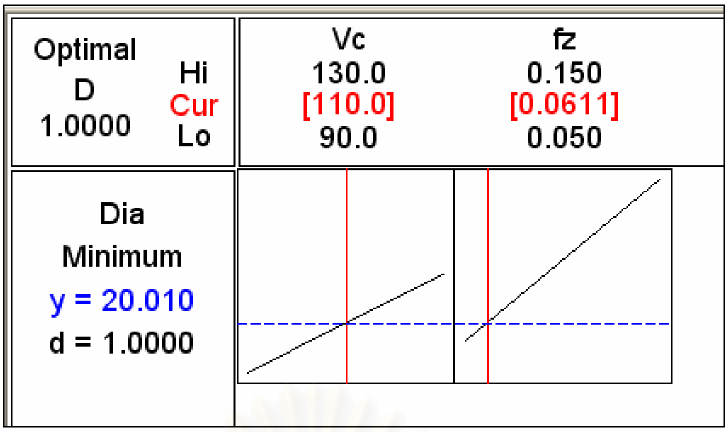


Figure 5.18 : Graphs Indicating the Optimal Reamer Parameter

From the analysis, the target diameter is set at 20.010 mm with the upper limit of 20.015 mm. The specification of the hole is 20 mm. with H7 tolerance, meaning that the required diameter is between 20.000 – 20.021 mm. The engineer decided to target the mid-value so that any variation in the diameter would keep the hole within its required tolerance. Minitab then generates the cutting parameter to achieve the required output.

1. Cutting Speed (Vc) = 110.0 mm/min
2. Feed Rate per Tooth (fz) = 0.0611 mm/tooth.

The calculation also indicates the desirability of the diameter. For this case, the desirability is 1. This can ensure that the response diameter will be within the desired range with 100% confidence.

Chapter VI

Production Statistic, Result and ROQI

6.1 Production Statistic and Result after Process Modification

This research was started in October 2006 with data collection and process analysis. Through various suggestion and discussion, many solution and process modifications are considered in order to solve quality issues of the tire mould production. The systematic and logical procedures provided by the quality tools allow the author to obtain valuable answers. The author prepared for the implementation, while waiting for the authority from the management. Once the management had approved to the modifications, the process modification started in January 2007. Production statistics and modification details were closely monitored. The statistics are collected from January to August 2007. They are summarized in the following tables and graph.

Monthly production statistics			
Month	Production	Defect	Defect %
Sep	20	10	50.00
Oct	22	8	36.36
Nov	22	6	27.27
Dec	20	8	40.00
Jan	23	6	26.09
Feb	17	6	35.29
Mar	23	6	26.09
Apr	28	7	25.00
May	23	7	30.43
Jun	28	5	17.86
Jul	31	8	25.81
Aug	28	5	17.86

Table 6.1 : Monthly Production Statistic between Sep 06 to Aug 07

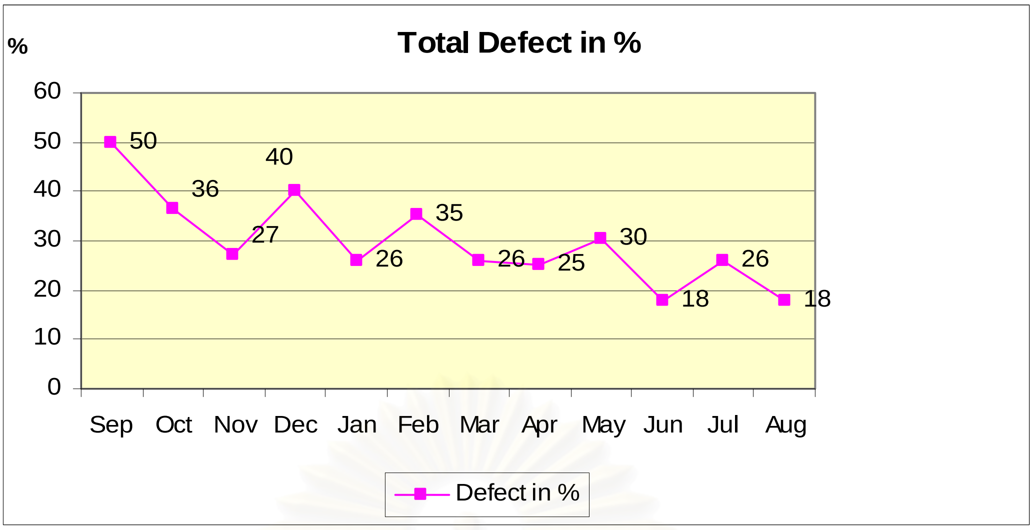


Figure 6.1 : Graph of Production Defect in Percentage of The Tire Mould Production Between Sep 06 to Aug 07 (Before)

From the graph, it can be seen that the number of defect found in the production process had been reduced slightly. The average number of defect was reduced from 38.1% between September – December 2006 to 24.8% between January – August 2007. However, the production statistic from January – April 2007 also include defects such as blowhole and raw material undersize. As discussed in the analysis, the company is not responsible for defects in this category as the raw material is supplied by the customer. The customer has to pay for the defective cost as well as the production cost that have occurred. Moreover, the company had discussed with the customer regarding these problems, but they still persist. It had been noticed that the number of defective casting with blowhole found after December 2006 had been increasing continuously between January – august 2007. The customer acknowledges the problem and trying to adjust the casting method.

