Defect Reduction in the Production of Capacitor Discharge Ignition Unit using Lean Six Sigma

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การลดของเสียในกระบวนการผลิตตัวจุดระเบิดด้วยตัวเก็บประจุ โดยใช้ลีน ซิกซ์ซิกม่า

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การศึกษาการผลิตชิ้นส่วนอะไหล่อิเล็กทรอนิกส์รถจักรยานยนต์ พบว่ามีปัญหาของเสียที่เกิดขึ้นในกระบวนการจำนวนมาก และมีแนวโน้มเพิ่มสูงขึ้น จากเป้าหมายที่ตั้งไว้โดยเฉลี่ยปีละร้อยละ 1 ปัญหาดังกล่าวส่งผลให้ต้นทุนการผลิตชิ้นส่วนอะไหล่อิเล็กทรอนิกส์ในรถจักรยานยนต์ สูง ดังนั้นงานวิจัยนี้มีวัตถุประสงค์เพื่อลดของเสียจากกระบวนการผลิต โดยมุ่งเน้นที่สินค้าหลัก 2 ตัวของการผลิต ได้แก่ สินค้าโมเดล A และ โมเดล B ซึ่งเป็นสินค้าที่มีของเสียสูงสุดในการผลิตชิ้นส่วนอะไหล่อิเล็กทรอนิกส์ในรถจักรยานยนต์ โดยประยุกต์ใช้แนวคิดลีน ซิกซ์ซิกม่า (Lean Six Sigma) เป็นเครื่องมือหลักในการปรับปรุงปัญหาดังกล่าว รูปแบบของลีน ซิกซ์ซิกม่าที่จะกล่าวถึงในวิทยานิพนธ์ฉบับนี้เป็นการใช้โครงสร้าง DMAIC ของซิกซ์ซิกม่า ร่วมกับแนวคิดของลีน ซึ่งมีจุดมุ่งหมาย คือ การมุ่งลดของเสียจากกระบวนการผลิต ทั้งนี้ กระบวนการปรับปรุงเริ่มจากการกำหนดปัญหา (Define) โดยจะมีการระบุถึงปัญหา และเป้าหมายไว้อย่างชัดเจน จากนั้นจึงเข้าสู่ขั้นตอนการวัด (Measure) เพื่อรวบรวมข้อมูลในการวิเคราะห์ปัญหา งานวิจัยนี้เลือกใช้ Modified Value Stream Mapping (MVSM) เพื่อแสดงภาพรวมของกระบวนการผลิตและบ่งชี้ปัญหาที่อาจก่อให้เกิดของเสีย ผลลัพธ์สำคัญที่ได้จาก MVSM ได้แก่ ข้อบกพร่องของกระบวนการ และภาพรวมของค่าตัวชี้วัดต่างๆ ที่สำคัญก่อนการปรับปรุง พบว่า สินค้าโมเดล A มีอัตราของเสียอยู่ที่ร้อยละ 2.07 หรือคิดเป็นค่าซิกม่าที่ 3.54 (3.54σ) ส่วนที่สินค้าโมเดล B มีอัตราของเสียอยู่ที่ร้อยละ 3.5 หรือคิดเป็นค่าซิกม่าที่ 3.31 (3.31σ) เปรียบเทียบกับค่าซิกม่ามาตรฐานของอุตสาหกรรม (ซิกม่าที่ 4 (4σ))

เมื่อทราบข้อมูลพื้นฐานของกระบวนผลิตแล้ว ผู้วิจัยจึงทำการวิเคราะห์ (Analysis) หาต้นเหตุของปัญหาโดยใช้แนวคิดและเครื่องมือของลีนแบบต่างๆ พบว่า ปัญหาของเสียในกระบวนการผลิต ประกอบด้วยสี่กลุ่มปัญหาใหญ่ เก้าสาเหตุย่อย และเมื่อใช้ Failure Mode and Effect Analysis (FMEA) ในการวิเคราะห์เพิ่มเติม พบว่า มีเพียงห้าสาเหตุย่อยจากสี่กลุ่มปัญหาใหญ่ที่ควรทำการปรับปรุง โดยในการปรับปรุง (Improve) โดยมุ่งเน้นที่การสร้างระบบและวัฒนธรรมองค์กร เพื่อป้องกันไม่ให้เกิดการประพฤติผิดต่อหน้าที่ การปรับปรุงการกระบวนการตรวจสอบสภาพสินค้า และการปรับเปลี่ยนขั้นตอนย่อยในกระบวนการผลิต ก่อนที่จะเข้าสู่ขั้นตอนการควบคุม (Control) ในลำดับสุดท้าย

