DEFECT REDUCTION IN PLASTIC PIPE EXTRUSION PROCESS

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การลดของเสียสำหรับกระบวนการฉีดท่อพลาสติก

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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ธเนตร์ตรี รัตนเรืองยศ : การลดของเสียสำหรับกระบวนการฉีดท่อพลาสติก (DEFECT REDUCTION IN PLASTIC PIPE EXTRUSION PROCESS) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร.ปารเมศ ชุติมา, 90 หน้า.

งานวิจัยนี้ได้ทำการศึกษาวิธีการลดของเสียสำหรับกระบวนการฉีดท่อพลาสติกในโรงงานแห่งหนึ่งในประเทศไทย กระบวนการลดของเสียนั้นได้ใช้หลักการ DMIAC ของซิกซ์ซิกมาซึ่งประกอบไปด้วยห้าหลักการหลัก โดยกระบวนการหลักของงานวิจัยนี้นั้นจะอยู่ที่การนิยามปัญหาที่ทำให้เกิดของเสีย การสร้างวิธีตรวจวัดปัญหา การวิเคราะห์หาวิธีแก้ปัญหา การแก้ไขปัญหา และการควบคุมกระบวนการทั้งหมดนี้ การนิยามปัญหาเพื่อที่จะค้นหาต้นเหตุในการเกิดของเสียนั้นประกอบไปด้วย แผนภูมิก้างปลา (Cause-and-Effect Diagram) การวิเคราะห์ความเสี่ยงและแผนภูมิพาเรโต การสร้างวิธีตรวจวัดปัญหานั้นจะทำการศึกษาการวิเคราะห์ด้วย FMEA (Failure Mode and Effect Analysis) เพื่อที่จะค้นหาตัวแปลหลักที่ก่อให้เกิดหรือเป็นต้นตอในการเกิดของเสีย ส่วนในตัวของการวิเคราะห์หาวิธีแก้ปัญหานั้นจะใช้การออกแบบการทดลอง (Design of Experiment) และ การวิเคราะห์ความแปรปรวน (Analysis of Variance) เพื่อที่จะหาค่าของตัวแปลหลักที่ก่อให้เกิดผลลัพธ์ดีที่สุดจากการทดลอง สำหรับกระบวนการแก้ไขปัญหานั้นค่าของตัวแปลหลักที่ก่อให้เกิดผลลัพธ์ดีที่สุดในการทดลองจะถูกนำมาตรวจสอบและทดลองใหม่และถูกเก็บข้อมูลอีกครั้ง ซึ่งจะต่อด้วยการวิเคราะห์ต้นทุนและผลประโยชน์ ท้ายที่สุดแล้วในขั้นตอนการควบคุมกระบวนการกลยุทธ์ในการรักษาและควบคุมตัวแปลหลักที่ก่อให้เกิดผลลัพธ์ดีที่สุดจะถูกนำมาวิเคราะห์อีกรอบ

ในตอนสุดท้าย งานวิจัยนี้สามารถนิยามตัวแปลหลักสี่ชนิดที่ทำให้เกิดของเสียในกระบวนการฉีดพลาสติกในโรงงาน และหลังจากที่ได้หาค่าที่ให้ผลดีที่สุดของแต่ละตัวแปลหลักแล้ว งานวิจัยนี้สามารถลดของเสียที่ผลิตออกมาจาก 8.8% ไปสู่ 5.25% ซึ่งการที่ทางโรงงานได้ลดของเสียไป 3.55% นี้ทำให้ทางบริษัทสามารถลดค่าใช้จ่ายในการผลิตไปได้ถึง 3,600,000 ล้านบาทต่อปี

ภาควิชา	ศูนย์ระดับภูมิภาคทางวิศวกรรมระบบการผลิต	ลายมือชื่อนิสิต	....
		ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
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TANATETEE RATTANARUENGYOT: DEFECT REDUCTION IN PLASTIC PIPE EXTRUSION PROCESS. ADVISOR: ASSOC. PROF. PARAMES CHUTIMA, Ph.D., 90 pp.

This thesis focuses on the study of defect reduction strategy for a plastic pipe extrusion company in Thailand. The objective of this research is to lower the plastic defect production in the company's main plastic pipe extrusion line. The main methodology revolves around the Six Sigma's DMAIC method of defining, measuring, analyzing, improving and controlling the defects created within the company. Define phase studies the Cause-and-Effect Diagram, Risk Analysis, and Pareto Analysis to identify the causes leading to defects production. The Measure phase involve the Failure Mode and Effect Analysis to study the key input factor affecting the causes of defects production. In the Analyze phase, the Design of Experiment (DOE) and Analysis of Variance (ANOVA) are used to determine optimal level for each critical key input factor. For the Improve phase, optimal level key input factors will be implemented and post-improvement data will be collected, followed by cost analysis. Finally, in the Control phase, strategy to sustain and control the optimal level key input factors will be discussed.

In the end, the research identifies four key input factors that are mainly responsible to creating defect within the company's main extrusion line. By finding the optimal parametric input, this research allows the company to reduce manufacturing defects from 8.8% to 5.25%; this 3.55% drop in defect production allows the company to save up to 3,600,000 million Baht on an annual basis.

Department:	Regional Centre for Manufacturing Systems Engineering	Student's Signature	....
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The author would like to express his sincere gratitude toward his thesis advisor, Associate Professor Parames Chutima, Ph.D for the valuable comments and advises he had given. In addition, kind regards to all professors and staffs of the Regional Center for Manufacturing Systems Engineering, Chulalongkorn University, for making the completion of this research possible.

Finally, the author would also like to thank his family and friends for their advice and supports throughout the project.

สารบัญ

หน้า

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List of Figures

List of Tables

Chapter 1: Introduction

1.1 Introduction

Founded in 2005, the case study company is a family enterprise that manufactures PVC pipes and fittings all across Thailand. It owns a medium-size manufacturing factory in the Chachoengsao province of Thailand.

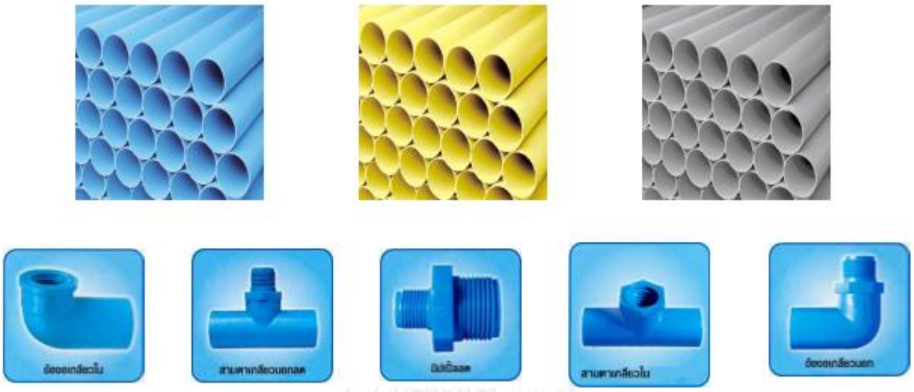


Figure 1 Products from the Company including Plastic Pipes of Different Color and Fittings

The company, however, suffers great loss due to waste defects from its PVC Pipes extrusion lines (the company's main source of profit); the accumulated waste created this way is roughly around 300 tons annually, which, even though is reusable, causes the company unfavorable amount of money. According to the managing director, the waste is roughly around 10% of the total production.

Most of the operation and manufacturing processes at the company are mostly entrepreneurial and have little to no specific standard. The managing director of the company believes that the defects number can be reduced if the operation and manufacturing processes at the case study company are reviewed and improved.

The pipes manufacturing process of the company is the standard plastic pipes extrusion process. PVC resin and other solution, mainly calcium, are mixed up and heated through the extrusion machine and extruded out as long PVC Pipes.

The company has 23 functional extrusion machines. The machines are either purchased first-hand from Chinese supplier or second-hand from Thai suppliers.

Depending on the mold, screw, and resin, the company can manufacture plastic pipes in different color, diameter, and thickness.

Mold

The mold, or die, is used to specify the diameter and thickness of the pipes extruded. Normal thicknesses of blue pipes for water irrigation in Thailand are 5mm, 8.5mm, and 13.5mm, also known as PVC 5, PVC 8.5, and PVC 13.5 in order. As construction tools for water and irrigation system, thicker pipes have more tendency to withstand water pressure and other external forces when embedded with other construction materials.

Screw

Screw is used for transporting raw materials from input to output through the extrusion process. Screw has two parameters: length and diameter, usually in the form of L:D ratio. These parameters affect how fast and how effective the plastic input is heated, melted and molded into pipes. 30:1 to 36:1 L:D ratio is currently the industry standard. In addition, some extrusion machines may have double screws to increase productiveness, flexibility, and consistency.

Resin

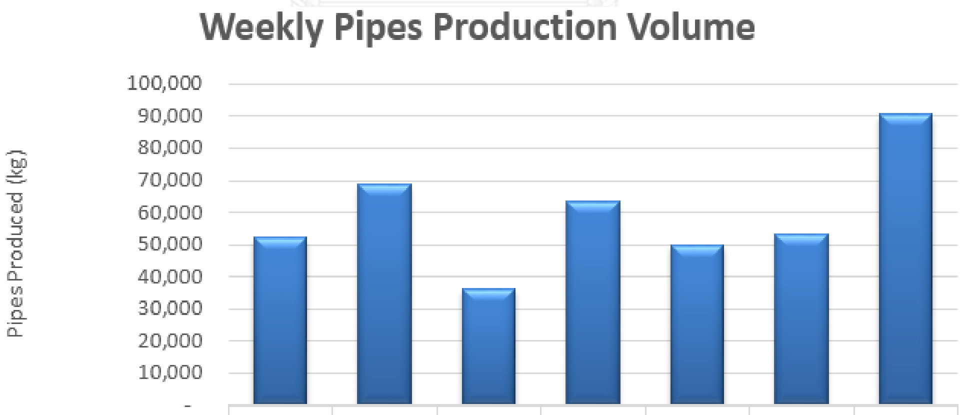
In Thailand, plastic resin are mostly colored. However, to ensure that the pipes extruded have consistent coloring, color additives are used as well.

In addition, since the company utilizes different suppliers for plastic PVC resins and other raw materials. Chemical composition for the extrusion processes oftentimes have to be readjusted so that the end-product pipes meet with industry standard.

The extrusion process starts by putting solid PVC resin, calcium and other additives into the hopper of the machines. The materials will then come in contact with the screw (or screws). The screw will rotate, causing the materials to be pushed toward the end of the extrusion line. At the same time, the materials will also be heated at high temperature (around 200°C, or the melting temperature of plastic polymer). Heated through melting temperature, the materials will then be conveyed by the screw into the mold or die, which will shape the molten plastic. The process must be designed so that molten plastic can flow out of the mold at evenly rate to create smallest defect possible. Plastic will flow out of the mold in cylindrical form and is then cooled down through water bath at the end of the extrusion line. Finally, the long cylindrical plastic will be cut into desired length of 4 meters, and the company's logo is later 'screen' onto the pipe through another additional process manually.

The work process is divided into dayshift and nightshift. Depending on the order, each shift might work on different process other than extrusion.

The company's manufacturing capability is around 40,000 to 70,000 kg of pipes weekly or around 3000 tons of PVC pipes annually. However, this number often fluctuate depending on the demand and supply. This is because the company has several extrusion and injection molding machines to cope with varying orders between different diameters and thickness of the pipes or even the different between the types for fittings. **Figure 2** illustrates the company's production volume on a weekly basis for the year 2014



Operating Week	3	4	5	6	7	8	9
Pipes Produced (kg)	52,220	69,009	36,344	63,616	49,890	53,340	90,474

Figure 2 The Company's Weekly Pipes Production Volume

Production volume is also relative to the line workers presented. The company heavily relies on labor forces from the neighboring countries of Thailand. Although these workers are relatively more cost-effective to hire, they are less reliable in term of knowledge and commitment to the manufacturing work.

1.2 Statement of Problem

According to the managing director, the company manufactures large amount of waste defects, and this leads to annual loss of over million baht. The company categorizes the end product of its extrusion line into four categories:

Conformance pipes – Quality products ready to sell

Scraps – Usually in the form of plastic dusts, reusable if collected back and mixed with resin.

Defects – Usually in the form on low standard pipes or defects. The case company usually dealt with by grinding them back into raw materials.

Wastes – Usually in the form of burnt plastic. Unable to be recycled through any means and discarded.

Rework is extremely rare for the company, as opposed to the much more frequent scraps and defects production.

Regarding the quality control criteria, there are many types of possible defects at the company's pipes extrusion process. These defects, along with the scraps, are recyclable if granulate back into small particles. Wastes are represented in form of burnt pipes, which almost all the times are discarded afterward.

The company classifies 'defects' as the following:

- Rough Surface – Rough surface on the pipes due to friction in the end-extrusion process or due to error during resin polymerization.
- Uneven Pipe Thickness – Uneven pipe thickness can be caused from bad extrusion mold quality and other error during extrusion process.
- Diameter Variation – Similar to thickness, diameter variation can be caused from bad mold quality and other error.

- Spots and Marks – Spots and marks are mostly caused by minor overheating during polymerization of the extrusion process or by physical contact between the extruded pipes and some part of the machines.
- Scratches – Scratches are mostly created by unwanted friction and collision between the pipes and some part of the extruders. While most pipes with minor scratches are still salable, pipes with scratch marks of more than 20% will often get rejected by the customers.
- Bend – Normally, plastic pipes are extruded in a long cylindrical shape. Bent pipes are unsalable as it has no functional use in hydro-agricultural-construction usage. Bent pipes are result of bad extrusion process, mainly in the error during polymerization.
- Fracture – Fracture on pipes are caused by physical reasons. Sometimes pipes are extruded out of the machine too fast causing unwanted collision resulting in fracture in output products.
- Misshaped – Similar to bend, misshaped pipes are unsalable as it serves no functional use. Misshaped pipes are often the result of error during polymerization process; however, the quality of extrusion mold may also influence this type of defect error. Example of misshaped pipes are non-circular pipes.
- Minor Burnt – Due to overheating from wrong temperature setups, sometimes pipes extruded are burnt. Burnt pipes are unsalable and most of the burnt pipes are unrecyclable. Pipes burnt less than 10% can still be recyclable in the company’s current process.

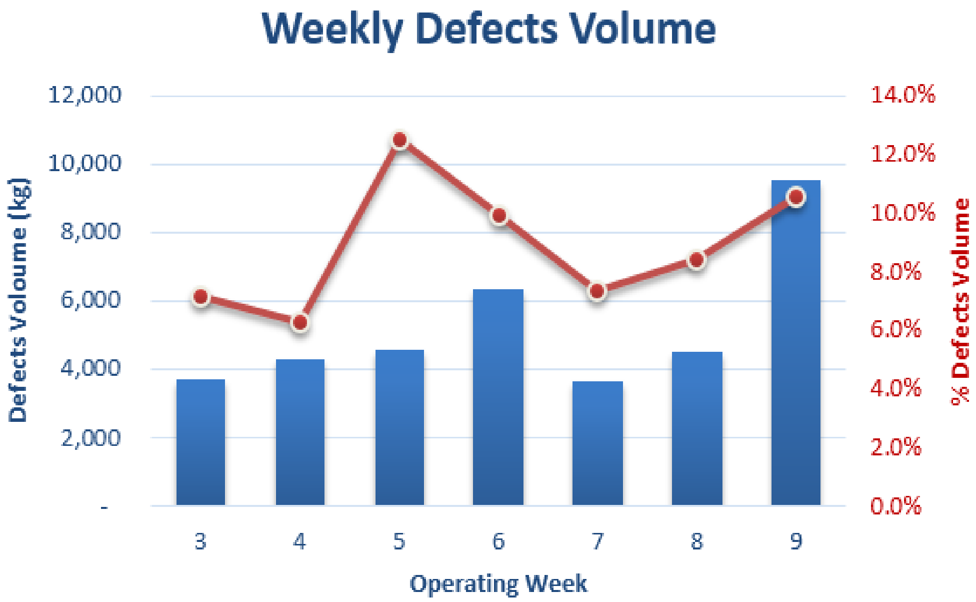


Figure 3 Weekly Defects Volume in kg and Percentage

As shown in **figure 3**, defects vary greatly with its production volume. On an average week, it has around 3500 to 7000 kg of pipe defects; this contributes to roughly 8-10% of the actual production volume. Cumulatively, this will be around 270 ton per year or more than 8 million baht in opportunity cost.