Since the blowhole does not derive from the company's manufacturing process, the defect in this category will be omitted. The new table and graphs of the production statistic will be as followed.

Monthly production statistics			
Month	Production	Defect	Defect %
Sep	20	10	50.00
Oct	22	8	36.36
Nov	22	6	27.27
Dec	20	8	40.00
Jan	23	1	4.35
Feb	17	1	5.88
Mar	23	1	4.35
Apr	28	2	7.14
May	23	2	8.70
Jun	28	2	7.14
Jul	31	2	6.45
Aug	28	1	3.57

Table 6.2 : Monthly Production Statistic between Jan 07 to Aug 07

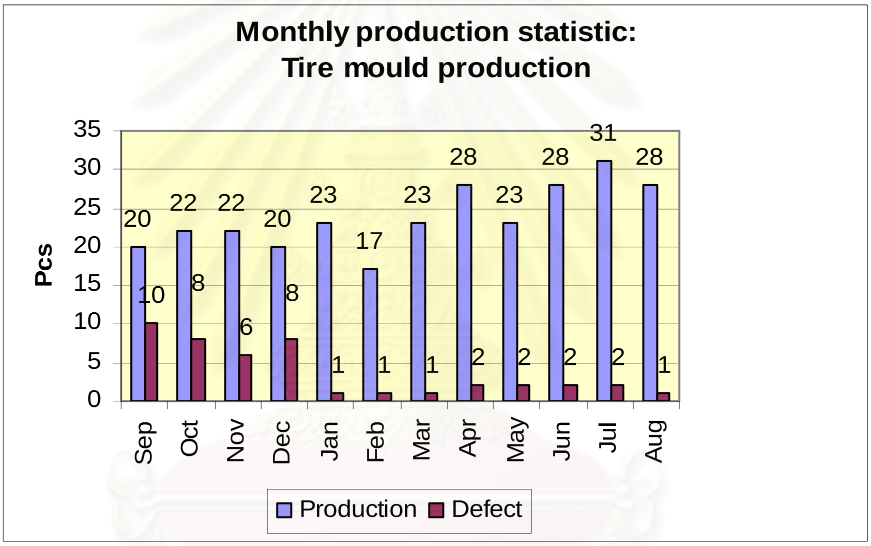


Figure 6.2 : Graph of Tire Mould Production and Defect

The tire mould production after the process modification is stable with an average production of 25 pieces per month compared to 21 pieces per month before the process modification. It can be clearly seen that the number of defect have been reduced significantly. The number of average monthly defects reduced from 8 pieces down to 1.5 pieces.

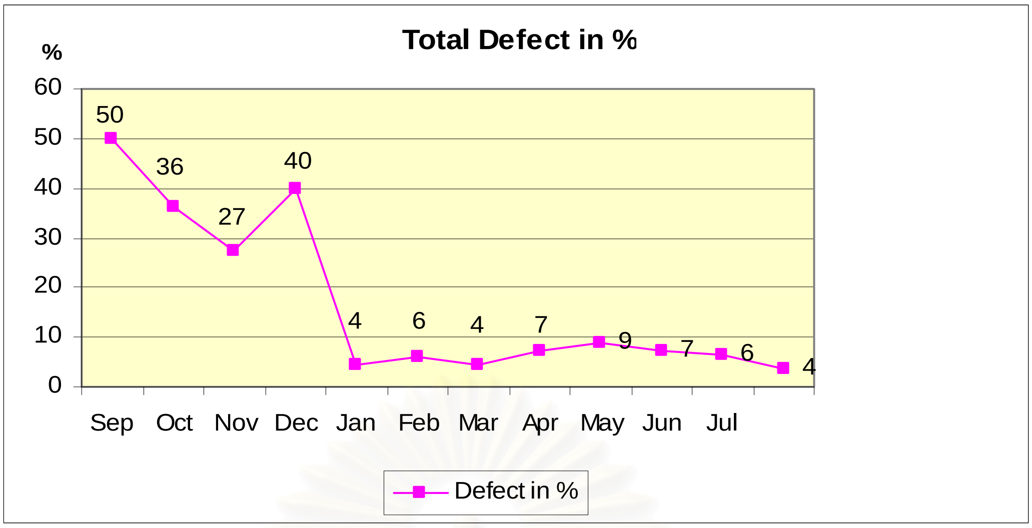


Figure 6.3 : Graph of Defect in Percentage of The Tire Mould Production between Sep 06 to Aug 07 (After)