ผลลัพธ์ที่ได้จากการปรับปรุงโดยแนวคิดลีน ซิกซ์ซิกม่า ส่งผลให้อัตราของเสียของสินค้าโมเดล A และโมเดล B ลดลงอย่างมีนัยสำคัญทางสถิติ โดยสินค้าโมเดล A มีอัตราของเสียอยู่ที่ร้อยละ 0.57 หรือคิดเป็นค่าซิกม่าที่ 4.03 (4.03σ) ในขณะที่สินค้าโมเดล B มีอัตราของเสียอยู่ที่ร้อยละ 0.9 หรือคิดเป็นค่าซิกม่าที่ 3.87 (3.87σ) ทั้งนี้ ภายหลังการปรับปรุง สินค้าโมเดล A มีอัตราของเสียอยู่ในเกณฑ์ที่บริษัทตั้งไว้และมีค่าซิกม่าอยู่ในเกณฑ์มาตรฐาน สินค้าโมเดล B มีอัตราของเสียลดลงอย่างมีนัยสำคัญ แต่มีค่าซิกม่าไม่อยู่ในเกณฑ์มาตรฐาน อาจเนื่องมาจากความซับซ้อนในการผลิตสินค้าโมเดล B ที่จำเป็นต้องอาศัยความชำนาญของพนักงานผู้ประกอบโมเดล ประกอบกับการเพิ่มขั้นตอนสำหรับการปรับปรุงในส่วนของสินค้าโมเดล B ส่งผลให้พนักงานต้องใช้เวลาในการเรียนรู้ก่อนที่จะเห็นผลลัพธ์อย่างเป็นรูปธรรมในภายหลัง

ภาควิชา ศูนย์ระดับภูมิภาคทางวิศวกรรมระบบการผลิต ลายมือชื่อนิสิต ....

สาขาวิชา การจัดการทางวิศวกรรม ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

ปีการศึกษา 2559

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KEYWORDS: LEAN SIX SIGMA, WASTE REDUCTION, PROCESS IMPROVEMENT, DEFECT REDUCTION.

PHATARAPHAT KITTIJETSADA: Defect Reduction in the Production of Capacitor Discharge Ignition Unit using Lean Six Sigma. ADVISOR: PISIT JARUMANEEROJ, Ph.D., 108 pp.

The case study company for this thesis is a company that produces electrical and electronic spare parts for motorcycles. This company has been facing defect problem, whose rate is higher than expected and it keeps increasing at an average rate of one percent a year. As defects lead to a rise in production cost, from reworks and scrap, Lean Six Sigma (LSS) approach has been adopted as a research tool, where we focus only on two main products of the company, that is, Models A and B.

In this setting, the applied LSS approach is typically a combination between DMAIC framework of Six Sigma and lean concepts, whose aim is to reduce defects from the production processes. In the first phase, i.e. Define phase, the problem and goal are set for each product model – the defects must be reduced below one percent and its sigma level must be at least at the standard level. Then, in Measure phase, all related information is collected and presented in the form of the Modified Value Stream Mapping (MVSM). Based on the constructed MVSM, the problems have become more visible, with all revealed pre-improvement metrics. In this pre-improvement stage, the defective rates are identified at 2.07%, or equivalently 3.54σ, for Model A and 3.5%, or equivalently 3.31σ, for Model B; whereas, the standard defective rate from the companies within the same industry is 4σ.

Once all decisive information is revealed, root causes are identified by means of lean tools and techniques in Measure phase. Based on our analysis, there are four main causes and nine sub-root causes in total. However, with Failure Mode and Effect Analysis (FMEA), only five sub root causes are diagnosed as critical. This leads to three main areas of improvement; (i) the development of system and working culture to prevent malpractices, (ii) the improvement of inspection processes, and (iii) the adjustment of instructions for manufacturing processes. Lastly, in Control phase, we introduce an np-chart to continually monitor the production from batch to batch. We also suggest the company to build working culture enhancing strong relationships among organisational members.