1.3 **Objective of Thesis**

The main objective of this research is to reduce the waste defect from the PVC pipes extrusion line of the case study company by implementing a DMAIC Six Sigma method.

1.4 Scope of Thesis

The scope of this research will be focusing on reducing the PVC pipes' defects created within the company. The definition and example of plastic defects are given in the earlier section. Although successful implementation of this research would greatly help the company in reducing waste production, some data gathering process and the implementation process can only be done for a few weeks to minimize the overall negative effects they will have for the production line. This is the request from the management of the company.

Pareto Analysis performed the later chapter will pinpoint several factors that contribute to 80% of the defects production; as such, these factors will be the main area of study for this research. Nevertheless, the primary focus will be specifically on reducing the most prominent factors of the top 80%.

There are limitations regarding the some specific factors as well. Factors revolving around new equipment and raw material purchase, where possible solution include but not limited to new supplier selection, require long implementation time and high investment cost, both of which are not preferable by the managing director of the company. As a result, the primary scope is limited by investment potential as well.

1.5 Expected Benefits

For the company, the expected benefits of this research is:

1. Reducing Defects and Waste – The main objective of this research is to implement strategy to reduce manufacturing defects and waste. This also include
2. Financial Gain - There are at least 8 million baht worth of opportunity cost in defects that can be minimized.
3. Manufacturing Process Improvement – By reducing defects and wasteful product, the overall process can be improved and thus improving the competency of the company.
4. Generate Framework and Structure – As the company operates in entrepreneurial working environment, the need to generate framework and structure will help improve the productivity and transparently of the operating processes. While this research mainly focus on plastic extrusion, further application can be applied to the company’s injection molding process, cutting process, screening process, and other business operation processes as well.

1.6 Methodology

The main methodology will be the DMAIC, as suggested in the introduction and methodology section. The five stages of DMAIC will help in deriving the roots cause as well as identifying the methods to prevent the defects problems.

Define Phase

The Define Phase will delve into identifying the important factors that may contribute to large waste defect within the company's plastic pipe extrusion line. Primary data collection and analysis will be conducted to study these factors. In addition, the overall company's plastic pipe manufacturing process will be mapped through the Input-Process-Output (IPO diagram). Then, the identification of risk factors that cause defects through the use of Cause-and-Effect diagram will be used. Then, each factor will be quantified and qualified, through the Pareto diagram quantitative analysis tool, to determine the primary risk factors that lead to manufacturing defect.

Measure Phase

The Measure Phase features analysis of causes that contribute to defects of the risk factors determined in the define phase. Using the Cause-and-Effect Matrix, each cause will be given a relevancy score depending on how much the cause relates with defects production. After the top percentage of the causes are selected, the Failure Mode and Effect Analysis (FMEA) will be performed to study the reliability of each causes through commonly used parameters, namely severity, occurrence, and detection. FMEA analysis will categorize each cause as key process input and rate the input with a risk priority number (RPM). Next, a Pareto analysis will filter the top percentage of key process inputs that contribute to majority of defects production. These identified, rated and weighted key process inputs will be used in the next phase where they will be quantitatively analyzed.

Analyze Phase

The Analyze Phase will take the primary Key Process Inputs that have high risk priority number from the previous phase into quantitative analysis. By determining the correct variations of key process inputs from employee interviews and surveys, a Design of Experiment (DOE) will be performed. Then, experiment runs at different variations of factors and levels will be conducted for in a two months period. After enough data is collected through experimental runs, quantitative tools such as ANOVA will be used to analyze and evaluate the optimal variation of the key process input. The ANOVA analysis will seek for interactions between each key process inputs to determine the most optimal standard factors.

Improve Phase

The Improve Phase will focus on the implementation of optimal setups determined by data from the analysis phase. Through implementation and feasibility study, post-improvement data will be collected: The identified optimal setups will be repeated and reran again in a one month timeframe to ensure that the data obtained during the design of experiment and analysis of variance are accurate and that the optimal setups are repeatable for a long run. Cost analysis will be performed to determine the potential annual cost saving from defect reduction within the company for this research.

Control Phase

The Control Phase will seek for a method to sustain the benefits setup in the previous phase. In this phase, post-implementation data will be analyzed and suggestions to control the change will be suggested. Control phase will considered detection of potential threats critical to implementing the problem as well as means to sustain and prevent the threats. Finally, summary of the positive change derived from the research as a comparison between pre-implementation and post-implementation will be discussed.

Chapter 2: Literature Review

This chapter discusses theories, literatures, and research articles related to the topic of this thesis:

2.1 The Seven Wastes

The Toyota Production System classifies '*muda*' (or more generally known as 'wastes') into seven types (EMS Consulting Group, 2003). Although they are normally recognized as part of lean manufacturing, the seven wastes were traditionally used for studying process flow and identifying process waste (Sullivan, et al., 2002). The seven wastes include:

- Overproduction
- Transporting
- Excess Motion
- Inappropriate Processing
- Waiting
- Inventory
- Defects

In this document, the core focus will be specifically on 'defects' production. Defects reduction is the more common form of seven wastes as it can be easily measureable in term quality and quantity, the later in form of both weight and cost. The approach to tackle any of the '*muda*' varies greatly as there are many tools and techniques developed to achieve so, including but not limited to: Total Quality Management (TQM), Total Productive Maintenance (TPM), Value Stream Mapping (VSM), Just-in-time Production/Delivery (JIT), and many more (Anand & Kodali, 2010). Furthermore, Peter Scoltes (1998, pp.5-20) has analyzed sources of problems that commonly occur in a process, all of which are relevant to either knowledge insufficiency, error and mistakes in execution, lack of preventive measures, unnecessary steps in process, variation in inputs, or variation in outputs.

2.2 Six Sigma

Similar to lean manufacturing, Six Sigma is another unique concept developed to specifically tackle wastes. Six sigma studies the interaction between factors, such as Man, Methods, Machines, Materials, Measurement, and Environment, and their relevancies to waste production and process degradation (Allen & Laure, 2006).

Furthermore, the Six Sigma concept can be interpreted differently depending on the people who utilize it and their interpretation toward quality and process improvement. Six Sigma varies in terms of definitions from such as the statistical terms of an extremely small number (3.4 defects per million - DPMO), to techniques to increase process efficiency, to improvement methodology to optimize production and minimize waste (Kanakana, et al., 2010).

Schroeder, Linderman, Liedtke, and Choo (2008) categorized the elements of Six Sigma and its definitions into the four main structures:

1. Parallel-meso Structure - Deployment of Six Sigma as 'extra creations' that will operate as external structure rather than directly changing the firm's traditional ways of operating.
    a. Strategic Project Selection – A mechanism to help derive Parellel-meso Structure's multilevel projects by filtering out Six Sigma projects that do not have significant strategic or financial implications
    b. Leadership Engagement – Mechanism that utilizes higher management team's involvement in delivering several multi-level Six Sigma project through enhanced authority, smart allocation of resources, and other means that may remove barriers to Six Sigma projects completion.
2. Improvement Specialists – Improvement Specialists are experts on Six Sigma within the firm who will help instruct and train employees as well as control and implement Six Sigma projects to ensure successful completion. They may also be known as 'Six Sigma Black belts'.

3. Structured Method – A method of implementing Six Sigma, such as the 'Plan-Do-Check-Act' diagram or the DMAIC diagram. Its usage is to ensure standardization of the Six Sigma adoption within the firm.
4. Performance Metrics – A performance management metrics used on several multilevel of the organizations to guarantee successful implementations.
    a. Customer-oriented metrics – One of the key performance metrics that focus on what customer wants such as by identifying Critical-to-Quality (CTQ) parameters for increased customer satisfactions. Customer requirements have been used in many Six Sigma projects to set the projects' ultimate goals and objectives.
    b. Financial metrics – Another key performance metric that gauges what some firm deems as the most significant factor: profits and cost. This factor is highly quantifiable and is often used to justify the success of Six Sigma projects.

To make the concept more practical, many frameworks have been developed to standardize the Six Sigma itself. One of the more popular framework to Six Sigma is the Design, Measure, Analyze, Implement and Control process, or commonly abbreviated as DMAIC.

Six Sigma has been solidly proven to produce benefits towards firms' profitability; however, the benefits will only be much more transparent over long period of time, for example 3 to 4 years after adoption (Swink & Jacobs, 2012). Swink and Jacobs also reported that notable benefits towards profitability include indirect cost efficiencies and influences on sales growth.

In addition, usage of Six Sigma is widespread over large ranges of businesses in manufacturing industry. For example, Motorola accredited benefits of having applied Six Sigma in lowering defects rate, Dow Chemical mentioned saving in capital expenditures, and General Electric reported improvement in turnaround time (Kwak & Anbari, 2006). Six Sigma's usage is also popular in other well-known sector such as Financial, Healthcare, and Engineering & Construction.

2.3 DMAIC

As aforementioned in previous section, the DMAIC framework is a tool developed to standardize and make the Six Sigma implementation easier, in term of communication and practical application (Vinodh, et al., 2011). Conceptualized in **table 1**, each steps of the DMAIC is as follow.

Table 1 DMAIC's Summary

DMAIC Phase	Explanation
Define (D)	Defining the problem or the causes of the problem. This is a project initiation phase that set baselines on how the rest of the framework will be implemented.
Measure (M)	Setting up measurable means to the project. This phase may require preliminary data collection and feasibility assessment on project performances.
Analyze (A)	Analyzing, identifying, and validating the root cause of the problems. This involve rigorous quantitative data analysis.
Improve (I)	Improving the process using data and information obtained from the previous phases.
Control (C)	Controlling and ensuring that solution found and implemented will be long-lasting and sustainable.

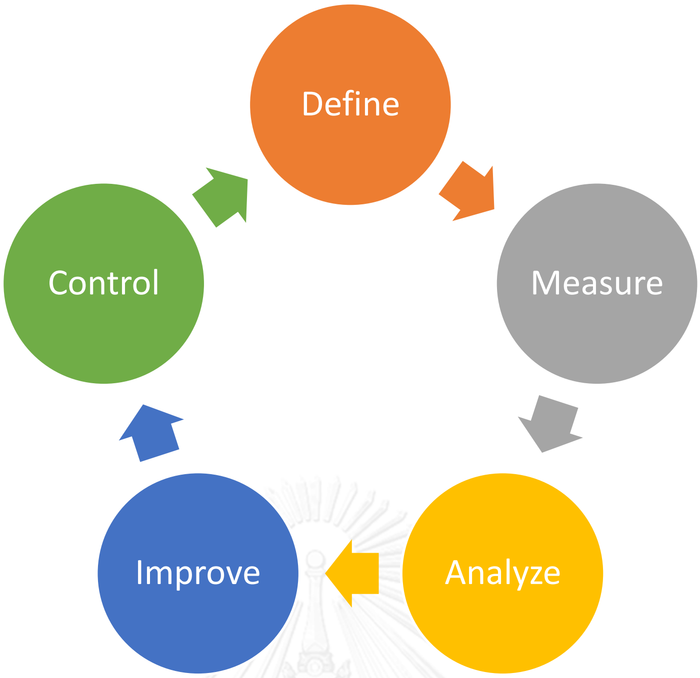


Figure 4 Six Sigma's DMAIC

To summarize, the DMAIC is a tool to help identify the cause of a problem, develop methods to reduce that cause, and implement the developed methods. The DMAIC itself is a continuously repeatable process. In other words, through rigorous and repeated pursuit of the DMAIC framework, an optimal process can be realized, that is, minimal waste production is reached.

2.4 Tools for DMAIC

Cause-and-Effect Analysis

The Cause-and-Effect Analysis, or oftentimes referred to as the Ishikawa diagram or the fishbone diagram, is a visual tool to illustrate causes and effects of a specific event. Causes are usually group into general categories including Man, Machine, Method, Material, Measurement, and Environment. Example of Cause-and-Effect diagram is shown below.

- Man – Causes involving human in the process
- Machine – Causes involving any equipment and tools required to complete the process
- Method – Causes involving procedure, policy, or regulation that is required to complete the process
- Material – Causes involving raw materials in the process
- Measurement – Causes involving data and how the data is used to evaluate the process
- Environment – Causes involving external conditions such as time, temperature or culture surrounding the process

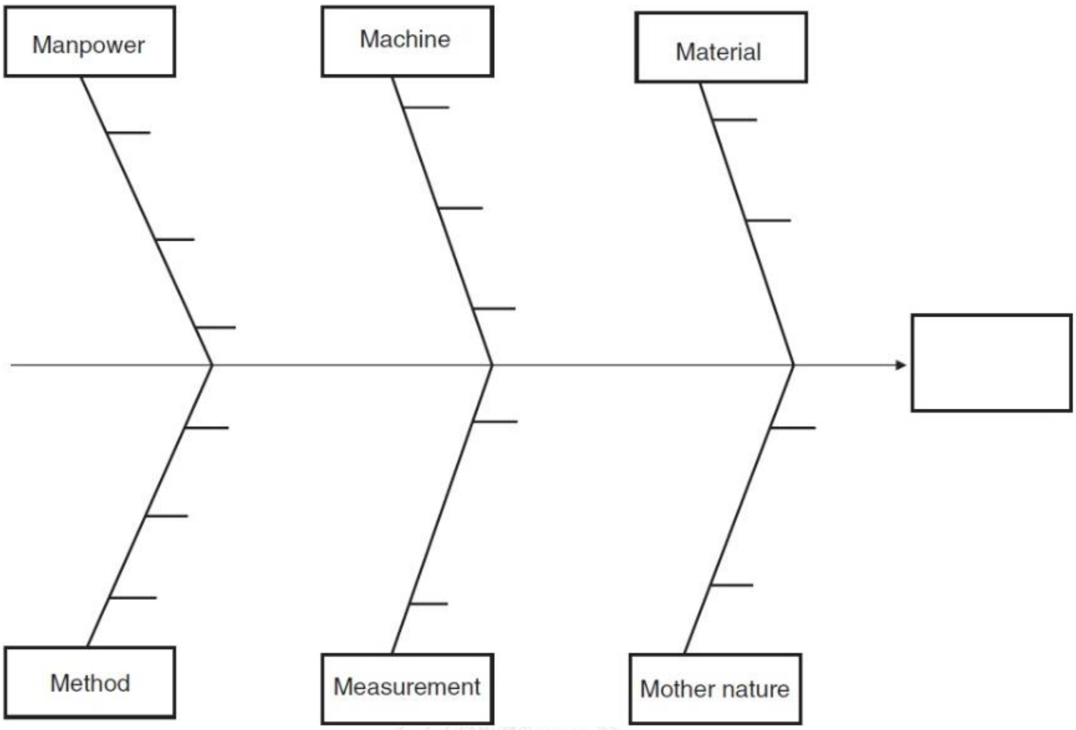


Figure 5 Example of Cause-and-Effect Diagram

Pareto Analysis

The Pareto Analysis is an analytical tool to identify and prioritize possible courses of action. The general approach to Pareto Analysis is the '80:20' split, which assumes that 80% of the problems identified are direct results of only 20% of the causes. Normally, this tool is used in combination with other analysis tools such as the Cause-and-Effect Analysis or the Pareto Analysis. The drawback of Pareto Analysis is that it excludes smaller problem that could potentially become dangerous in the long term.