From the graph, it can be clearly seen that the percentage of defect found in the manufacturing process had dropped tremendously after the process modification has been made. Before the process modification, the average percentage of defect between September – November 2006 was 38.1%, however, the average percentage of defect between January – August 2007 was reduced to only 5.9%. From this evidence, it is clear that the process modification has an effect on the amount of defect in the production process.

The monthly production defect after the process modification is less than 10% from January – August 2007.

6.2 Return on Quality Investment

The analysis of the production processes leads to a series of process improvement and process control in the tire mould production. Process modifications have been implemented and tested for a period of 4 months. The modifications have been proven as the number of defects has been reduced significantly. It is undeniable that these improvements come with a price tag. The company had invested on new tools, man power, equipment and other instrument which are suggested and approved by the company's management. Here, the cost of quality associated with the improvement of the tire mould production will be calculated. It will be followed by the determination of the return on quality investment which is one of the key of this research. The following table will illustrate the expenses made during this research.

Expenses Made During Research

No.	Cost description	Amount	Cost/Month
	Problem Analysis process		
1	Labor cost of team member (meeting)	12,344	3,086
	Machining M2 Process		
1	Check sheet (2 year)	1,968	82
2	8 hours CNC class (1year)	10,328	861
3	Work instruction (2 years)	3,890	162
	Turning T1 & T2 process		
1	Check sheet (2 year)	1,288	54
2	4 hours CNC class (1year)	6,948	579
3	Calibrate linear bench (1year)	4,500	375
4	Work instruction (2 years)	3,842	160
5	850mm. external micrometer (8 years)	85,000	885
6	700mm. internal micrometer (8years)	30,000	313
	Machining M3 Process		
1	Check sheet (2 year)	1,986	83
2	Work instruction (2years)	3,890	162
3	8 hours CNC class (1year), join M2		
	Total	165,984	6,801

Table 6.3 : Expenses during The Research Period, from Sep 06 to Apr 07

For those expenses involving labor cost, the detail can be found in the following table.

Process	Labor Cost/hour	Number of hour	Total
Problem Analysis process			
Labor cost of team member (meeting)	1543	8	12,344
Machining M2 Process			
Check sheet (2 year)	492	4	1,968
8 hours CNC class (1year)	1291	8	10,328
Work instruction (2 years)	486	8	3,890
Turning T1 & T2 process			
Check sheet (2 year)	322	4	1,288
4 hours CNC class (1year)	1737	4	6,948
Work instruction (2 years)	480	8	3,842
Machining M3 Process			
Check sheet (2 year)	492	4	1,968
Work instruction (2years)	486	8	3,890

Table 6.4 : Calculation of the Expenses Involving Labor Cost

In the calculation method, the labor costs per hour of the people involved are added up, multiplying by the number of hour that they spent doing the task.

Saving Made from Drill and Reamer Process Modification

The change in the cutting tools has resulted in the reduction in machining time in the drill and reamer process. The following table will summarize the detail of the old and new process.

Process	Description	Time (second)
	Old method	
1	Hss Center Drill (D=10 mm.)	5
2	Hss Drill (D = 14 mm.)	51
3	Hss Drill (D = 19.5 mm.)	54
4	Hss Endmill (D = 18 mm.)	47
5	Insert Chamfer (D = 30 mm.)	5
6	Hss Reamer (D = 20 mm. H7)	140
7	Total tool change time (6 tools)	125
8	Total time for tools to travel (6 tools)	1020
	Total time per piece	6581(109 min)
	New Method	
1	Carbide Drill (D = 19.8 mm.)	56
2	Insert Chamfer (D = 30 mm.)	5
3	Insert Reamer (D = 20 mm. H7)	11
4	Total tool change time (6 tools)	50
5	Total time for tools to travel (6 tools)	340
	Total time per piece	1686 (28.1 min)

Table 6.5 : Comparison between the New Setting and Old Setting for Process Time

The following table will illustrate the effect of the new drill, reamer as well as their conditions. The cost of the drill and reamer process will be calculated for both old and new settings. The cost will be based on unit of production.