The results from the improvement for the selected two models show significant defect reduction, and so increase the production's sigma level. For Model A, the defective rate drops to 0.57%, or equivalently 4.03σ. This defective level surpasses both company goal and standard sigma level of the industry. For Model B, however, the defective rate falls short of its sigma level's goal of 4σ, where we achieve the sigma level at 3.87σ, or 0.9%. This could be explained by Model B's complexities, which require skilled assemblers. Additionally, as we introduce new inspection procedures and adjustment, it would take some time before the assemblers get used to the new instructions.

Department: Regional Centre for Manufacturing Systems Engineering
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1 Introduction

This chapter describes company background, problem statement and short overview of this thesis. It shows rough plan of the thesis giving guideline of working structure. Also, literature reviews are for building solid foundation of the structure by gathering and analysing these methods and evidences.

1.1 Background Company

In Thailand, motorcycles are the most common means of transportation as they are affordable and suited to Thailand's road conditions. Focused on Thailand, a manufacturer which could be categorised as a small and medium enterprise (SME) has been manufacturing electronic spare parts for commercial motorcycles for decades. As shown in Figure 1, this manufacturer has three main product categories: motorcycle coils, regulators, and capacitor discharge ignition (CDI) units. Both regulators and CDI units have no physical moving parts requiring many electronic components, while motorcycle coils are moving parts and require fewer electronic components.

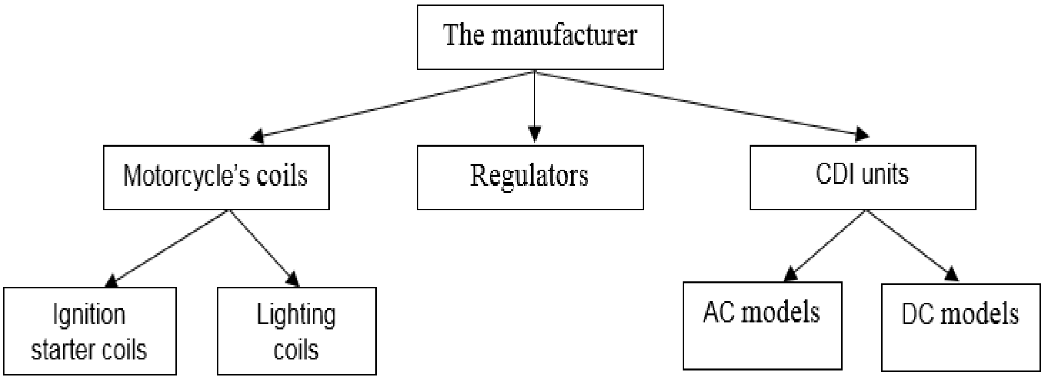


Figure 1: The product tree of the company

Motorcycle coils can be divided into two sub-products: ignition starter coils and lighting coils. These two parts are used for converting physical movements into an electricity supply for other components such as headlamps, CDI units, and batteries. As copper wires and metal cores are their main components, manufacturing these products is not especially complicated, requiring fewer working processes than the regulators and CDI units.

However, this is because they consist of several electronic components such as resistors, capacitors, transistors, and many more. These components have wide ranges of values in terms of electronic characteristics and prices. The costs of these products are quite high due to the variety of raw materials and electronic components used in them, such as the expensive microprocessors of CDI units.

As can be seen in Figure 2, CDI units are regarded as high-value products since they are complex electronic products. Moreover, the company makes greater profits from this type of product. There are hundreds of models of the CDI unit, as it is an ignition control unit for motorcycles, but it could be divided into two sub-groups: AC and DC units. AC units require fewer components and less complex circuit boards than DC units. However, they are similar in terms of assembly procedures. Therefore, this case study will focus on this type of product because it is crucial to the company.