FMEA Analysis

The Failure Mode and Effect Analysis (FMEA) is one of the tools used in the DMAIC process. According to Nannikar, Raut, Chanmanwar, Kamble, and Patil (2012), there are six steps to preparing the FMEA analysis:

- Determine the potential failure mode

This step addresses potential failure mechanism and failure mode distributions within the identified production scope. It covers answers to the question ‘What can go wrong?’

- Determine the potential effects of the failure mode

The effects of failure mode can be categorized by two parts: as a part (such as subassembly) and as a whole (the system). Some research uses customer satisfaction as the main effect of failure mode, which can be used as ranking criteria for severity effect. Depending on the nature of the research, effects of potential failure mode can also be relevant to wastes, defects, time and cost.

- Determine the potential cause of the failure

This step involves the examination of the most probable causes associated with the failure modes, such causes may include design problem, operation problem, time management problem, preventive measure and maintenance problem, and others.

- Determine current control/fault detection

This step investigates the current criteria used by the organization to prevent the causes from happening. It involves reviews of guidelines, detection methods, recovery methods, safety manuals and etc.

- Determining the risk priority number (RPN)

Risk priority number is a quantifiable analysis given to prioritize all potential failure modes.

RPN = Severity x Occurrence x Detection

RPN is defined by severity, occurrence and detection, each of all is rated at scale from 1 to 10 and with 1 being the least important. Failure mode with severity at 10 is considered to have the worst effect as opposed to the failure mode with severity at 1. Similarly, occurrence at 10 has a high likelihood for failure mode to happen and detection at 10 means that the failure mode is least likely to be prevented and detected before it reaches end-user. Once RPNs of all failure modes are quantified, a Pareto Analysis can be performed to distinguish the most important modes.

- Preparation of FMEA worksheets

Using analysis from the previous steps, all information is gathered within the sheet and actions can be done to reduce the risk identified. The following is example of how FMEA worksheet can be done:

Table 2 FMEA Sample

Item	Key Process Input	S	Potential Cause	O	Current Control	D	RPN	Priority
1	Factor A: Machine Maintenance	10	Lack of maintenance schedule cause machine breakdown and lead to waste and defect	4	Schedule weekly machine checkup and bi-weekly maintenance process.	5	200	High
2	Factor B: Employee's Carelessness	3	Employee's carelessness in multiple process lead to miscommunication, operation error, and process redundancy.	4	Have quality assurance team monitor line worker and other employees dedicatedly.	5	60	Low

2.5 Applications of Six Sigma and DMAIC

Several researches have investigated the Six Sigma's DMAIC. Pranckevicius, Diaz, and Gitlow (2008) studies the '5s' approach of DMAIC using SIPOC (supplier anaylsis) and "Voice of the Customer" (VoC) analysis. The 5s involves study of Seiri (Organize), Seiton (Order), Seiso (Clean), Seiketsu (Standardize), and Shitsuke (Personal Desclipline). Using plastic extruding and packaging company as study baseline, this research shows how the whole supply chain can be integrated into waste and defects reduction. By tackling the 5s through analyzing factors identified from customers, suppliers, and internal employees, optimization of process resulting in reduction in unwanted product variation and increase in cycle time were reached.

There are many criteria to define quality process during measure phase of the DMAIC. Haefner, Kraemer, Stauss, and Lanza (2014) identified the following as methods of process analysis and quality management:

1. Business Analysis Process – Approach the concept of quality management by evaluating weakness and identifying opportunities for improvement. Its objectives are often measurable such as costs, time and defect rates.
2. Value Stream Mapping (VSM) – This method critically involved customer controlled value stream, such as by creating a process that tries to generate most values for customers: for example lowering lead time.
3. Process Failure Mode and Effect Analysis (FMEA) – This is a process revolving around identifying and quantifying risk factors, or risk priority number (RPN), that will help determine causes leading to bad quality management.
4. Process Mapping – A visualized tool to map the flow of process involving input and output variables.
5. Stream of Variations (SOV) – A math model used for analyzing performance prediction of manufacturing processes with multistage operation platform. It usually involved the use of dimensional variation and dimensional variation to layout key operational sequences.

Narasimha and Rejikumar (2013) have done research on plastic defects minimization of a High-Density Polyethylene (HDPE) pipe extrusion line. The research categorized defects into eight main points: uneven wall thickness, off-center, dimension variation, sink marks, scratching, discontinuity, bend, and poor surface finishing. Using Pareto Analysis, inappropriate operational parameters are determined as root causes of the defects. The factors that are considered to be relevant to high defects extrusion included vacuum pressure, screw speed, take-off speed and temperature profile, where temperature was identified as the most crucial factor. Through the design of experiment process and analysis of variance process, using MiniTab program, optimal parameters are found, and variations in output was reduced. In the end, the research improved the operational procedure by reducing HDPE pipe defects by over 85%.

In identifying the optimal process parameter in manufacturing, the Taguchi optimization method has shown an increase in usage recently (Wang, et al., 2014). This method involves three design steps to identifying factors and parameters for statistical design of experiment (DOE). Firstly, system design revolves around understanding the engineering application of current manufacturing and production process. Then, parameter design will identify the optimal number for parameters revolving around the said manufacturing and production process in order to obtain quality improvement. Lastly, tolerance design calculates how much tolerance, or variation from the optimal value, can the current manufacturing and production process hold. This research features the study of Taguchi method on a plastic valves injection molding company, whereas the varying-parameters it studied are number of valves gates, gate size, molding temperature, resin temperature, switch over by volume field, switch over by injection pressure, and curing time, and the end-parameters it studed are resin vicosity, plastic curing percentage, and compression strength.

Chen, Chuang, Hsiao, Yang and Tsai (2009) have demonstrated of the design of experimennt (DOE) technique can be applied to waste reduction in plastic manufacturing industry. Started by analyzing the basic property of plastic, including density, percent fiber, tensile strength, tensile flexural strength, elongation, heat distortion temperature, and mold shrikage, the reseach then seek to setup analytical experiment using plastic melting temperature, mold temperature, inject speed, and packing pressure. The study classified three variations for each of the four factors, and, by picking interesting combinations, a total of eighteen unique runs were identified; these runs were both tested by simulation and by real experiment. The variables, sigma X and sigma Y, were used to define distortion in X and Y axis respectively, whereas the lower the number, the more desirable the outcome. Lastly, by using ANOVA and normal probability plot, the optimal setting for both simulation and experiment that have the lowest distortion value, and therefore highest desirability value, are found.

Kanakana, Pretorius, and Wyk (2010) have also used the DMAIC framework in their research to increse the throughput rate. In a more customer-orientied project, they used the define phase to outline customers' needs and requirements in order to identify opportunities. In this phase, Pareto analysis and process value stream mapping is used. The measure phase concern with measurement system analysis (MSA) to identify critical cost to quality (CTQ) as major parameters to measure the output. The analysis phase used cause-and-effect analysis and statistical tools such as ANOVA and regression analysis to verify factors that cause output variation and error. The improve phase utilized both statistical and non-statistical tools focusing around design of experiment (DOE) and comparative hypothesis F and T test. It also used the Taguchi optimization method aforementioned in Wang, Kim and Song (2014)'s research. Finally in the control phase, this research used Thinking right, Managing the process, Valuing workers, Leading improvements and Counting the change as five core to enforce sustainable quality.

A research by Camposeco-Negrete (2013) focused on using the quantitative ANOVA method to determine the optimal parameters for cutting/machining tools to save energy. This cutting machine has three unique setup parameters: depth of cut, feed rate, and cutting velocity, all of which have three levels of variations. Using the design of experiment approach, a total of 33 or 27 total experiment numbers are required, a concept called ‘Orthogonal Arrays’. The three levels of variations for each parameters are found through studying and analyzing the current operational procedures employed by the company. Nevertheless, by eliminating obvious wasteful experiments to reduce time and cost, only nine experiment numbers are selectively pinpointed. Each experiment number is run three times to collect the average value for computation and further analysis. Values for computation in this research include surface roughness, mean power and energy consumed and mean cutting power and energy consumed. Furthermore, while measuring each experiment run, the S/N ratio, or Signal-to-Noise ratio is also introduced in addition to the mean to help measure the mean as well as reduce the mean’s variation and deviation from desired target value. Next, by plotting the main effects plot for means and S/N ratio, the trend in effects of each factors can be visualized. Finanlly, Analysis of Variance (ANOVA) is performed at confidence level of 95% (α=0.05). Through the P-value testing, ANOVA test found that factor such as cutting velocity is not relevant to power consumption, while in test for energy consumption, all factors can be significant. In practical term, the author of the research has explained that level of power consumption is directly related to how the cutting machine was built. All in all, Camposeco-Negrete (2013) concluded from many researches that each factors have different level of significances when compared with one another, and the term “percent of influence” exists. In the end, after determining the relevant factors and their contribution to low energy and power consumption, an ideal setup parameter can be found. To validate the findings, a confirmation test is repeated to affirm the optimal setup combinations.

In another literature, the Failure Mode and Effect Analysis (FMEA) has been used to study and minimize the seven wastes (Souza & Carpinetti, 2014). By rating and weighting causes of waste by seversity, likelihood, and effectiveness in detection, a priority number is given to each causes; thus allowing prioritization of waste management strategy. After all causes are rated, pareto analysis can be performed to identify top 20% causes that contribute to 80% of the waste production in designated area of study.

Chakravorty (2009) has established six steps to successful Six Sigma model. The first Performing Strategic Analysis is an overview analysis of the firm's ability to deliver the Six Sigma program. Through studying the firm's background, current situation and competency, research has shown that some firm may have qualificaiton and knowledge in the Six Sigma program but still lack the champion and experience to deploy it successfully. To deliver, commitment and willingness, continuous planning, training, and management's availability are important. The second step, Forming Cross-Functional

Team, concerns the selection of the cross-funcitonal team to impliment the Six Sigma program. Started with selecting members with specialized technical skills, the newly established cross-functional team should include six sigma researcher, champion, and management to push the program forward. Within the team, there should also be a leading member to track budget, manage timeline, and delegate resources. The leader is responsible for process planning, implementing change, establishing KPIs, and following up projects. The third step is *Choosing Improvement Tool*. Some of the popular Six Sigma programs include Total Quality Management, Business Process Re-engineering, Team Building and etc. Chakravorty suggests reducing the Six Sigma program to the core value will make the program more efficient; as such, statistical tools such as histrograms, statistical process control, pareto analysis, regression analysis, and design of experiment are nescessary. In addition, the research explains that there are four levels to deliver this step. In the first level, the Six Sigma's executive overview must be communicated to top management and core competency member of the program on day one. Then, in the second level, the Six Sigma champion must be specifically informed, most of the time being the managers and directors. In the third and fourth level, the green level and black level Six Sigma members must be addressed accordingly. Finally, to complete the third step, other criticla efficiency improvement theory such as the Lean Theory can be enforced. Optionally, the DMAIC approach can also be pursued. In the fourth step, the *Executing High-Level Process Mapping and Prioritizing Improvement* is highlighted. In the step, process flow mapping is studied and redesigned to fit with the program's core value identified earleir. By doing so, redundant steps, outdated information, long and confusing workstep can be reduced.

After reviewing this process over and over again, wasteful activities can be minimized and cost-saving opportunities/revenue generations are seized. However, additional approvals, inputs, and comments from authorities such as management and president may also be nescessary to drive the change. The fifth step, *Developing Detailed Implementation Plan*, involves a six activities implementation. The first activiy is micro-managing enterprise's department improvement. Each department in the company is to establish a small team. Then, during the second activity, a team leader of each team is selected. The team leader needs both specialized technical skills as well as human skills to lead. Afterward, several project leaders can be selected to lookover many of the newly created team at once, to ensure successful team development. In the third activity, each team is required to draw and redesign the process flow in their respective team and in the fourth activity, a clear communication scheme must be executed throughout the entire department to ensure that everyone in the deparment view the implementaiton as both feasible and acceptable. Next, in the fifth activity, the entire company's management meeting is set to ensure that improvement process can run continuously and in the sixth step, training process is designed to make sure that the overall program can be sustained in the long run. In this step, change management to display management's commitment is nescessary as research has shown that employees seldom question the purpose of the change as well as doubth its purposes. Lastly, the last step is *Implementation, Documentation and Revision*. The process involves how to successfully maintain the change program identified from the previous five steps. For example, in order to launch the DMAIC methodology, the project leader is required to revise the whole process flow over and over again to make sure that there is as little redundency as possible. As such, time management is also greatly nescessary as each stage of the DMAIC methodology runs at different rate and pace as well as require careful consideration and monitoring from the project leader. Furthermore, to sustain the DMAIC, training programs should be consistenly enforced as the DMAIC methodology runs in cycle repeatedly. Lastly, both bottom-up and top-down approaches are executed simutaneously, including having engineers and technicians comment on the process as well as having management consider on the strategic decision making process to ensure successful implementation of the Six Sigma program. A diagram illustrating the six steps identified by Chakravorty is shown in the next page.

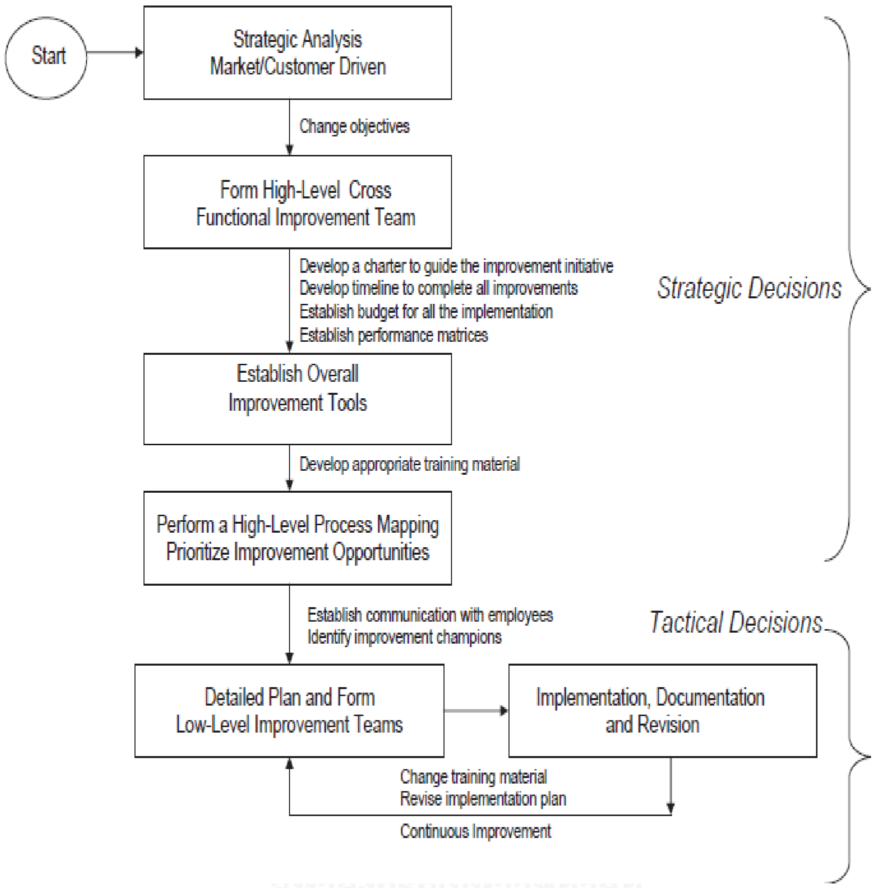


Figure 6 Six Sigma Implementation Model (Satya S. Chakravorty, 2009)

In regarding the recycling of waste materials in plastic extrusion process, Ladany and So (1994) discussed how reusing recycled plastic materials in production not only help reduce the cost but also reduce the yield. The reduction in yield is mainly attributed to plastic deteorerations and uniform melting indexes. The research concurs that continuous usage of reground waste materials deteriorate the melting index of polymer and that there is an optimal profit per batch. Laday and So concluded that after the 15th reground batch, the profit per batch will be insensitive to further change. As a result, when considering the cost of production, depending on where the plastic is sold, how much it was bough, and the quality of the original virgin resin, at some point it can be optimal to just sell the reground resin rather than reusing them.