Description	Old setting	New setting
No. of tools used in drill &reamer process	6	3
No. of holes per piece	18	
Drill and reamer cost per piece(Bath)	2943	1648.4
Cost of machine per hour (Baht)	2000	2000
Production time (drill & reamer) (hr)	1.83 (109 min)	0.47 (28 min)
Machine cost (drill & reamer) (Bath)	3660	940
Total cost of drill & reamer process (Bath)	6603	2588.4

Table 6.6 : Comparison between the New Setting and Old Setting

From the calculation, the cost of drills and reamers per mould is 2943 Bath. With the new setting found from the DOE, the cost of drills and reamers is calculated to be at 1648 Bath per mould. These are calculated by finding the tool life of the drills and reamers and use the values to find the cost per hole. The numbers of holes are 18 holes per piece, therefore, the cost of drills and reamers per mould can be found. The new setting reduces the tooling cost per mould by 1295 Bath or 44%.

The new setting also affect the production time of the drilling process. With the old setting, several drill have to be use to enlarge the hole as the high-speed drill and the machine can not drill 20mm. hole at one go. As a result, the old setting requires 6 tools to do the drill and reamer process compared to 3 tools from the new process. The reduction in the number of tools also reduces the tool change time of the process. The feed rate of the high-speed drill is lower than the carbide drill, causing the drilling process to become longer. The time taken for the old setting is 109 minutes, while the new setting takes 28 min. The cost of the machine is 2000 bath per hour. The cost of machine per piece of mould for the old setting and the old setting would be 3660 bath and 940 bath respectively. The saving per mould is 2720 bath or 74%.

The total production cost of the drill & reamer process (machine cost + tooling cost) for the old setting and the new setting added up to 6603 bath and 2588 bath respectively. The total saving in this process per piece of mould is 4015 bath or 60.8%.

Average monthly production	22 pcs
Saving in Drill and Reamer process	4,015 bath/pc
Monthly saving from new setting	88,330 bath

Table 6.7 : Saving from New Setting.

Table shows the monthly saving of the new setting. The average monthly production is around 22 pieces. The new setting will save 4015 bath per piece. The monthly saving of the new setting will be 88,330 bath with average production of 22 pieces.

Expenses made during the finding of the optimal cutting condition

The following table will summarized the expenses made during the study and the DOE process during the finding of the optimal cutting condition.

No.	Cost description	Amount	Cost/Month
	Problem Analysis Process		
1	Labor cost of team member (meeting)(1 year)	1,160	97
	DOE Process		
1	Labor cost of team member (meeting)	2,500	208
2	Machine cost during drill & reamer testing	20,000	1,667
	(2000 bath/hour x 10 hours)		
	Data Analysis Process		
1	Labor cost of team member (meeting)	1,160	97
	Total	24,820	2,069

Table 6.8: Expenses during Finding of Optimal Cutting Condition

With the cost and the benefit of the process clearly established, the ROQI of the investment of new drill and reamer can then be calculated.

$$\text{ROQI} = \frac{\text{Benefit per month}}{\text{Cost per month}}$$

Benefit per month = Total monthly saving from using new drill and reamer

= 88,330 Bath

Cost per month = Expenses made during the research on monthly basis

= 2,069 Bath

$$\text{ROQI} = \frac{88,330}{2,069}$$

= 42.69 times

Production Statistic and Cost of Quality

In the following table, the internal and external failure costs before and after the process modification will be summarized.

Product: Tire Mould	Period: Oct 06-Dec 06	
Cost type	Amount	Cost/Month
Internal Failure Cost		
1. Scrape	121,000	30,250
2. Repair, Replacement, Rework	111,650	27,913
3. Defect/Failure Analysis	30,551	7,638
4. Reinspection/Testing	35,200	8,800
External Failure Cost		
1. Warranty/Claim		
2. Product Reject & Return	72,600	18,150
10% overhead cost are included		
Total	371,001	92,751

Table 6.9 : Internal Failure Cost and External Failure Cost between Oct 06 – Dec 06

Product: Tire Mould	Period: Jan 07 - Aug 07	
Cost type	Amount	Cost/Month
Internal Failure Cost		
1. Scrape	0	0
2. Repair, Replacement, Rework	49,200	6,150
3. Defect/Failure Analysis	0	0
4. Reinspection/Testing	10,500	1,313
External Failure Cost		
1. Warranty/Claim	0	0
2. Product Reject & Return	0	0
10% overhead cost are included		
Total	59,700	7,463

Table 6.10 : Internal Failure Cost and External Failure Cost between Jan 07 – Aug 07

From the above tables, the failure cost is shown in term of the total cost before and after the process modification. The total cost is also divided by the number of month in that period to obtain the monthly failure cost. Generally, it can be seen that the failure cost has reduced significantly after the process modification. The monthly failure cost had decreased from 92,751 Bath to 7,463 Bath, before and after the process modification respectively. This reduction is equivalent to 91%, which is a significant amount. These figures will be used to calculate the ROQI of the research and process modification.