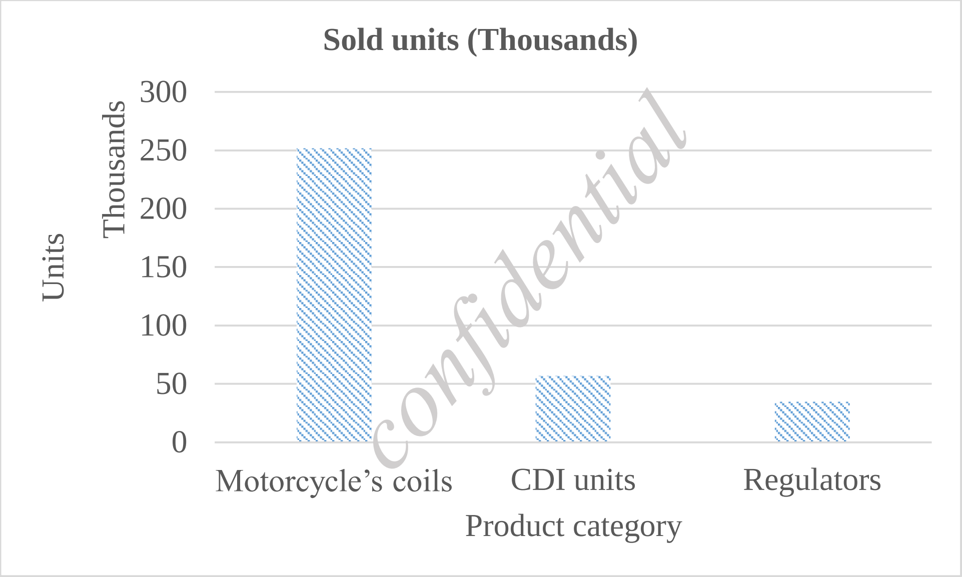


Figure 2: Units sold for each product in 2015 (confidential)

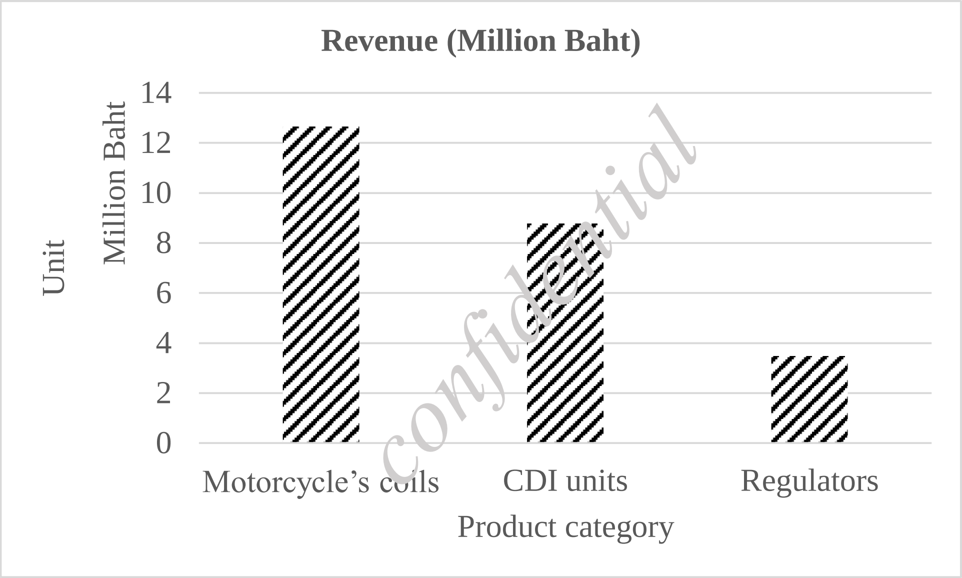


Figure 3: Revenues for each product in 2015 (confidential)

1.2 Problem Statement

As labour shortages and frequent job changes have become common problems for Thai SMEs (Monitor, 2012), the company’s assembly process has become less effective and efficient because the workforce changes too often. Most new workers are inexperienced and unfamiliar with electronic assembly. Lately, the number of defects in the assembly line of CDI units has increased significantly compared with those of other product categories, as shown in Figure 4. Since quality is one of the five completive objectives (Nigel Slack, 2010), a failure to deliver high-quality products is a critical problem which possibly damages the company competitiveness. In general, every company wants to keep defects close to zero. The higher the rates, the greater costs of production will become, decreasing profits of the companies. Therefore, the defects should be solved and prevented from occurring in the future.