In a manufacturing research about setup times and cost, time reduction usually imply cost and resource reductions (Allahverdi, et al., 2008). In addition, Dang (2014) has made a research to study how different types of simulation frameworks can help optimize the process parameters for plastic manufacturing protocol. Using the different process simulation methods, both frameworks are tested for accuracy and deliverbility. Nevertheless, the research concluded that regardless of simulation frameworks used, optimization modeling methods possesss several limitations when compared with actual physical experiments, as the prior is prone to error from simplification and approximation mistakes. In the end, to test for optimized setup parameters for resource and time reduction, real physical experiment is still the main preference, with simulations usable as supporting and verifying framework.

Karasu, Cakmakci, Cakiroglu, Ayva, & Demirel-Ortabas (2014) discusses how the Taguchi's method on Design of Experiment (DOE) can be used to reduce the changeover time in plastic manufacturing process. The research introduces a process called "Single Minute Exchange of Dies" (SMED), which, as the name imples, is a technique that allows setup and changeover time to

be reduced to less than 10 minutes. Prior to SMED, the research shows that process preparation, including materials and tools checking, contributes to over 30% of the setup times, machine calibartion contributes to 15% and trial runs and adjustment contributes to 50%. The research's DOE features four factors, each with three variables; resulting in a total of 34 possible experiment runs. Nonetheless, through the use of Taguchi's method and elimination of obvious non-constructive experiments, the run can be minimized to nine run. As pre-SMED study has suggested, DOE will help determine how to reduce 15% contribution of the trial runs to minimize changeover time. With additional implementation of 5S and lean management, the total changeover time was reduced from 93 minutes to 61 minutes, a constructive change of over 33% reduction.

Yang (2013) classifies several key practices that help improve manufacturing capability: production planning practice, quality management practice, human resource management practice, capacity management practice, supplier relationship management practice, process maturity management practice, project complexity management practice, time management practice, and team management practice. Over thirty key advices to achieving better manufacturing capability, there are crucial advices that align with other aforemention researches such as implementation of defining quality objectives, implementation of six sigma quality improvement, declaring quality management policy, setup and changeover time management, process standardization, variation reduction, continuous improvement, process control and resource reduction.

A recent research article also discussed the usage of Design of Experiment analysis on water nozzle and waterjet machines (Dittrich, et al., 2014). With five parameters and two variables each, the control factors of pressure, nozzle speed, abrasive flow rate, offset distance and impact angle were identified for further investigation; these are setup parameters identified as significant to the process in the research. Using the fractional factorial design method, the total designs is reduced from 25 to 25-1 or 16 instead. Then, Pareto Chart of Standardized Effects is used to determine which of the single and two-factor interactions are significant and less important.

Dabade & Bhedasgaonkar (2013) also used the Design of Experiment and Analysis of Variance method to determine optimal setup parameters for defects reduction in casting industry. The research focused on four process parameters, with one parameter at two levels and three parameters at three levels. The research utilized L18 orthogonal array that uses 18 experiment runs. Through the Main Effects plot, one of the four process parameters was identified as less important to the defects reduction process and three optimal parameters were selected. In addition through ANOVA analysis, material process simulations were also performed to generate visualized model for process optimization.

Additionally, Singhtuan and Prasartthong (2012) have also done a similar Design of Experiment and Analysis of Variance method to reduce defects in production. Three process factors were obtained from product investigation of the defected outputs as well as from studying the setup processes and parameters. Each of the identified factors has two levels, hence contributing to total of 2^3 or 8 experiment runs. Before running the analysis of variance, hypothesis testing was performed to confirm that all of the three factors actually affect the response and interact with one another. Moreover, the Normal Probability Plot and Histrogram analysis showed that the experiments ran in normal distribution and were independently distributed. Finally, main effect and interaction plots revealed which the optimal factor. This design of experiment and analysis of variance method reduced the operation cost by over 10% annually. One of the noteworthy parameters of this research is cleaning time. While high level cleaning time (longer cleaning time) showed least defects production; it also led to other additional cost as it will consume more operation time and have incremental cost suc as labor, facility and infrastructure. In conclusion, though DOE and ANOVA may dictate optimal setup parameters (or cost reduction) in a selected environment, it may or may not reflect the actual cost reduction when factored in additional costs from new process improvement implementation.

In regarding the Improve phase and Control phase, Tenera and Pinto (2014) suggested that for case where more than one solution are identified for the Improve phase, framework to prioritze solutions can be applied before solutions implementation. Several criteria to consider whether the solutions are viable include scope, integration feasibiltiy, schedule management, and project management risks. In addition, other criterias that can be considered as well include implementation cost, implementaiton time (quickness), problem resolution and impact level, and implementation risk. Finally for Control phase, Tenera and Pinto proposed techniques such as internal audit, training actions, manuals updating and periodic measures to ensure smooth six sigma implementation.

To sustain change after Improve phase, Chow, Finney and Woodford (2010) proposed using the same six sigma framework on training to increase labor efficiency as well as precision in controlling the machine. According to Kumar and Antony (2008), the following in **table 3** are barriers that hinder quality improvement (QI) initiatives within some organizations:

Table 3 Barriers to implementation of quality improvement initiatives in SMEs (Kumar & Antony, 2008)

Barriers to implementation of QI	Count	Percentage
Availability of resources	42	71.2
Lack of knowledge	35	59.3
Lack of training	33	55.9
Internal resistance	32	54.2
Poor employee participation	27	45.8
Inadequate process control techniques	24	40.7
Changing business focus	21	35.6
Lack of top mgmt commitment	18	30.5
Poor delegation of authority	17	28.8
Poor supplier involvement	16	27.1
Poor project selection	5	8.9

Out of the total pool of company surveyed, 71% mentioned that resources is the main factor hindering quanlity improvement. This may include financial resource, human resource, time, and other tangible resources. Other than that, other barriers to quality improvement include lack of knowledge, lack of training, internal resistance, andn poor employee participiation, all of which are factors related to human resource that can be prevented with proper control and training process. Kumar and Antony further explained that firms that are successful in lowering these barriers are more likely to perform better in other operational metrics such as scrap reduciton, delivery time reduction and increase in productivity. Other benefits of the improvement on operations may include reduced expenses, increased outputs and competitiveness, enabled smoother flow, lower inventory, faster deliveries, and higher margins on orders above minimum (Allahverdi & Soroush, 2008).

Chapter 3: Define

3.1 Introduction

The define phase revolves around analyzing which factors are the most prominent amongst those that create defects in the case company. In this chapter, the Cause-and-Effect analysis, Risk analysis, and Pareto analysis will be performed. The analysis approach involve both quantifying and qualifying different sources of defects through internal survey and manufacturing data collection. The most prominent factors that fit the scope and limitation feasibility will be prioritized and selected as the factor of study.

To begin the research, the following is the Input-Process-Output (IPO) diagram explain how the pipe extrusion process at the company is done:

Table 4 Input-Process-Output (IPO) Diagram on the Company

• Plastic Resin
  • Virgin Resin
  • Scrap Resin
• Additives
  • Colorants
  • Stabilizers
  • Calcium
  • Lubricants
• Input Temperature and Pressure
	• Compound Mixture
	• Extrusion
	  • Machine Adjustment
	  • Cooling Down
	  • Cutting
	• Printing
		• Conformance Pipes
		• Defects
		• Wastes
		  • Burnt pipes

Input

As shown in diagram above, most of the variations in the IPO diagram came from input. There are two main variations in the plastic resin, being virgin raw resin and scrap resin. Pipes from the company are manufactured using polyvinyl chloride (PVC) resin. Virgin resin varies in quality and melting indexes (k-value) depending on different types of suppliers. Scrap resin is resin derived from grinding defects plastics. The company also uses different type of additives to help control the compound mixture. Colorants are used to add color to output pipes; namely blue, gray and yellow. Stabilizers allow plastic and compound to melt uniformly through the extrusion process. Calcium helps improve the strength of pipes while at the same make the cost more economical.

Process

Compound mixing process depends on incoming order. As explained in earlier section, the company manufactures pipes at different thicknesses and diameters; because of that, it oftentimes need to adjust its extruders and molds. Adjusting mold and extruders frequently also lead to more time consumption in cleanup and setup time. Material compounds are inserted to the extruder, melted as the screw carries them from then input toward the output, and extruded out into shape at high temperature through mold of desired thickness and diameters. Finally extruded pipes are left to cool down, cut into salable sizes, and finally printed.

Output

At the company, outputs are categorized into three parts: conformances, defects and wastes. Usually, wastes are burnt pipes that are no longer usable or reusable; therefore, they are very much thrown away afterward. Defects are rarely subject to rework; oftentimes, defects are granulated back into scrap resins, and later reused in another extrusion process. Conformance pipes are stored and packaged into salable products.

Overview

Using the IPO diagram, the company's pipes extrusion process is outlined in table below:

Table 5 The Company's Plastic Pipes Extrusion Process

Step	Description
1	Check order
2	Select machine and mold necessary to manufacture the order
3	Check whether cleaning machine, cleaning mold or installing new mold is necessary
4	Mix raw materials to compound
5	Insert the compound into plastic extruder machines
6	Adjust the machine setup including temperature and pressure
7	Start the extrusion process
8	Machine melted compound as they flow with the screw's rotation
9	Machine extruded pipes out into molded shape at high temperature
10	Wait for extruded pipes to cool down
11	Cut pipes into required length for sales
12	Quality check the pipes
13	Print company's logo and other manufacturing requirements onto the pipes
14	Quality check the printing process
15	Store the pipes

3.2 Cause-and-Effect Analysis

To identify and prioritize the factors affecting manufacturing defects, the Cause-and-Effect diagram is used to determine **the** relevant risks associated with defects creating in the extrusion process. For manufacturing business, the Cause-and-Effect diagram studies manpower, machine, material, method, measurement, and environment. According to the managing director, most of the factors revolve around machine, material, and method, all of which are mainly due to that the company is an entrepreneurial company with little standardization.

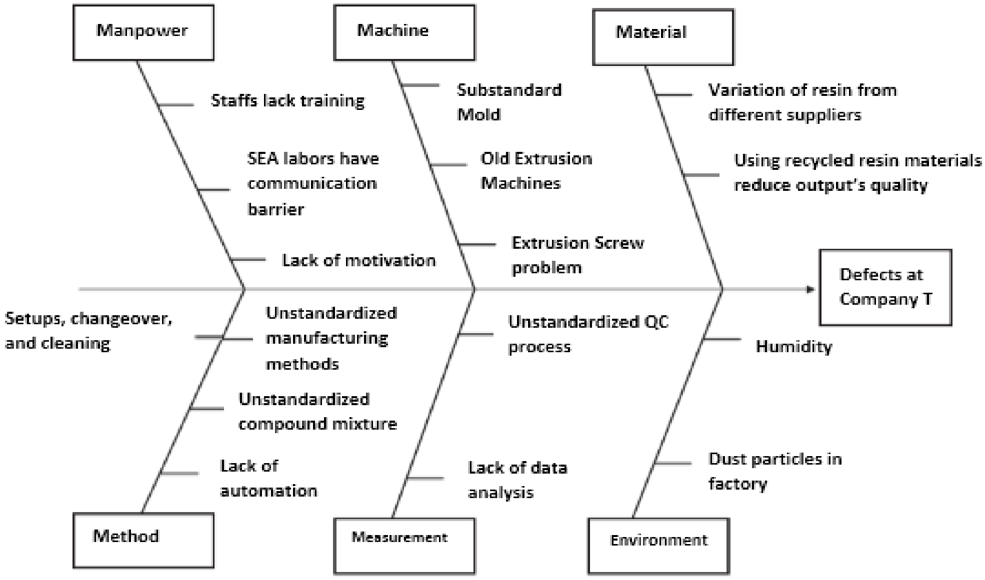


Figure 7 Cause-and-Effect Diagram of Manufacturing Defects in the Company

Manpower

The Manpower cause mostly revolve around complexity in handling the factory workers. As aforementioned, factory workers at the company are mainly undereducated labor workers recruited from all around Southeast Asia. Although the company has enforce production standard and adequate training, turnover rate, lack of motivation, carelessness, and communication and language barriers between management and labor workers have consistently resulted in unfortunate wasteful production.

Machine

Machine in this sense are objects apart from raw materials that help transform the input into the desired output. For the company, machine refers to the extrusion machine and its components such as extrusion screws and mold. The company does not use all of its machines at the same time and there are some machines that are used majority of the time. Most problem in this factor comes from the quality of the machine itself. For example, some machine was purchased long time ago or purchased second-handed and some of the screws and molds were not taken care of properly and have deteriorated in quality.

Material

Materials include all physical inputs such as resin, additives, and calcium. As a major ingredient, plastic resin plays the most important role in determining the quality of the output pipes. The percent scrap resin used in comparison with the percent of virgin resin is important to the company. Also, since the company has many suppliers who bring raw materials at different quality, compound mixture is also one of the important consideration as well.

Method

Methodology factor at the company usually revolve around how each process is handled. For example, unstandardized setups, changeover and cleaning process has created a lot of defects as consequence. In fact, due to the entrepreneurial nature of the company, unstandardized work process, compound mixture and lack of automation are some of the key point of improvement that can be done.

Measurement

Compared with other prominent factors, Measurement can be considered the less important one. Example of measurement error that lead to defects are lack of quality control process and lack of rigorous data-collection on some important part of the production.

Environment

Environment is also one of the less important and uncontrollable factor. Humidity in factory and floating dust particles can affect compound mixture process.

3.3 Uncertainty, Impact, and Risk Analysis

To assess the factors from the cause-and-effect diagram, risk analysis using impact and uncertainty is suggested. The uncertainty and impact ratings are taken from survey with managing director, factory manager, and some of the old employees. These factors are being rated mainly on their relevancy with waste and defects production only, and the uncertainty and impact of these risks regarding other business competencies are not being considered. Scoring for uncertainty will be ranked at '3' if the risk is considered most frequent and at '1' if the risk rarely happen. In addition, scoring for impact will be ranked at '3' if the risk has the most impact and at '1' if it has the least. Through identifying both uncertainty and impact, the risk can be identified as follow:

Risk = Uncertainty * Impact

Table 6 Risk Analysis on the Company's Defects Production

Main Factor	Sub-factor	Uncertainty	Impact	Risk
Manpower	Staffing Lack Training	3	1	3
	SEA Labors Communication Barrier	1	2	2
	Lack of Motivation	2	1	2
Machine	Substandard Mold	2	2	4
	Old Extrusion Machines	2	2	4
	Extrusion Screw Problem	1	3	3
Material	Variation in Resin Suppliers	2	2	4
	Recycled Resin Materials	3	2	6
Method	Setups, Changeover, Cleaning	3	2	6
	Unstandardized Manufacturing Procedures	2	2	4
	Unstandardized Compound Mixture	2	2	4
	Lack of Automation	1	2	2
Measurement	Unstandardized QC process	3	1	3
	Lack of Data Analysis	1	1	1
Environment	Humidity	1	1	1
	Dust Particles in Factory	1	1	1
Risk = Uncertainty * Impact Uncertainty: 3=frequent, 2=medium, 1=rarely; Impact: 3=large, 2=medium, 1=small				

Affirmed in **Table 6**, machine, material and method are the most crucial factors considered by all stakeholders within the company. To quantify this, the 36 ton defects produced within six operating weeks in **Figure 2**, are categorized into each of the six categories.

3.4 Pareto Analysis

In addition to the risk analysis, interviews and employee surveys with the managing director, factory manager, and some of the line workers also allow us to collect extra information regarding relevancy scoring. Each of the interviewees was asked to distribute the risks ranking number according to their experience and best understanding of the company's manufacturing line. Each interviewees will have a total of 100 risk score to attribute to the 16 previously identified sub-factors. Then, a final number will be calculated from taking the average risk score give to these sub-factors by several interviewees. This final number will represent the average risk distribution that each sub-factor may attribute to defect production within the company. After obtaining the average risk distribution, the average risk distribution percentage can be used to estimate how many defects were created during the selected time period, in this case, 36,607 kg.