The ROQI calculated will be based on the monthly basis for easier calculation. The ROQI can be defined as the ratio between the benefit and cost. The formula of ROQI in this case can be represented as followed.

$$\text{ROQI} = \frac{\text{Benefit per month}}{\text{Cost per month}}$$

Benefit per month = Total monthly saving from defective parts

= 92,751 – 7,463

= 85,288 Bath

Cost per month = Expenses made during the research on monthly basis

= 6,801 Bath

$$\text{ROQI} = \frac{85,288}{6,801}$$

= 12.54 times

6.3 Process Modification Result

The production statistics has shown a significant amount of defect reduction after the process modifications have been made. The success is a combination of a number of factors. The result of the process modification will be summarized in the following paragraphs.

1. The problem regarding technical shill such as programming error and wrong tool usage has been improved by the training classes. The basic CNC classes were given to the machine operator in machining M2, M3 and turning T1 and T2. These classes provide correct information and technique which is essential in operating CNC machines. It enabled the operators to work together using the same technique and in logical programming sequences. In addition, tool speed and feed calculation as well as their usage were taught in the glass. This information allows the operator to choose tools correctly and effectively, matching the right tool with the right job. Not only the existing operators were provided with the training, regular classes (quarterly) are given to new operators who joined the company.

Figure 6.4 : Training Classes given to CNC Machine Operators

2. Production statistics in the form of graphs are pasted on the main production board, so that the operator can keep track on their performance. These graphs are posted on a weekly and monthly interval. The information includes the number of production, the internal and external defect found, and the amount of waste that has cost. This information makes the operators aware of the resources that have been wasted and be willing to reduce them. Most importantly, each department has to set their quality target in the aim to reduce the defect within their department. With the statistics pasted on the main board, every department tried to reduce the defect, so that they are not humiliated when compared with other department.

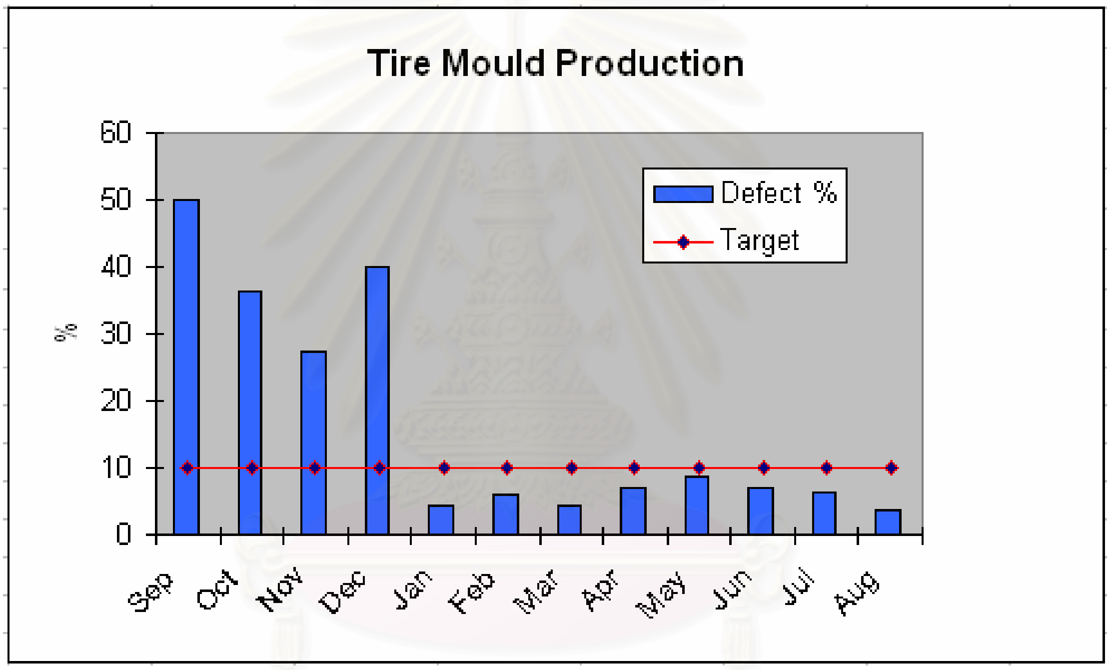


Figure 6.5 : Example of Production Statistics and Target

3. The inline inspection is increased. The purpose of the increase inspection is to make the operators aware of their work and their dimension. The operators have to fill up the check sheets given to them step by step before they can move on to the next process. The check sheet is accompanied by the dimensions in the drawing, so they can be compared easily. The regular checking also provides early detection of the defect and they can be dealt with quickly before it became too late to repair or reworked. It also reduces the dependence of the QC personal that usually has to check the mould in the production regularly.