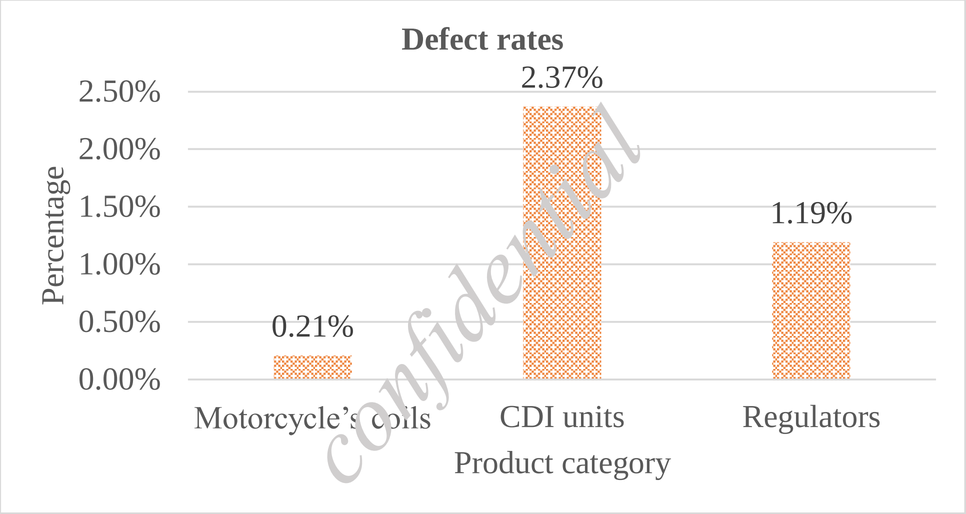


Figure 4: Percentages of defects of each product category in 2015 (confidential)

It can be derived from Figure 4 that CDI units has the highest rates of defects of the measured product categories. Since the revenue for this product is high (Figure 3), the company would be highly profitable by responding to the market and focusing on the improvement of this product.

By selecting CDI units based on AC and DC units, each unit shares some differences and similarities in terms of assembly processes, materials, volumes, and prices. Concerning the differences, the AC unit has a low price tag but high volume, while the DC unit has a high price tag but low volume. In addition, the DC unit is produced by more complex processes based on its circuit designs. The Printed Circuit Boards (PCBs) of DC units are comprised of several components which require complicated soldering process, which increases the amount of soldering per unit of the AC unit's PCBs with the same size.

As to the similarities, both have similar production processes. They also consist of the same raw materials, such as the same values of resistors and diodes. In figures 5 and 6, manufacturing processes of CDI units are shown using System Flow Diagram (SFD) to represent processes in a flow diagram.