Table 7 provides the estimated distribution of the defects production per category derived from the average risk distribution percentage found earlier. Given that the total defects created within the company during the selected time period is 36,607 kg, risk distribution shows that the top sub-factor that was estimated to lead to high defect creation is Setups, Changeover, and Cleaning, which attributed to over 23% or 8 tons of defects created within the time period. Within these defects, Pareto Analysis shows that the top cumulative defects produced revolves around Setups, Changeover, Cleaning factor (method), Recycled Resin Materials factor (material), Substandard Mold factor (machine), and Variation in Resin Suppliers factor (material), all of which attribute to over 27,000 kg of defects or more than 75% of total defects created.

Table 7 Defects produced in kg categorized by factors

Code	Sub-factor	Average Risk Distribution Percentage	Estimated Attributed Defects (kg)	Cumulative
Method 1	Setups, Changeover, Cleaning	23.1%	8,456	23.1%
Material 1	Recycled Resin Materials	20.1%	7,365	43.2%
Machine 1	Substandard Mold	19.7%	7,219	62.9%
Material 2	Variation in Resin Suppliers	12.8%	4,689	75.8%
Machine 2	Extrusion Screw Problem	8.6%	3,145	84.3%
Machine 3	Old Extrusion Machines	5.2%	1,893	89.5%
Method 2	Unstandardized Compound Mixture	3.9%	1,428	93.4%
Method 3	Unstandardized Manufacturing Procedures	3.3%	1,201	96.7%
Manpower 1	Staffing Lack Training	1.3%	483	98.0%
Method 4	Lack of Automation	1.0%	370	99.0%
Manpower 2	SEA Labors Communication Barrier	0.3%	113	99.3%
Measurement 1	Unstandardized QC process	0.3%	92	99.6%
Measurement 2	Lack of Data Analysis	0.2%	70	99.8%
Manpower 3	Lack of Motivation	0.1%	44	99.9%
Environment 1	Dust Particles in Factory	0.1%	29	100.0%
Environment 2	Humidity	0.0%	11	100.0%
Total		**100.0%**	**36,607**	**100.0%**

As shown in **table 7**, the most prominent factor is on reducing setups, changeover time, and cleaning defects. Moreover, the others amongst the top 80% potentially revolve around material purchase and supplier selection, which are not preferable by the managing director as stated in the scope and limitation section

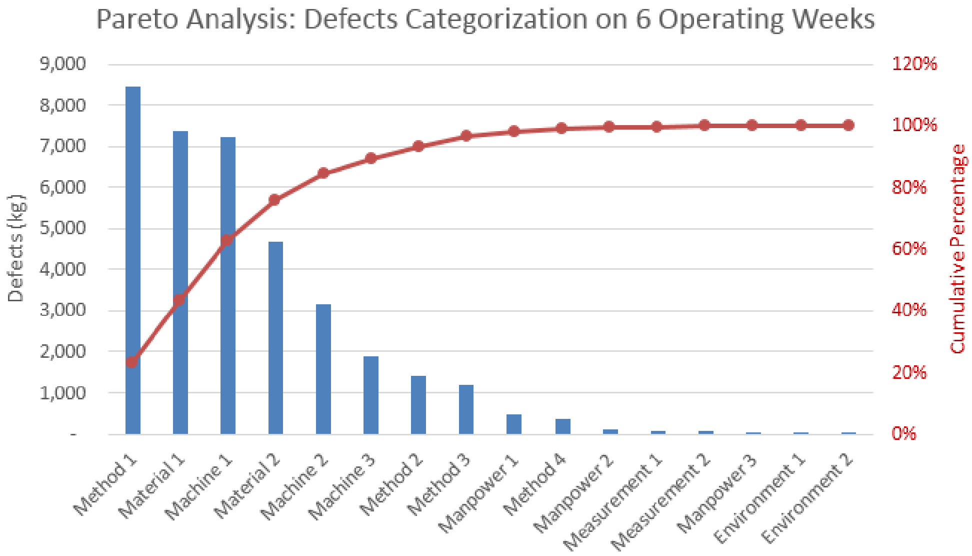


Figure 8 Pareto Analysis of the Company's Defects Production by Category

From this data, Pareto Analysis in **Figure 8** shows that the top 80% of cumulative defects produced revolves around Setups, Changeover, Cleaning factor (method), Recycled Resin Materials factor (material), Substandard Mold factor (machine), and Variation in Resin Suppliers factor (material). These four factors are amongst the sixteen identified factors that contribute to the most waste; hence, the four factors are the top 20% of all the factors. The following is a description on what each factor is:

Setups, Changeover, Cleaning

This sub-factor represents defects that caused as consequences of error or inconsistency during Setups, Changeover, and Cleaning period. This includes but not limited to wrong setup procedure and parameters, aperiodic cleaning schedule, and defects created when mold head are changed.

Recycled Resin Materials

To fully utilize defects through recycling, scrap resin is used in the production. Scrap resin comes from both external suppliers and through grinding defected or substandard pipes back into scrap resin. Using scrap resin, however, causes more complexity in production system as the compound formula for input material now varies with the percent of virgin resin and scrap resin. Although using scrap resin can allow the company to optimize the recycling and production cost, using too much scrap resin also has a chance to lower the quality of the produced pipes; thus causing the outputs to be frail.

Substandard Mold

As explained in the introduction section, extrusion mold (or die) plays a major role in determining the shape, diameter, and thickness of the output pipes. Generally, using substandard mold will cause variation in the output. The company has some problem with substandard mold usage, for example, some of the molds are getting too old and require replacement and some of the mold are purchased second-handed from other manufacturers in the industry. Using substandard mold also causes the defects after changeover process to increase as well.

Variation in Resin Suppliers

The company has six major suppliers for plastic resin and several other smaller suppliers on rare occasions. These variation in resin suppliers, unfortunately, cause complexity in production process as resin from different suppliers come at different grade and require different machine configuration. In addition, some suppliers also have low reliability. Hence, the dire consequence of all of these factors is that arranging a production schedule to optimize production system is extremely difficult. According to the management, sorting new supplier within the country has also proved to be challenging and the most feasible alternative may be to look for more suppliers from the neighboring countries in Southeast Asia or even from China.

Pareto Analysis in **Figure 8** pinpoints four factors that contribute to 80% of the defects production; as such, these factors will be the main area of study for this research. The primary focus will be specifically on reducing setups, changeover time, and cleaning time, which is the most prominent factor of all four. Nevertheless, sub-factors “Recycled Resin Materials” and “Substandard Mold” still contribute to a crucial amount of defects production on a similar level as “Setups, Changeover, & Cleaning”. According to the managing director, these three factors have tendency to overlap with one another when considering their effects to defects production; as a result, the three factors will be the main scope of this research study.

Table 8 Factors that contribute to 80% of the company's defects

Method 1	Setups, Changeover, Cleaning	23.1%	23.1%	✓
Material 1	Recycled Resin Materials	20.1%	43.2%	✓
Machine 1	Substandard Mold	19.7%	62.9%	✓
Material 2	Variation in Resin Suppliers	12.8%	75.8%	-

On the other hands, the “Variation in Resin Suppliers” factor contributes to the least amount amongst the top four factors in the 80% percentile range. In addition, this factor scarcely overlaps with the other threes in term of defect production. As a result, due to its irreverence with primary factor, the “Variation in Resin Suppliers” factor is to be excluded from the range of the thesis.

3.5 Conclusion

In summary, the Input-Process-Output is used to outline relevant parameters that can be influential on the company. From that, a Cause-and-Effect diagram is drawn and later quantified as a preliminary analysis on causes of defects production.

The subsequent Pareto Analysis determines that most prominent factors that contribute to high defect production at the company include Setups, Changeover, Cleaning factor, Recycled Resin Materials factor, Substandard Mold factor, and Variation in Resin Suppliers factor. The primary factor, Setup, Changeover, and Cleaning, has shown ton contribute to over 23% of overall defects created within the company.

Considering that their scopes are highly likely to overlap with one another, only the top three of the four factors meet the criteria within the scope and limitation set. As financial imposition and time limit requirement, the least prominent factors, "Variation in Resin Suppliers", will be excluded for consideration and analysis in the subsequent chapter.

Chapter 4: Measure

4.1 Introduction

After the prominent factors are identified and quantified, the measure phase will help setup parameters crucial to this research. The define phase has determined that the prominent factor for defects creation in the company is from Setup, Cleaning, and Changeover factor, the Recycled Resin Material factor, and the Substandard Mold factor. In this chapter, the Cause-and-Effect Matrix will be used to rate potential reasons for defects creation thus so. Furthermore, Failure Mode and Effect Analysis (FMEA) will be performed by rating each of the reasons identified.

As an introduction to the measure phase, the following are some examples of input parameters relevant to quality pipe extrusion:

- Temperature
- Pressure
- Resin Melting Index (K-value)
- Raw material compound
- Additives (ie. colorants, calcium, lubricant, thermal stabilizers)
- Percent Scrap Resin
- Extruder quality
- Mold quality
- Screw quality
- Resin quality
- Machine worker
- Machine maintenance

4.2 Cause-and-Effect Matrix

Through reinvestigating and delving specifically into defects produced during the three prominent factors, 25 causes that lead to defects specifically during this period were identified. Similar to the Cause-and-Effect diagram in the Define chapter, the identified causes can be categorized by Man, Machine, Material, Method, Measurement and Environment. In addition, the causes' relevancy with defects created during the period were rated with 100 being the most relevant and 0 being the least relevant.

Table 9 Cause-and-Effect Matrix with Relevancy Rating

Item	Causes	Relevancy
1	Method: Setup temperature not standardized	47
2	Method: Pressure at the end of production caused pipes to break	42
3	Material: High percentage of scrap resin used	38
4	Machine: Lack of machine maintenance	38
5	Material: Resins from different suppliers have variation in quality	35
6	Method: Compound not standardized	34
7	Material: Substandard mold quality	33
8	Method: Bad machine cleaning procedure and schedule	32
9	Method: Substandard resin quality	30
10	Material: Varying resin melting index (K-value)	28
11	Method: Bad mold cleaning procedure	27
12	Machine: Machine too old	25
13	Machine: Low quality machine's screw	23
14	Machine: Lack of mold maintenance	20
15	Material: Bad raw material inventory management	19
16	Machine: Lack of good mold storage procedure	18
17	Man: Carelessness	18
18	Man: QC standard too high or too low	15

19	Method: Chemical materials degrade during storage	13
20	Material: Raw material degradation from storing for a long time	12
21	Man: Lack of training	11
22	Man: Human Error	11
23	Method: Lack of resin quality assurance process when received from suppliers	9
24	Environment: Dust particles	8
25	Environment: Humidity	6

Using the Cause-and-Effect Matrix in **table 9**, the top ten causes with the highest relevancy factor is determined. The following are evaluation on how each factors can affect the pipes production:

1. **Setup temperature**

Temperature controls how uniform raw materials melt and mixed together. Normally, melting temperature for virgin resin is around 200°C but since other compounds such as scrap resin, additives such as colorant and stabilizers, and calcium are added as well, the melting temperature setup often varies. In addition, resins provided from different suppliers have different grade as well, which complicated the setup system. Setting up temperature too high will not only lead to defects but also create non-recyclable waste such as burnt plastic.

2. **Melt Pressure**

Pressure at screw tip of extrusion process relates to safety, compound mixture, melting temperature, pumping rate and thrust. High pressure may demand more work from extrusion motor as well as may have a chance to break the output pipe at the end of extrusion line; at worst case scenario, extremely high pressure can potentially break down the machine or blow the extrusion head off. As the general rule of thermodynamics, pressure is related to setup temperature. In addition, as pressure relates to friction between the resin material and the extrusion screw, melt pressure also indirectly relates to the types of raw material and compound used.

3. Percent of scrap resin

Unlike virgin resin, scrap resin's quality is even harder to control and measured. Ideally, a 100% virgin resin in production is desired but to maximize profit and sustain waste management protocol, usage of scrap resin is required. Too much of scrap resin will result in poor quality pipes.

4. Machine maintenance

Extruder malfunction often leads to uncontrollable amount of defects. There has been cases when machine breakdown led to hours of no production. Nonetheless, while the company rarely has a routine schedule for machine maintenance, there has not been recent report on defects from lack of maintenance.

5. Resin suppliers

To fulfill the production demand, the company sorted virgin resin from several suppliers. Unfortunately, local resin suppliers are oftentimes unreliable and have given the company substandard resins which impeded the production process and led to defects. In addition, since resin supplied from different suppliers come in different quality, the company finds it difficult to standardize compound mixture and machine setup using these varying raw materials.

6. Material compound

Material compound standardization also affect variation in production output. Raw materials such as resin, additives, and calcium are mixed at a specified formula before being put into the extruders. Material compound, however, cannot be easily standardized as different product variations, different suppliers, and different extruders that have different setups lead to over hundreds of possible combination.

7. Mold quality

As mold defines the thickness and diameter of the pipe outputs, mold quality is oftentimes identified as the key part of plastic extrusion. Similar to resin material, molds are also supplied by different suppliers. In addition, the company sometimes purchase second-handed molds from suppliers as well; these second-handed molds usually come at lower grade than normal and are more prone to break down. Depending on how many times the mold is used, mold quality degrade at different rate. On a rare occasion, there has been cases of mold being broken which turn batches of potential production into wastes and defects. Molds that broke down are rarely fixed and have to be replaced.

8. Machine cleaning procedure and schedule

Normally, high machine cleaning time is not desirable by the company as it reduces production time. Unfortunately, failure to include in machine cleaning has resulted in high defect value due to addition of impure substances such as dust particles. At the company, although some machine cleaning procedure is done, the process is far less than being standardized. According to the managing director and line manager, the part that needs the most focus is the extruders' nozzles/tips/heads. While the extruders' nozzles do not traditionally require much attention, due to their long operating time and due to several bad extrusion in the past, the current nozzles the company used often have leftover or burnt plastics inside them. Prevention is difficult but simple solution is to have line workers check the nozzles regularly.

9. Resin quality

Resin quality directly influences the output pipes. Substandard resin quality leads to brittle pipes. Unfortunately, resin quality is difficult to detect and prevent as the company has no technology to detect the quality of resin in scale. So substandard resin can get into the extrusion process before the line worker could notice.

10. Resin melting index

Resin melting index determines how well the resin melt in the extruders. This is the factor that prevents the company from mixing resin from different suppliers with one another as the temperature melting index will be different. Resin with different melting index will not melt at the same time and rate, thus making the resin melt uniformly. In the end, the melting index complicated the machine setup process as it adds in much more variables.

4.3 Failure Mode and Effect Analysis (FMEA)

The ten causes with highest relevancy with defects production during the most prominent factors have been identified. Using these causes as Key Process Input, a Failure Mode and Effect Analysis (FMEA) is used to quantify the causes into Severity (S), Occurrence (O), and Difficulty to Detect (D). Finally, using the Severity, Occurrence, and Difficulty to Detect, a Risk Priority Number (RPN) can be calculated.

The following are criteria for Severity, Occurrence, and Difficulty, with qualitative and quantitative descriptions.

Severity scoring is based on the amount of defects created, which is directly relevant to the cost. The affect is also rated in short term and long term.