Figure 6.6 : Operator Checking the Dimension

4. The check sheets are introduced for every piece of work. In the check sheet, the dimension and the drawing of the mould are given along with important remarks. The operators can get the dimension and the drawing from the check sheet. During the operation, the operators have to measure and fill in the check sheet before they can move onto the next step. The dimensional value can be compared with the actual value in the check sheet. This allows the operator to monitor the process carefully. The engineer can check the work easily by looking at the check sheet. This helps to speed up the production process. The operators have to sign and get approval from the head of department before passing the job to the next department. This indicates the responsibility clearly, making operators more aware of their work.

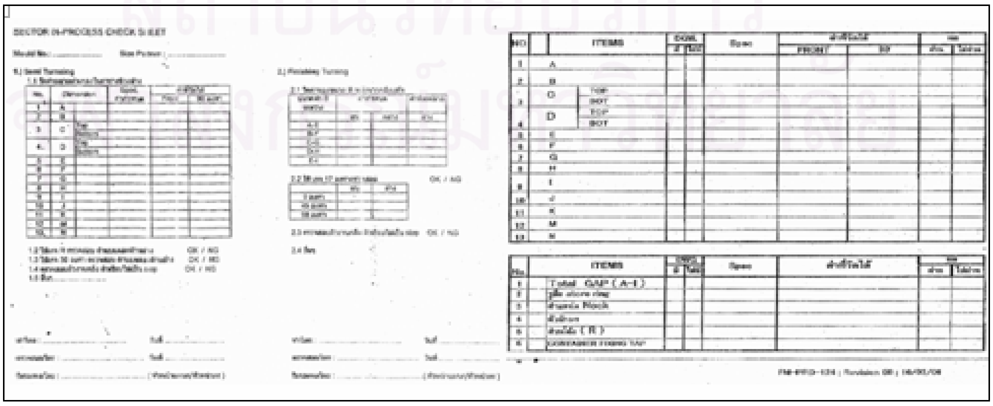


Figure 6.7 : Example of Check Sheet

5. Work instruction is made for the working processes in the mould production. The work instruction provides the correct working steps for the operators. The operators do not have to hesitate as the instruction is clearly given in the work instruction. The instruction also includes pictures for better understanding. The new operators can understand the working procedures easily and defects can be reduced. The work instruct is also updated consistently when operators or engineer have a good suggestion to improve the working processes.

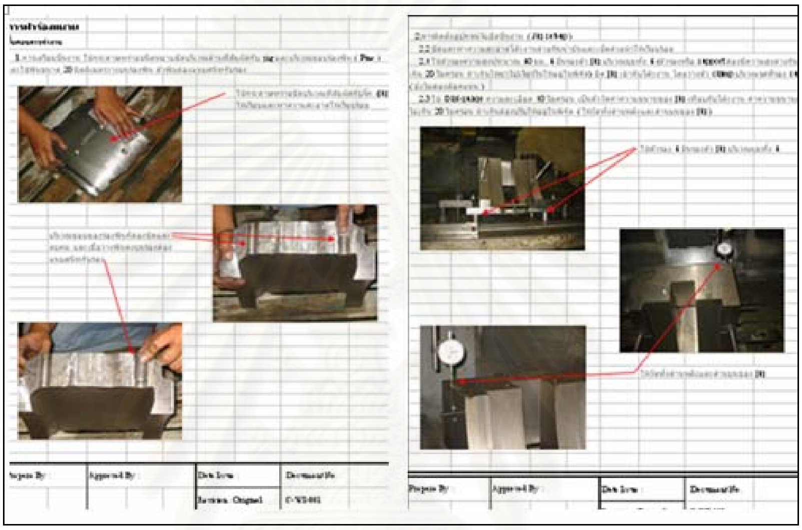


Figure 6.8 : Example of Work Instruction

6. The new measuring instruments such as large venire caliper and micrometer screw gauge is purchased. This instrument is easier to use and has a universal application when compared with the old measuring instruments. It enable the operators to measure the work more conveniently, resulting in a more accurate reading and regular checking.

Figure 6.9 : Example of Old Measuring Instrument (left) and New Instrument (right)

7. The success in defect reduction in the drill and reamer process came from the ability to test and find the optimum cutting parameters for the new carbide drill and reamer. The achievement is more than expected as the defects which come from this process has been eliminated. The types of tools chosen for the replacement are corrects and matches with the type of raw material being cut. The tool life is correctly calculated and tested so that it is fully used before being replaced.

Figure 6.10 : New Drill During Work

Chapter VII

Conclusion and Recommendations

The purpose of this thesis is to reduce the number of defect found in the tire mould production process. The amount of defect found has been high since the start of the production. The average amount of defect found for the first four month of data collection is 61.9%. The research has been formed with the aim of improving the production statistics. The improvements are done via several analysis and quality tools. The suitable methods are selected for the implementation. The results of the process modification are then checked via the calculation of return on quality investment.