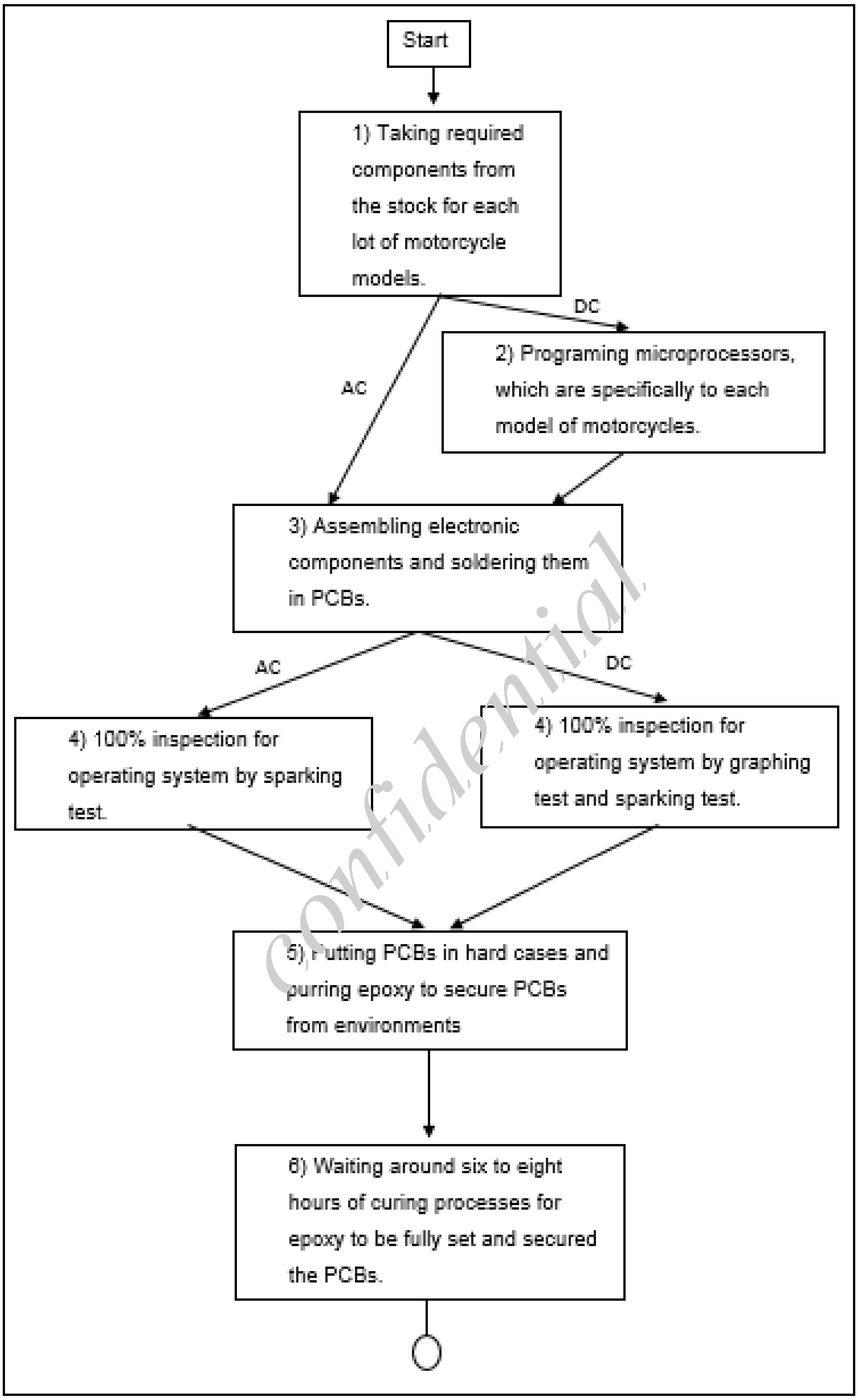


Figure 5: Manufacturing processes of CDI units (confidential)

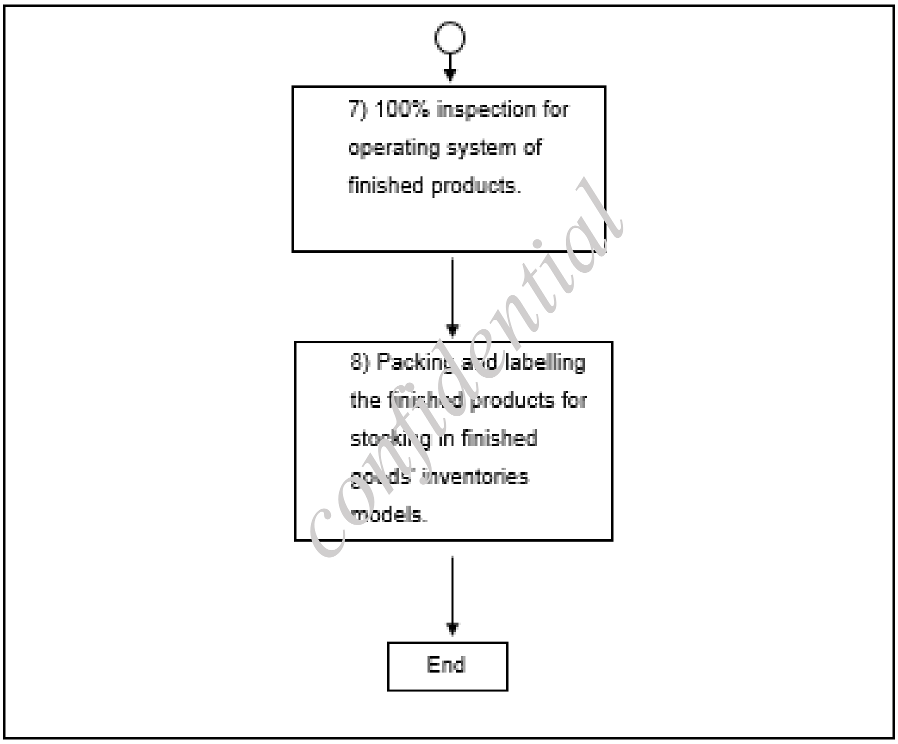


Figure 6: Manufacturing processes of CDI units (continued, confidential)