Table 10 Severity Scoring Criteria

Severity Score	Qualitative Description	Quantitative Description
1	The input factor contributes to little or no defects to the production process. Possess no affect to cost in short or long term.	Relevant to less than 0.1% of the defects created.
2	The input factor contributes to little or no defects to the production process. Possess a little affect to cost in short or long term.	Relevant to less than 1% of the defects created.
3	The input factor contributes to some defects in the production process. Possess a little affect to cost in short or long term.	Relevant to less than 3% of the defects created.
4	The input factor contributes to some defects in the production process. Cost a near-significant amount in short or long term.	Relevant to less than 5% of the defects created.
5	The input factor contributes to a medium amount of waste. Cost a near-significant amount in short or long term.	Relevant to less than 10% of the defects created.
6	The input factor contributes to a medium amount of	Relevant to less than 15% of the defects created.

	waste. Cost a sizable amount in short and long term.	
7	The input factor contributes to a medium amount of waste. Cost more than a sizable amount in short and long term.	Relevant to less than 25% of the defects created.
8	The input factor contributes to a large amount of waste. Cost more than a sizable amount in short and long term.	Relevant to less than 35% of the defects created.
9	The input factor contributes to a very large amount of waste. Cost a large amount in short and long term.	Relevant to less than 50% of the defects created.
10	The input factor contributes to a very large amount of waste. Cost a very large amount in short and long term.	Relevant to 50% or more than the defects created.

Occurrence is based on chances for defects to occur. Qualitatively, it is based on how many employees recall the event happening.

Table 11 Occurrence Scoring Criteria

Occurrence Score	Qualitative Description	Quantitative Description
1	None – The input factor has a near-zero chance of contributing to defect and nobody in the factory remembers the last time it happened	Less than 0.1 percent chance of occurrence
2	Unlikely – The input factor has a near-zero chance of contributing to defect and some people involved in the process recall the events happening once or twice	Less than 1 percent chance of occurrence
3	Rarely – Some people involved in the process recall the events happening a few times	Less than 3 percent chance of occurrence
4	Slight Chance – Some people involved in the process recall the events happening	Less than 5 percent chance of occurrence
5	Few Occurrence – Most People involved in the process recall the events happening a few times	Less than 10 percent chance of occurrence

6	Some Occurrence – Most People involved in the process recall the events happening	Less than 15 percent chance of occurrence
7	Frequently – Important figures in the company recall the events happening a few times	Less than 25 percent chance of occurrence
8	Very Frequently – Important figures in the company recalls the events happening	Less than 35 percent chance of occurrence
9	All the time – Everyone in the company recalls the events happening	Less than 50 percent chance of occurrence
10	All the time – Everyone in the company recalls the events happening frequently	50 percent or more chance of occurrence

Detection is scored based on failsafe mechanism and inspection criteria provided by the company.

Table 12 Detection Scoring Criteria

Detection Score	Qualitative Description	Quantitative Description
1	Defect cause can be certainly detected before it happens and there are failsafe mechanism to prevent the cause from happening	Able to detect and avoid occurrence 100% of the times
2	Defect cause is very likely to be detected before it happens and there are failsafe mechanism that almost always prevent the cause from happening	Able to detect and avoid occurrence 85% of the times
3	Defect cause is somewhat likely to be detected before it happens and there are failsafe mechanism that almost always prevent the cause from happening	Able to detect and avoid occurrence 70% of the times
4	There are chances of defect cause being detected and there are failsafe mechanism to prevent the cause from happening some of the times	Able to detect and avoid occurrence 50% of the times
5	Small chances of defect cause being detected and there are failsafe mechanism to prevent the cause from happening few times	Able to detect and avoid occurrence 30% of the times

6	Very small chances of defect cause being detected and there are failsafe mechanism to prevent the cause from happening in a rare occasion	Able to detect and avoid occurrence 10% of the times
7	There is no failsafe mechanism but there are inspections process available	Unable to avoid the occurrence but able to detect 90% of the occurrence before affecting client
8	There is no failsafe mechanism but there are inspections process available half of the time	Unable to avoid the occurrence but able to detect 50% of the occurrence before affecting client
9	There is no failsafe mechanism but there are inspections process available a few time	Unable to avoid the occurrence but able to detect 10% of the occurrence before affecting client
10	There is no failsafe mechanism and inspections process available	Unable to avoid the occurrence but able to detect 1% of the occurrence before affecting client

Using the three scoring criteria, a Failure Mode and Effect Analysis (FMEA) is performed. Each key input factor defined from the previous sections is quantified by the severity, occurrence and detection scoring criteria, then the three numerical values are used to calculate the RPN value. The RPN value for each key input factor will represent how 'critical' each key input value is to the defects production. Input value with top percentile of RPN will be given high risk priority. Logically, subsequent medium and low percentile of RPN will be given medium and low risk priority respectively. Lastly potential cause of defects and current control of the input factors employed by the company is given.

Table 13 FMEA Analysis

Item	**Key Process Input**	**S**	**Potential Cause**	**O**	**Current Control**	**D**	**RPN**	**Priority**
1	Setup temperature	9	Unstandardized heating temperature causes output pipes to be disfigured	8	Line worker check the setup temperature before running the machine. However, this is susceptible to carelessness.	7	504	High
2	Melt Pressure	8	Too much pressure in the extrusion causing pipes to fracture	8	Line worker check the setup pressure before running the machine. However, this is susceptible to carelessness.	8	512	High

3	Percent scrap resin	10	Using too much scrap resin resulted in poor quality pipes	9	There are no preventive measure other than line worker's estimation of how much percent scrap resin would be too much.	7	630	High
4	Machine maintenance	4	Machine maintenance is not routinely scheduled, causing defects production to vary	5	Machine maintenance can be tracked through the efforts of employee. Even though it is a manual tracking, it has been effective so far.	3	60	Low

5	Resin suppliers	5	Suppliers supply resins at different quality and quantity. In addition, their inconsistency can also affect defects production	6	It can be difficult to determine the ‘true quality’ of resin supplied by suppliers without going through trial run, which cost time. Inconsistency, fortunately, does not occur that often.	5	150	Medium
6	Material compound	5	Incorrect material compound due to worker’s carelessness or unstandardized procedure often let to variation in production	6	There are no preventive measure other having quality team assure the compound mixture before using the	6	180	Medium

					mixture for production.			
7	Mold quality	6	Bad mold quality results in uneven thickness and diameter in final pipes output	7	Bad mold quality can be visually detected most of the time.	3	126	Low
8	Machine cleaning procedure and schedule	8	Extruders' nozzles/heads/tips often stockpile unwanted plastic leftover due to its long operating time resulting. Leftover can cause unnecessary friction at tips causing scratch marks or even fail extrusions.	7	Unlike maintenance, cleaning is harder to monitor and detect; sometimes dust accumulated faster than expected and some chemical additives are harder to wash over. In addition,	7	392	High

					there is no current workforce looking over the cleaning procedure specifically.			
9	Resin quality	5	Poor resin quality will cause the pipes to be brittle and susceptible to fracture upon heating and molding into shape	5	As the company possess no technology or procedure to quality control the resin quality in chemical scale, resin quality is hard to detect independently other than what is supplied from the suppliers. Neverthel	5	125	Low

					ess, visual inspection oftentimes works efficiently.			
10	Resin melting index	4	Unstandardized procedure to select melting index from different types of resin	5	Melting index is a parameter that can be provided by the resin suppliers; unfortunately, there is a rare chance that suppliers provide the company with wrong melting index.	3	60	Low

FMEA Summary

Table 14 Key Process Input Summary

Key Process Input	RPN	Percentage	Cumulative
Percent scrap resin	630	23.0%	23.0%
Melt Pressure (Setup Pressure)	512	18.7%	41.7%
Setup temperature	504	18.4%	60.1%
Machine cleaning procedure and schedule	392	14.3%	74.4%
Material compound	180	6.6%	81.0%
Resin suppliers	150	5.5%	86.5%
Mold quality	126	4.6%	91.1%
Resin quality	125	4.6%	95.6%
Machine maintenance	60	2.2%	97.8%
Resin melting index	60	2.2%	100.0%

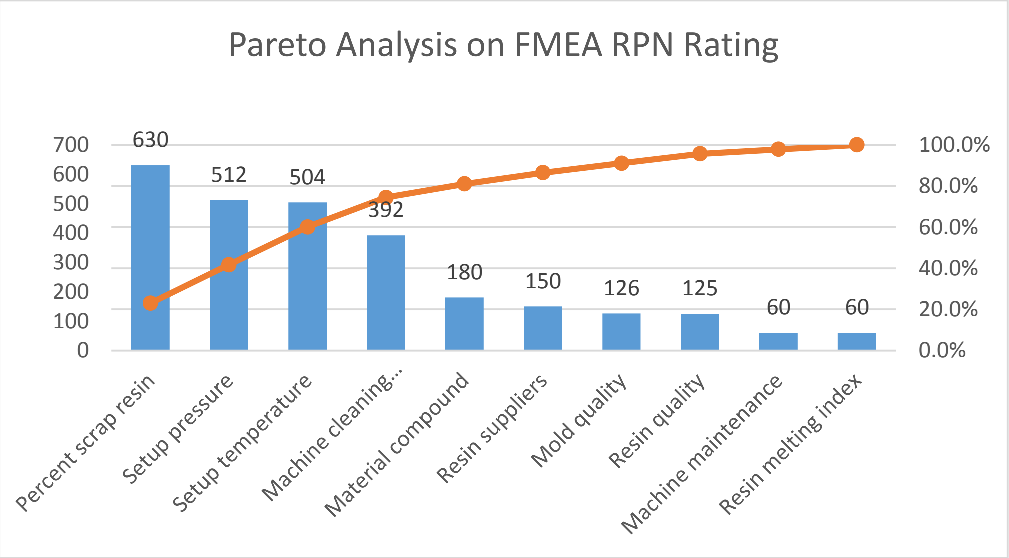


Figure 9 Pareto Analysis on RPN Rating

The total RPN scoring for the top-ten key process input is 2739. The diagram in the previous chapter ranks these key input factors through their RPN score from their highest to lowest. Through plotting the Pareto Distribution of this FMEA Analysis, it can be clearly seen that the top four key process inputs that lead to the majority of the total Risk Priority Number are Percent Scrap Resin, Melt Pressure, Setup Temperature and Unscheduled Machine Cleaning Procedure. Their combined RPN scoring is 2038, which attributes to over 74% of the total RPN score combined.

Table 15 Top Key Input Factors

Item	Key Process Input	RPN
1	Percent scrap resin	630
2	Melt pressure	512
3	Setup temperature	504
4	Machine cleaning procedure and schedule	392

After the key input factors with high relevancy and high key input factors are identified, the actual causes of defects are then re-aligned with these factors.

Table 16 Potential Factor Classification

Causes	Key Input Factor	Experimental Factor	Detail	Remark
Setups, Changeover, Cleaning	Percent scrap resin	-	Percent scrap resin is part of compound mixture	Excluded Factor
	Melt pressure	Pressure	Pressure is one of the setup parameters. High extrusion pressure may cause brittle pipe to crack upon end-of-line extrusion.	Controllable Factor

	Setup temperature	Temperature	Setup temperature is one of the setup parameters. Temperature too high will cause plastic to burn and temperature too low will cause uniform melting	Controllable Factor
	Machine cleaning procedure and schedule	Cleaning Frequency	Machine cleaning procedure is relevant to cleaning parameters	Controllable Factor
Recycled Resin Materials	Percent scrap resin	Percent scrap resin	Percent scrap resin is directly relevant to recycled resin materials	Controllable Factor
	Melt pressure	Pressure	Using high percent scrap resin resulted in brittle pipes that are easier to crack under high pressure.	Controllable Factor
	Setup temperature	Temperature	Temperature determine the uniformity of how compound with scrap resin melt	Controllable Factor
	Machine cleaning procedure and schedule	-	Machine cleaning schedule has no relevancy with defects created from high percent scrap resin.	Excluded Factor
Substandard Mold	Percent scrap resin	-	Percent scrap resin has no relevancy with defects created	Excluded Factor

			from substandard mold.	
	Melt pressure	Pressure	Substandard mold combined with high output pressure can cause pipe to crack or break in the end of the production process.	Controllable Factor
	Setup temperature	-	Machine setup temperature has no relevancy with mold quality.	Excluded Factor
	Machine cleaning procedure and schedule	-	Machine cleaning has no relevancy with mold quality.	Excluded Factor

Shown in **table 16**, each key input factor can be classified as Controllable Factor, Excluded Factor, and Noise Factor, depending on each of their impact on the primary causes. Controllable Factors are parameters that can be controlled and managed through the skill of the company's workforces and that need to be tested to define the significances between the key input factor and the specific primary cause. Excluded Factors are factors that are uncontrollable through the current operation process and cannot be controlled through any viable potential process change in the scope of this research. Finally, Noise Factors are factors that are hard to control due to their unpredictability and uncertainty such as factors involving environment like humidity and air temperature. By classifying each key input factor into these three viable scopes, a design of experiment can be conducted to test how each factor can play its role against the primary cause.

4.4 Conclusion

In this step, an in-depth analysis of the factors identified in the previous chapter is delved into. Through the Cause-and-Effect Matrix, the top 25 factors that have the most relevancy with defects created with the Setup, Cleaning, and Changeover factor, the Recycled Resin Material factor, and the Substandard Mold factor were identified, rated, and weighted. The top 10 factors amongst the 25 within the matrix then undergo another thorough Failure Mode and Effect Analysis. By quantifying each factors by severity, occurrence, and detection, the FMEA pinpointed that out of ten key input factors that attribute to 2739 total Risk Priority Number (RPN), four of them attribute to the majority of 2038, which is 74.4% of the total combined RPN score. These four factors will be used in further analysis in the next chapter to identify their contributions to reducing the defects created in the company.

Chapter 5: Analyze

5.1 Introduction

This chapter brings the key input factors identified in the previous chapter into a more in-depth analysis. The four factors identified in the previous chapter are:

- Percent Scrap Resin
- Melt Pressure
- Setup Temperature
- Machine Cleaning Procedure and Schedule

Before these factors can be escalated into a more quantitative analysis, the factor's parameters used in real experimental use must be evaluated. Using factor selection method, different variation, or factor levels, can be found. By testing and performing experiment runs with different combinations of each factors at different levels, the company can outline all scenario of its best manufacturing procedure setups. Finally, after obtaining useful data from this design of experiment, in-depth data analysis can be performed.

5.2 Factor Level Selection

From the previous chapter, four top key input factors are identified. Using the design of experiment approach, these factors will be used as variables that affect the response.

Table 17 Factor Level Selection

Factors	Level		Remark
	-1	+1	
Temperature (ºC)	170	210	From studying past manufacturing data and discussing with the factory manager, two of the most prominently used setup temperature are selected. Pipe outputs above the high temperature often resulted in burnt pipes and outputs below the low temperature resulted in

			high defect rate from uniform melting.
Melt Pressure (bars)	100	200	From studying past manufacturing data and discussing with the factory manager, two of the most prominently used pressure are selected.
% Scrap Resin	10%	30%	From discussing with the line manager and resin supplier and from several research articles, 30% scrap resin is the high threshold resin compound. Normally pipes extruded with more than 30% scrap resin are very brittle. Pipes extruded below 10% are not cost-effective for the company at the current manufacturing process as well.
Cleaning Frequency before Run	A (Clean once during the first setup or changeover each day)	B (Clean once every setup and changeover)	From discussing with the factory manager, machine cleaning frequency at the company is not standardized. According to his experience, the factory manager suggested two cleaning frequency that he found to be the most effective from several months of trial testing.

While temperature, melt pressure and percent scrap resin are parameters taken from observing several parameters employed in the past and from the factory manager's suggestions. The cleaning procedure and schedule, however, is a new parameter that has to be devised. Interviews with factory manager and line workers suggested that most of the time, the problem lied in the nozzles or the extrusion tips. There are several cases that, due to large defects production, the nozzles eventually accumulate large amount of scrap particles inside causing friction between these particles and the extruded pipes, leading to scratch mark or even fracture. In reality, the best approach is to definitely clean the machine's nozzles every time the extrusion is done; however, while this may decrease the percent defects, it is not optimal as it disrupt the production flow, resulting in high changeover time and lower yield. Rather, two alternatives for cleaning procedure are suggested: A, Cleaning the nozzle once during the first machine setup or changeover each day, or B, Cleaning the nozzle once during every machine setup or changeover each day.