7.1 Conclusion

This thesis started with the study of the production process, the types and symptoms of the defect as well as the background information of the production. The production statistics are then collected and analyzed. With the information in hand, the block diagram of the production process is established. Failure Mode and Effect Analysis (FMEA) is then used to analyze each of the production processes. These production processes are selected as they have produced defective parts. The production processes which have been analyzed are as followed.

1. Machining M2
2. Turning T1
3. Machining M3
4. Turning T2
5. Numbering & Marking

After the analysis, the process, the potential failure modes, the potential cause, the current process control and the Risk Priority Number (RPN) are obtained. The critical risk priority number is then calculated. The critical risk priority number is set at 150 (severity = 5, occurrence = 5 and detection = 5). This will be used as a base line for the RPN, the failure modes with RPM more than 150 will be further analyzed. From the FMEA, 9 failure modes are found with RPN above 150.

1. Dimensional error from T2
2. Hole diameter over from M2 (reamer)
3. Internal angle error from T2
4. Segmentation error from M3
5. Angle out of specification from T1
6. Hole diameter from M2 (drill)
7. Drill wrong pin position from M2
8. Drill too shallow from M2
9. Drill wrong pin height from M2
10. Bore holes & screw not centered from M2
11. Internal height too large from turning T2

These failure modes come from 4 manufacturing processes. They are Turning T2, Machining M3, Turning T2 and Machining M2. These processes are further analyzed with the fish-bone diagram to find the cause and effect of the failure modes. This analysis will base on the 4 Ms category, consisting of man, machine, material and method.

The result of the fishbone analysis revealed that most of the problems are caused by the lack of production control and the inexperience operators. The causes come from human error, therefore, CNC programming classes and tutorial were conducted to increase the knowledge and skill for the operators. Check sheets are introduced into the production line, along with every piece of mould. Each sheet includes important dimension and specification highlighted for the operators. The responsibility of the operator and the quality control personal are also clearly stated. After the implementation, the result was satisfying, the number of defect from human error had significantly reduced. It is under control.

The fishbone analysis also provides another piece of important information. The defect found in Machining M2 process is high and related to the diameter size of the hole. The main cause of the problem is the inappropriate high-speed drill and reamer used. The author decided that the new carbide drill and inserted reamer must be tested via DOE and used in the production.

In order to investigate the cutting parameter of the new set of drill and reamer, DOE are carried out. The drill is tested first before moving on to the reamer. For the drill process, a factor screening experiment is done to check on the 3 variable factors, cutting speed (Vc), feed rate per tooth (fz) and cutting depth (z) and their effect on the diameter of the hole. 2^k factorial technique is employed. The levels for each factor are as followed.

	Low (-1)	High (+1)
Cutting depth (z)	3 mm.	5 mm.
Cutting speed (Vc)	80 m/min	110 m/min
Feed rate per tooth (fz)	0.05 mm/tooth	0.15 mm/tooth

Other factors involved in the experiment are kept constant to ensure that any bias in the experiment is kept to the minimum. Randomization of the experiment order is done to increase the accuracy of the result. 6 replicates are used for each combination, resulting in a total of 48 set ups. The diameter of the drilled hole is the response of the experiment. The target diameter of the hole is set between 19.80-19.86 mm.

From the factor screening experiment, it is found that the significant factors in determining the diameter of the hole are the cutting speed (Vc), feed rate per tooth (fz) and the interaction between Vc and fz. The F-value for the 3 factors is 0.000 which is less than the critical value. The cutting depth does not affect the diameter significantly as the F-value is 0.451 which is higher than the critical factor. The experiment also shows that the increase in both cutting speed and feed rate per tooth reduces the mean diameter. It is also noticed that at high cutting speed, the surface of the hole is better.

The information is used to further analyze the drilling parameter and the optimal drilling condition. There are 2 factors tested, cutting speed (Vc) and feed rate per tooth (fz). 3 levels are used with the 3^k factorial technique for the investigation. 12

replicates are used for each factor combination, resulting in the total of 108 setups. The drilling conditions are as followed.

	Low (-1)	Mid (0)	High (+1)
Cutting speed (Vc)	80 mm/min	95 mm/min	110 mm/min
Feed rate per tooth (fz)	0.05 mm/tooth	0.1 mm/tooth	0.15 mm/tooth

The result of the experiment has confirmed the finding of factor screening experiment. The significant factors are the cutting speed (Vc), feed rate per tooth (fz) and the interaction between Vc and fz as indicated by the F-value.

The result of the experiment is then used to find the regression equation which will be used to calculate the optimal drilling condition. Minitab is used to calculate the regression equation, which is as followed.