5.3 Design of Experiment

As each of the four factors has two variations, a total of 2^4, or 16, different runs have to be performed. Each run is repeated four times to ensure data accuracy. For each experiment, a total of 100kg batch will be produced using the identified setup parameters, A to D, and the weight of the defects will be measured for each batch. The product produced will be the 8.5mm thickness and ½ inch diameter PVC pipe, which is one of the most commonly manufactured types of pipes in the company.

Table 18 Experimental Factors

Factors	Levels	
	-1	+1
A=Temperature (ºC)	170	210
B=Melt Pressure (bar)	100	200
C=% Scrap Resin	10%	30%
D=Machine Cleaning	A	B

5.4 Type of Design

The experiment is set to have four factors with two variation levels. By focusing on the optimal factor for manufacturing process, the defects created can be linked with the four previously defined causes such as Setups, Changeover, Cleaning problem and Recycled Resin Material problem. In the end, the average number of percent defects is calculated from four total experiment runs from each run number. The experiment is designed to have three main characteristics:

Replication

The experiment must be repeatable. Replication helps reduce mistakes in the experiment as well as increase the accuracy of the results.

Randomization

Randomization means that all of the experiments will be conducted in a randomized order, as determined by the MINITAB program in the Run Number section. Randomization reduces the effects of external factors to the experiment runs.

Number of Experiment

As each of the unique 16 different experiment runs is repeated three times, there will be a total of 48 experiment runs.

Table 19 Factors Level

Standard No.	Run No.	A	B	C	D
1	8	+	+	+	+
2	9	+	+	+	-
3	6	+	+	-	-
4	2	+	-	-	-
5	16	-	-	-	-
6	4	-	-	-	+
7	5	-	-	+	+
8	10	-	+	+	+
9	15	+	-	+	+
10	14	+	-	-	+
11	11	+	+	-	+
12	3	-	+	+	-
13	1	-	-	+	-
14	12	+	-	+	-
15	13	-	+	-	+
16	7	-	+	-	-
A = Temperature, B=Melt Pressure, C=% Scrap Resin, D=Machine Cleaning					

Over the timeframe of three months, from February to April 2014, a total of sixteen different experiment runs are repeated three times each. The following table shows the percent number of defects found in each run number.

The experiment procedure must be strictly controlled to maintain the same standard in all 48 experiment runs and reduce unnecessary variation that may lead to inaccurate data. The following external factors are set to be controlled:

- Line workers – the same set of line workers will be in charge of all experiment runs
- Machine and materials – the extrusion machine used, the mold used, and all raw materials used, other than percent scrap resin, will be the same
- Output products – the extruded pipes in this experiment are controlled to be at the same diameter and thickness
- Quality control worker – in addition to using the same set of line workers, the quality control worker is controlled as well.

Table 20 Experiment Runs

Standard No.	Run No.	A	B	C	D	Percent Defects			
						1	2	3	Average
1	8	+	+	+	+	6.77%	6.60%	6.55%	6.64%
2	9	+	+	+	-	6.72%	6.89%	6.64%	6.75%
3	6	+	+	-	-	5.66%	5.14%	5.31%	5.37%
4	2	+	-	-	-	6.31%	6.46%	5.98%	6.25%
5	16	-	-	-	-	7.88%	8.25%	8.26%	8.13%
6	4	-	-	-	+	8.20%	7.96%	8.17%	8.11%
7	5	-	-	+	+	8.91%	8.44%	9.02%	8.79%
8	10	-	+	+	+	7.42%	7.35%	7.37%	7.38%
9	15	+	-	+	+	7.11%	7.02%	7.05%	7.06%
10	14	+	-	-	+	6.21%	5.89%	6.47%	6.19%
11	11	+	+	-	+	5.35%	5.42%	5.49%	5.42%
12	3	-	+	+	-	7.17%	7.47%	7.68%	7.44%
13	1	-	-	+	-	8.98%	8.87%	8.88%	8.91%
14	12	+	-	+	-	7.26%	7.56%	6.96%	7.26%
15	13	-	+	-	+	6.79%	6.88%	6.88%	6.85%
16	7	-	+	-	-	6.83%	6.84%	6.91%	6.86%
A = Temperature, B=Melt Pressure, C=% Scrap Resin, D=Machine Cleaning									

Table 20 displays results of the Design of Experiment runs. Depending on the variables, the average percent defect ranged from of 5.37% to the 8.91%. Each run

number is repeated three times to increase data precision and accuracy; as shown above, there are not so much variation between each experiment of the same standard run. This means that the standard deviations between each experiment in the same standard run are relatively low and are in an acceptable range, meaning the experiment setups for the 16 unique runs are highly repeatable in term of results.

In addition, **table 21** displays the elaborated two-level, three-level, and four-level relationships between factors A, B, C, and D (being Temperature, Melt Pressure, Scrap Resin, and Cleaning Method respectively). The interactions include AB, AC, AD, BC, BD, CD, ABC, ABD, BCD, ACD, and ABCD.

Table 21 ANOVA on Manufacturing Defects

Factorial Fit: Percent Defects versus Temperature, Melt Pressure, % Scrap Resin, and Machine Cleaning

Estimated Effects and Coefficients for Percent Defects (coded units)

Term	Effect	Coef
Constant		0.070881
Temperature	-0.014413	-0.007206
Melt Pressure	-0.009988	-0.004994
Scrap Resin	0.008812	0.004406
Cleaning Method	-0.000663	-0.000331
Temperature*Melt Pressure	0.003537	0.001769
Temperature*Scrap Resin	0.002388	0.001194
Temperature*Cleaning Method	-0.000138	-0.000069
Melt Pressure*Scrap Resin	0.000462	0.000231
Melt Pressure*Cleaning Method	0.000337	0.000169
Scrap Resin*Cleaning Method	-0.000562	-0.000281
Temperature*Melt Pressure* Scrap Resin	0.001337	0.000669
Temperature*Melt Pressure* Cleaning Method	0.000162	0.000081
Temperature*Scrap Resin* Cleaning Method	-0.000188	-0.000094
Melt Pressure*Scrap Resin* Cleaning Method	0.000037	0.000019
Temperature*Melt Pressure* Scrap Resin*Cleaning Method	-0.000088	-0.000044

S = *   PRESS = *

Analysis of Variance for Percent Defects (coded units)

Source	DF	Seq SS
Main Effects	4	0.00154228
Temperature	1	0.00083088
Melt Pressure	1	0.00039900
Scrap Resin	1	0.00031064
Cleaning Method	1	0.00000176
2-Way Interactions	6	

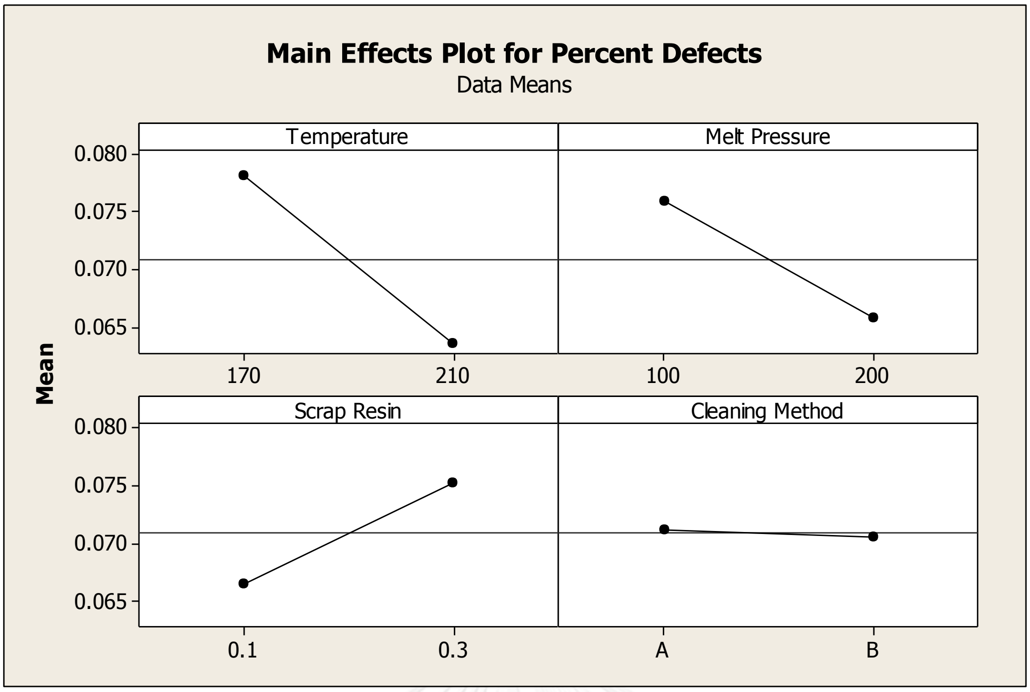


Figure 10 Main Effects Plot for Percent Defects

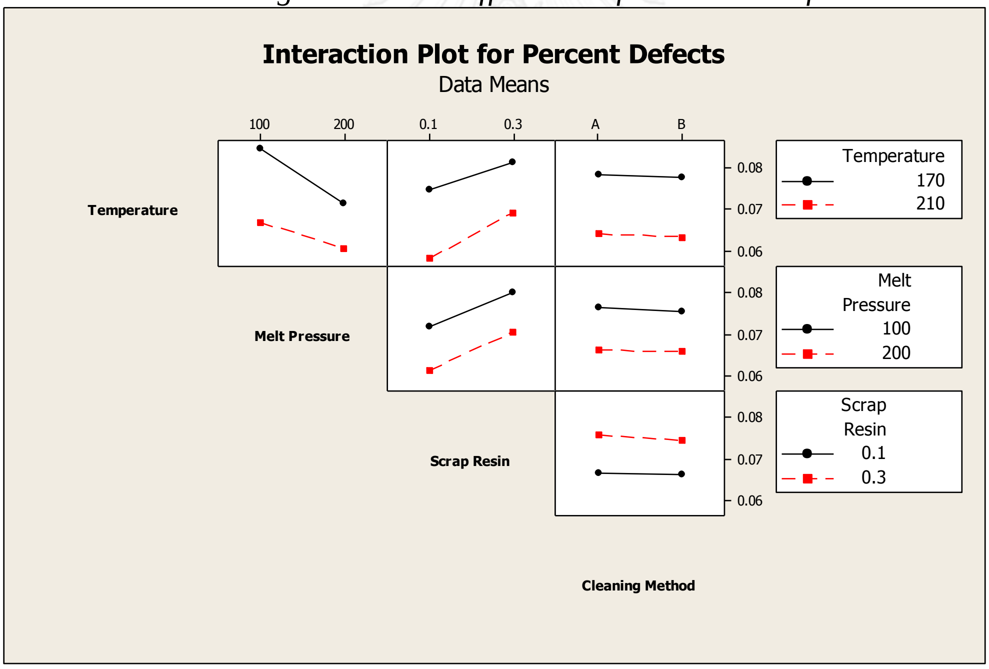


Figure 11 Interaction Plot for Percent Defects

The Main Effect plot can help determine which parameters are significant to the experiment; by observing the slope of the graph, one can see that the greater the change in the slope between the high and low value, the more significant the interaction is to the response, which, in this case, is defect production. According to the Main Effects Plot for Percent Defects, Temperature setup has the most significant role in percent defects contributions. In addition, melt pressure and % scrap resin were also the main factors. Machine cleaning, however, did not show to be significant according to this design of experiment setup.

As shown in the Interaction Plot above, all factors including temperature, melt pressure, % scrap resin and machine cleaning are parallel to one another, meaning there is no interaction between any of the factors on one another.

From the Design of Experiment and Analysis of Variance approach, the Analysis phase can be concluded that the optimal parameter for Temperature, Melt Pressure and %Scrap Resin are:

Table 22 Optimal Parameters for Lowest Defect Production

% Scrap Resin	Temperature (ºC)	Melt Pressure (bar)
10%	210	200
30%	210	200

The design of experiment, however, showed that Machine Cleaning Schedule A and B have no effect on defects reduction. This may be the result of some flaw in design of experiment setup; since most of the defects coming from unstandardized cleaning schedule creating plastic leftovers in nozzles, which in turn cause scratch marks or even failed extrusions, and since, in this experiments setups, the nozzle was cleaned more frequently than usual, it is highly likely that the high cleaning frequency in limited scope and time period from this design of experiments caused less defects production than usual.

The most optimal setup temperature and melt pressure are found to be at 210 ºC and 200 bar respectively. At standardized temperature, raw material compound, including plastic resins and other stabilizers, can melt and flow through the extruders at minimal waste defects output. By setting a fixed standard of temperature and melt pressure, the company can reduce setup complexity and setup time from having too many parameter variations.

The most optimal percent scrap resin is at 10%. However, sometimes to lower cost, it may be useful to consider producing at 30% scrap resin as well. Further studies on additional cost analysis will be performed in the next chapter to calculate the value gained from using recycled resin compared with value lost from manufacturing too many defects.

Although machine cleaning schedule and procedure were identified as not important to defects creation, due to the probable flaw in design of experiment setups, it is not a factor to be completely disregard. Especially when the variation in percent defect between Machine Cleaning Setup A and B were relative small. In addition, under the conclusion that all experimented setup parameters have no interaction, the average defect level between the two setups were only around 7% rather than the 8.8% average in defect level during the pre-research's phase.

Since there were no standard of procedure in machine cleaning before the experiment, implementing standard to control is essential. Between the two experiments, cleaning once during the first setup or changeover each day and cleaning once every setups and changeovers, the prior is more practical to the company as it demands less operation time, hence cost, to implement.

Chapter 6: Improve

6.1 Introduction

According to the previous chapter, optimal parameters for defects reduction at the company are identified. Using these parameters, the extrusion process is repeated again in a two weeks period, during May 2014, also for the 8.5mm thickness and ½ inch diameter PVC pipe. Similar to the Analyze phase, the following external factors are controlled:

- Line workers
- Machine and materials
- Output products
- Quality control worker

6.2 Implementation

- Setups: 10% Scrap Resin, 210 ºC Temperature, 200 bar Melt Pressure, Cleaning Method A

Table 23 Post-Improvement Production Data for 10% Scrap Resin

Date	Week Number	Daily Pipes Produced (kg)	Daily Defects (kg)	Percent Defects
6/2/2014	23	8,837	467	5.29%
6/3/2014	23	9,028	475	5.26%
6/4/2014	23	9,600	507	5.28%
6/5/2014	23	10,043	527	5.25%
6/6/2014	23	9,453	492	5.20%
6/7/2014	23	9,647	506	5.24%
6/8/2014	23	9,750	511	5.24%
6/9/2014	24	8,967	473	5.27%
6/10/2014	24	9,694	505	5.21%
6/11/2014	24	9,719	514	5.29%

6/12/2014	24	8,862	465	5.25%
6/13/2014	24	9,284	488	5.26%
6/14/2014	24	9,058	478	5.28%
6/15/2014	24	8,879	463	5.22%
Average		9,344	491	5.25%

The trail run of the optimal setup was executed during June 2, 2014 to June 15, 2014, a two week period, and shown in **table 24.** Using the optimal setup identified, the defect rate is reduced from annual average of 8.82% to a number of 5.25%. This is a 41.2% reduction in defects. The reduction would save the company 3,614,239 THB per year, or 40.5% cost saving from the current operational procedure.