Regression Equation

$$\text{Diameter} = 19.8546 – 0.0042Vc- 0.0057fz + 0.005Vc*fz$$

Minitab is then used to calculate the optimal drilling condition. The response optimization is employed with the target value of 19.85 mm. and maximum value of 19.86mm. The suggested cutting speed (Vc) and feed rate per tooth are 95 m/min and 0.1404 mm/tooth respectively. The composite desirability is 1, which is a high value, making the result more reliable. These values are used to drill the pre-reamer hole which is used to test the reamer.

The reamer is then tested with 3^k factorial technique. In reamer process, there are only 2 variable, therefore factor screening is omitted. The 2 factors in consideration are cutting depth (z) and 3 levels with 5 replicates are used for this experiment.

	Low (-1)	Mid (0)	High (+1)
Cutting speed (Vc)	90 mm/min	110 mm/min	130 mm/min
Feed rate per tooth (fz)	0.05 mm/tooth	0.1 mm/tooth	0.15 mm/tooth

From the experiment, only 2 factors have significant effect on the diameter of the hole. They are cutting speed (Vc) and the feed rate per tooth (fz). The result shows that the increase in both Vc and fz will increase the mean diameter. It has been noticed at this stage that the increase in cutting speed would provide better surface finish.

Minitab and response optimization is employed to calculate the optimal cutting condition. The Regression equation for the reamer process is

$$\text{Diameter} = 20.0106 + 0.0007Vc + 0.0016fz - 0.0004Vc*fz$$

From the calculation, the optimal reamer conditions are cutting speed (Vc) at 110 mm/min and feed rate per tooth at 0.061 mm/tooth. The composite desirability is 1, with the target of 20.01mm and 20.015mm. This can be accepted as the customer's specification is 20.00mm with the tolerance of + 0.02mm.

After the product modification process, the production statistic in monitored closely to check on the result. On monthly basis, the number of defect reduces from 38.1% to 5.9% with stable number of tire mould production. This significant reduction can also be check with the ROQI. The ROQI of the process modification as compared with the loss by defect is 12.54 times

As for the change of the new drill and reamer, the defect found from this process has been eliminated for the period of 8 months under study. The new drill and reamer help to save the tooling cost, reduce production time and minimizing the defect rate. This benefit has been calculated in term of ROQI. On 2 years basis, the ROQI of the tool change is 42.69 times.

7.2 Further Recommendations

The use of the PAF model will only inform the organization of the production cost and locating the critical production process. The organization must keep in mind that it does not help to reduce defect directly. It must rely on the skill, experience and skill to minimize the cost. The use of the PAF model is more useful in long term, the organization must be patient and give sometime for the result to be proven.

The establishment of the training classes and the introduction of the data sheet and check sheet are only in the initial stage. It is important for the organization to emphasize the use and educating everyone on their importance. It must monitor the use of these tools closely as the momentum of the operators might be faded with time. The effort of the organization will be at waste if the use of these tools comes to an end. Encouragement and support from the management will help to keep the wheel turning. In addition to the introduction and the application of these tools, the organization must promote continuous improvement of the tools. This means that the people involved must keep updating the documents and search for ways to improve the production.

The cost collection and the data collection during this thesis are done manually, resulting in a time consuming process. In order for the application of these tools to become more effective and user friendly, computer software such as Microsoft Excel can be used to develop a data base for the collection system. This would help to save much valuable time.

In DOE, there is only 1 set of new drill and reamer tested due to limited time and resources. Further study could be made by trying out combinations of other sets of drill and reamer for improvement. The cutting parameters are limited to a single machine and one type of raw material only. In the future, if the production is moved to other machine or there is a change in raw material, these data can only be used as guidance only. DOE has to be conducted again to find the optimal parameters. The sample size of the experiment can be increased to provide better accuracy and distribution of data. The use of DOE to find the optimal parameters can be developed and use for other machine and job. The use of the DOE will provide a long term benefit such as reduce production time, increase tool life, minimize defect and production cost. The optimal data can be kept for further references.

In the DOE, factorial design was used with a number of replications for each set of experiment. This resulted in a lot of investment and was time consuming. Other design such as Central Surface Design can be used as it require less experiment and less samples. It would help the researcher to save time and cost.

Central surface design can also help the researcher to explore points which is beyond the target point of the researcher. It will allow the researcher to have better rotation of the factors that are being explored. This can be accompanied by the use of plot such as international plot, contour plot or surface plot. These plots will helps to illustrate the results in different views, allowing the researcher to have batter access to the result.

The use of statistical software has helped to reduce the amount of work significantly. It also provides systematic experimental procedures. It can be developed for other use such as for the production data analysis and statistical process control.

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