- Setups: 30% Scrap Resin, 210 ºC Temperature, 200 bar Melt Pressure, Cleaning Method A

Table 24 Post-Improvement Production Data for 30% Scrap Resin

Date	Week Number	Daily Pipes Produced (kg)	Daily Defects (kg)	Percent Defects
6/16/2014	25	8,613	568	6.59%
6/17/2014	25	9,033	599	6.63%
6/18/2014	25	9,459	628	6.64%
6/19/2014	25	9,694	635	6.55%
6/20/2014	25	8,551	565	6.61%
6/21/2014	25	8,386	553	6.59%
6/22/2014	25	8,095	536	6.62%
6/23/2014	26	9,169	610	6.65%
6/24/2014	26	8,041	529	6.58%
6/25/2014	26	8,312	548	6.59%
6/26/2014	26	9,979	662	6.63%

6/27/2014	26	9,429	622	6.60%
6/28/2014	26	8,168	542	6.64%
Average		8,927	669	6.66%

Table 25 represents the post improvement production data for 30% scrap resin ran during June 16 to June 28 of 2014. With 30% scrap resin, the defect rate is reduced from annual average of 8.82% to a two-month trial average of 6.66%. This change will help the company save annual defect cost of around 2,188,081 THB, a change of 24.5% in cost saving. It will also reduce defects reduction by 24.5% as well.

Summarized in **table 26**, as PVC resin contributes to the majority of the raw material cost, it is critical to analyze whether the 20% drop in percent scrap resin is worth the 1.14% drop in defects. According to the company's historical data, 1.41% drop in defects is equivalent to approximately 118,846 THB cost saving in defect production per month. However, from discussing with the management of the company, a 20% drop in percent scrap resin is approximately equal to the cost of around 72,339 THB per month. As a result, it is determined that the 10% scrap resin, and consequently 5.25% defect production, is the optimal setup in term of cost saving for the company.

Table 25 Summary of Improve Phase

Scrap Resin	Temperature (ºC)	Melt Pressure (bar)	Cleaning Method	Percent Defects	Cost Saved from Scrap	Cost Saved from Defects

					Recycling (THB/ month)	Reduction (THB/ month)
10%	210	200	A	5.25%	466,743	301,186
30%	210	200	A	6.66%	539,082	182,340
Difference	-	-	-	1.41%	72,339	118,846

Chapter 7: Control

7.1 Introduction

After the problem is defined, measured, and analyzed and solutions are implemented, the next step is to control and sustain the procedure. This chapter will consider options to control the implemented solutions involving detection and prevention methods to avoid further mistakes.

7.2 Detection

Detection is a process to ensure that problems can be prevented and will not be repeated. The first step to enforce detection is to look at the overall procedure, prior and after the change implemented in the company. This also means that some key performance indicator (KPI) or parameter may need to be develop to ensure quantifiable and measurable results. The most direct KPI in the company's point of view would need to be associated with costs as it directly affect the company's financial performance. Additionally, it can also be associated with other added benefits or qualities acquired through the implemented program.

There are different means for detection to prevent defects within the company. Out of all the detection method, visual detection is the easiest and the most feasible to implement. It involves having line workers check the machine setups on a routine basis. Inconsistencies in factors such as melt temperature and melt pressure can be visually detected from the extrusion machine setups. Cleaning can also be detected and inspected before each extrusion runs as uncleansed, leftover materials within the extruders can be easily observed.

7.3 **Control**

Since the optimal setups have been proposed, standard control procedure can be implemented to ensure that workers and engineers are constantly looking over these parameters on a routine basis. To do so, a machine setup and maintenance Form is suggested to monitor key input factors that lead to defects creation, illustrated in **table 27**.

Machine Setup and Maintenance Form will have to be monitored everyday by the Line Manager of the company. By limiting the respondent to only one person, the company will be able to guarantee one set of standard throughout its production process. Nevertheless, since there are over 30 extrusions and injection molding machines within the factory, this machine setup and maintenance form will only be used for the company's main extrusion line in order to reduce complexity and increase flexibility on less significant productions.

The form is designed to monitor over the four identified key input factors. Melt temperature and melt pressure were defined in earlier stage to be optimal at constant 210 ºC and 200 bar respectively. Temperature and pressure can be controlled through machine setups and inspections can be done visually through the extruder's digital display and through the control pads. These two parameters will monitored every 12 hours, one per beginning of the day shift and one per beginning of the night shift. Because extrusion lines often run in sequences throughout the whole day, the parameters can be expected to be constant, assuming there is no external factor that influences them; as a result, checking over these parameters should be relatively easy.

Resin compound mixtures, or percent scrap resin, will be more difficult to monitor as there is no visual inspection available. As a result, line manager will have to play an active role in monitoring the compound mixture process. The control process for this has to be more frequent as well, usually at every new setups and changeovers each day.

As identified in the previous chapter, the more practical method for the company to look over machine cleaning is to clean the extruder, especially on its nozzle, once during the first setup or changeover of the day. Therefore, to control that machine is cleaned before the extrusion process, the line manager is required to confirm whether the extruder is cleaned once during the first setup or changeover each day and, the data should be recorded in the Machine Setup and Maintenance form every day.

rTable 26 Machine Setup and Maintenance Form

Date			**Shift: Day / Night**			**Machine Number**		
No.	**Process**	**Monitor Input Factors**	**Control Process**			**Worker**		
			Specification	**Frequency**	**Control Method**	**Responsible**	**Name**	**Contact**
1	Extrusion Setups/Changeover	Melt Temperature	210 ºC	Every 12 hours	Machine Setup and Maintenance Sheet	Line Manager		
2	Extrusion Setups/Changeover	Melt Pressure	200 Bar	Every 12 hours	Machine Setup and Maintenance Sheet	Line Manager		
3	Resin Compound Mixture	Scrap Resin	10%	Every setups & change over	Machine Setup and Maintenance Sheet	Line Manager		
4	Machine Cleaning Process and Schedule	Machine Cleaning	Clean once during the first setup or changeover each day	Every 24 hour	Machine Setup and Maintenance Sheet	Line Manager		

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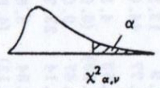
ภาคผนวก

Example of Company Products

Percentage of X^2 Distribution

PERCENTAGE POINTS OF THE χ^2 DISTRIBUTION

Table of $\chi^2_{\alpha;\nu}$ — the 100 α percentage point of the χ^2 distribution for ν degrees of freedom



α =	.995	.99	.98	.975	.95	.90	.80	.75	.70	.50	.30	.25	.20	.10	.05	.025	.02	.01	.005	.001	= α
ν = 1	$.0^4393$	$.0^3157$	$.0^3628$	$.0^3982$	.00393	.0158	.0642	.102	.148	.455	1.074	1.323	1.642	2.706	3.841	5.024	5.412	6.635	7.879	10.827	ν = 1
2	.0100	.0201	.0404	.0506	.103	.211	.446	.575	.713	1.386	2.408	2.773	3.219	4.605	5.991	7.378	7.824	9.210	10.597	13.815	2
3	.0717	.115	.185	.216	.352	.584	1.005	1.213	1.424	2.366	3.665	4.108	4.642	6.251	7.815	9.348	9.837	11.345	12.838	16.268	3
4	.207	.297	.429	.484	.711	1.064	1.649	1.923	2.195	3.357	4.878	5.385	5.989	7.779	9.488	11.143	11.668	13.277	14.860	18.465	4
5	.412	.554	.752	.831	1.145	1.610	2.343	2.675	3.000	4.351	6.064	6.626	7.289	9.236	11.070	12.832	13.388	15.086	16.750	20.517	5
6	.676	.872	1.134	1.237	1.635	2.204	3.070	3.455	3.828	5.348	7.231	7.841	8.558	10.645	12.592	14.449	15.033	16.812	18.548	22.457	6
7	.989	1.239	1.564	1.690	2.167	2.833	3.822	4.255	4.671	6.346	8.383	9.037	9.803	12.017	14.067	16.013	16.622	18.475	20.278	24.322	7
8	1.344	1.646	2.032	2.180	2.733	3.490	4.594	5.071	5.527	7.344	9.524	10.219	11.030	13.362	15.507	17.535	18.168	20.090	21.955	26.125	8
9	1.735	2.088	2.532	2.700	3.325	4.168	5.380	5.899	6.393	8.343	10.656	11.389	12.242	14.684	16.919	19.023	19.679	21.666	23.589	27.877	9
10	2.156	2.558	3.059	3.247	3.940	4.865	6.179	6.737	7.267	9.342	11.781	12.549	13.442	15.987	18.307	20.483	21.161	23.209	25.188	29.588	10
11	2.603	3.053	3.609	3.816	4.575	5.578	6.989	7.584	8.148	10.341	12.899	13.701	14.631	17.275	19.675	21.920	22.618	24.725	26.757	31.264	11
12	3.074	3.571	4.178	4.404	5.226	6.304	7.807	8.438	9.034	11.340	14.011	14.845	15.812	18.549	21.026	23.337	24.054	26.217	28.300	32.909	12
13	3.565	4.107	4.765	5.009	5.892	7.042	8.634	9.299	9.926	12.340	15.119	15.984	16.985	19.812	22.362	24.736	25.472	27.688	29.819	34.528	13
14	4.075	4.660	5.368	5.629	6.571	7.790	9.467	10.165	10.821	13.339	16.222	17.117	18.151	21.064	23.685	26.119	26.873	29.141	31.319	36.123	14
15	4.601	5.229	5.985	6.262	7.261	8.547	10.307	11.036	11.721	14.339	17.322	18.245	19.311	22.307	24.996	27.488	28.259	30.578	32.801	37.697	15
16	5.142	5.812	6.614	6.908	7.962	9.312	11.152	11.912	12.624	15.338	18.418	19.369	20.465	23.542	26.296	28.845	29.633	32.000	34.267	39.252	16
17	5.697	6.408	7.255	7.564	8.672	10.085	12.002	12.792	13.531	16.338	19.511	20.489	21.615	24.769	27.587	30.191	30.995	33.409	35.718	40.790	17
18	6.265	7.015	7.906	8.231	9.390	10.865	12.857	13.675	14.440	17.338	20.601	21.605	22.760	25.989	28.869	31.526	32.346	34.805	37.156	42.312	18
19	6.844	7.633	8.567	8.907	10.117	11.651	13.716	14.562	15.352	18.338	21.689	22.718	23.900	27.204	30.144	32.852	33.687	36.191	38.582	43.820	19
20	7.434	8.260	9.237	9.591	10.851	12.443	14.578	15.452	16.266	19.337	22.775	23.828	25.038	28.412	31.410	34.170	35.020	37.566	39.997	45.315	20
21	8.034	8.897	9.915	10.283	11.591	13.240	15.445	16.344	17.182	20.337	23.858	24.935	26.171	29.615	32.671	35.479	36.343	38.932	41.401	46.797	21
22	8.643	9.542	10.600	10.982	12.338	14.041	16.314	17.240	18.101	21.337	24.939	26.039	27.301	30.813	33.924	36.781	37.659	40.289	42.796	48.268	22
23	9.260	10.196	11.293	11.688	13.091	14.848	17.187	18.137	19.021	22.337	26.018	27.141	28.429	32.007	35.172	38.076	38.968	41.638	44.181	49.728	23
24	9.886	10.856	11.992	12.401	13.848	15.659	18.062	19.037	19.943	23.337	27.096	28.241	29.553	33.196	36.415	39.364	40.270	42.980	45.558	51.179	24
25	10.520	11.524	12.697	13.120	14.611	16.473	18.940	19.939	20.867	24.337	28.172	29.339	30.675	34.382	37.652	40.646	41.566	44.314	46.928	52.620	25
26	11.160	12.198	13.409	13.844	15.379	17.292	19.820	20.843	21.792	25.336	29.246	30.434	31.795	35.563	38.885	41.923	42.856	45.642	48.290	54.052	26
27	11.808	12.879	14.125	14.573	16.151	18.114	20.703	21.749	22.719	26.336	30.319	31.528	32.912	36.741	40.113	43.194	44.140	46.963	49.645	55.476	27
28	12.461	13.565	14.847	15.308	16.928	18.939	21.588	22.657	23.647	27.336	31.391	32.620	34.027	37.916	41.337	44.461	45.419	48.278	50.993	56.893	28
29	13.121	14.256	15.574	16.047	17.708	19.768	22.475	23.567	24.577	28.336	32.461	33.711	35.139	39.087	42.557	45.722	46.693	49.588	52.336	58.302	29
30	13.787	14.953	16.306	16.791	18.493	20.599	23.364	24.478	25.508	29.336	33.530	34.800	36.250	40.256	43.773	46.979	47.962	50.892	53.672	59.703	30
40	20.706	22.164	23.838	24.433	26.509	29.051	32.345	33.660	34.872	39.335	44.165	45.616	47.269	51.805	55.759	59.342	60.436	63.691	66.766	73.402	40
50	27.991	29.707	31.664	32.357	34.764	37.689	41.449	42.942	44.313	49.335	54.723	56.334	58.164	63.167	67.505	71.420	72.613	76.154	79.490	86.661	50
60	35.535	37.485	39.699	40.482	43.188	46.459	50.641	52.294	53.809	59.335	65.227	66.981	68.972	74.397	79.082	83.298	84.580	88.379	91.952	99.607	60
70	43.275	45.442	47.893	48.758	51.739	55.329	59.898	61.698	63.346	69.334	75.689	77.577	79.715	85.527	90.531	95.023	96.388	100.425	104.215	112.317	70
80	51.171	53.539	56.213	57.153	60.391	64.278	69.207	71.145	72.915	79.334	86.120	88.130	90.405	96.578	101.880	106.629	108.069	112.329	116.321	124.839	80
90	59.196	61.754	64.634	65.646	69.126	73.291	78.558	80.625	82.511	89.334	96.524	98.650	101.054	107.565	113.145	118.136	119.648	124.116	128.299	137.208	90
100	67.327	70.065	73.142	74.222	77.929	82.358	87.945	90.133	92.129	99.334	106.906	109.141	111.667	118.498	124.342	129.561	131.142	135.807	140.170	149.449	100

For values of $\nu > 30$, approximate values for χ^2 may be obtained from the expression $\nu\left[1-\frac{2}{9\nu}\pm\frac{x}{\sigma}\sqrt{\frac{2}{9\nu}}\right]^3$, where $\frac{x}{\sigma}$ is the normal deviate cutting off the corresponding tails of a normal distribution If $\frac{x}{\sigma}$ is taken at the 0.02 level, so that 0.01 of the normal distribution is in each tail, the expression yields χ^2 at the 0.99 and 0.01 points. For very large values of ν it is sufficiently accurate to compute $\sqrt{2\chi^2}$, the distribution of which is approximately normal around a mean of $\sqrt{2\nu-1}$ and with a standard deviation of 1. This table is taken by consent from Statistical Tables for Biological, Agricultural, and Medical Research, by R. A. Fisher and F. Yates, published by Oliver and Boyd, Edinburgh, and from Table 8 of Biometrika Tables for Statisticians, Vol. 1, by permission of the Biometrika Trustees.

Murdoch and Barnes, (1986: 17)

Example of Machine Maintenance Form

Date			**Shift: Day / Night**			**Machine Number**		
No.	**Process**	**Monitor Input Factors**	**Control Process**			**Worker**		
			Specification	**Frequency**	**Control Method**	**Responsible**	**Name**	**Contact**
1	Extrusion Setups/Changeover	Melt Temperature	210 ºC	Every 12 hours	Machine Setup and Maintenance Sheet	Line Manager		
2	Extrusion Setups/Changeover	Melt Pressure	200 Bar	Every 12 hours	Machine Setup and Maintenance Sheet	Line Manager		
3	Resin Compound Mixture	Scrap Resin	10%	Every setups & changeover	Machine Setup and Maintenance Sheet	Line Manager		
4	Machine Cleaning Process and Schedule	Machine Cleaning	Clean once during the first setup or changeover each day	Every 24 hour	Machine Setup and Maintenance Sheet	Line Manager		

ประวัติผู้เขียนวิทยานิพนธ์

Born and raised in Bangkok, Thailand, Tanatetee Rattanaruengyot, graduated from Chulalongkorn University in 2011 with a Bachelor's degree in Engineering, majoring in Nanoengineering. He had years of experience working in several functional departments of a plastic manufacturing company. As of 2014, he is currently pursuing his graduate studies in Engineering Business Management at the Regional Centre for Manufacturing Systems Engineering and University of Warwick.