The manufacturing processes of CDI unit for both AC and DC units have mainly eight processes. Firstly, raw materials and electronic components are taken out from material inventory. Also, their amounts of units are corresponding to planned production CDI units. Secondly, microprocessor as one of main components in DC unit for controlling different ignition timings are programmed from pre-written data. Thirdly, electronic components are assembled and soldered in PCBs from referenced models and records. Fourthly, completed PCBs from a previous process are moved to first inspection stage. The inspection is divided into two processes, which are testing ignition spark and graph. The ignition graph tests for DC unit only. Fifthly, each of tested PCBs is putted in a hard plastic box and filled with epoxy as a containing process for PCBs' protection from vibration, water and air. Next, contained units are left in room-temperature and curing process of epoxy are taking place in order to get harden epoxy. During this process, epoxy is changing physical form as liquid to solid from chemical reaction, which releases heat from the reaction. After getting fully covered units, the units are inspected for the second time after contained. This process is the same as the first inspection by using the two methods. Lastly, finished units are packed into boxes with detail labels for each different motorcycle model.

1.3 Objective of the Research

To reduce defects in the Capacitor Discharge Ignition Unit by using Lean Six Sigma (LSS).

1.4 Scope of Study

This case study focuses on implementing Lean Six Sigma in the Thai SME manufacturing process;

1. DMAIC method from Six Sigma, together with, the lean concept is the framework for the case study.
2. Defects for CDI units are mainly focused.
3. Assembly lines for CDI units are mainly focused
4. All raw materials and specifications of non-in-house components are fixed according to the designs.
5. The chosen root causes are based on the most critical dimensions affecting the performance of the company.

1.5 Expected Benefits

1. Reduction in defects.
2. Reduction in costs and losses.
3. Product quality improvement.
4. Improvement of working performances.
5. Increase competitiveness of the company.
6. Structural production processes.

1.6 Research Procedure

By gathering pieces of information from literatures, a framework of Lean Six Sigma for this case is formed, as shown below. Since Lean Six Sigma has no ideal structure for all cases, the framework is applied to achieve the best possible outcome for this specific case. There are five phases in this framework: Define, Measure, Analyse, Improve, and Control. Moreover, this framework can be evolved and developed during implementation for better results because it is a guideline to follow and important information may be discovered through its implementation.

- Define phase: to define issues and the expected outcome.
- Measure phase: to measure current performances and to identify the wastes in the production processes.
- Analyse phase: to identify the root-causes of defects and to map out the process flow in detail for the identification of opportunities to eliminate wastes and to add value.
- Improve phase: using lean tools such as 5S and work standardisation to prevent problems from occurring, and to make the most effective and efficient production; and then collecting the outcome for comparison with the expectations.
- Control phase: to monitor and to control the stability of implemented processes and with Continuous Improvement (CI).

2 Literature Review

Reviewing past literatures are for gathering solid information to improve the plan of working process for the thesis by forming solid methodology. Starting with, Lean Six Sigma (LSS) is the main methodology for the thesis. After that, working tools using in the methodology are reviewed. Lastly, case studies are important part to be support evidences as well as guidelines from other successful projects.

2.1 Lean Six Sigma

2.1.1 Lean

Over the past decades, there is a knowledge that has been significantly implemented in organisations and firms, especially in the automotive industry, which is Lean thinking. Lean thinking is a concept of continuously identifying and eliminating all types of wastes in working processes. It brings substantial benefits to the manufacturers and organisations applying this concept. Two main benefits from this are reducing costs of productions and speeding up working processes. However, Lean thinking is difficult to successfully implement in the actual system. This is because it is more like philosophy, so many adjustments and commitments are required to use this in the system (Stone, 2012).

There are five key principles of the Lean, which are value, value steam, flow, pull, and perfection. For value, value added activities need to respond to the preference of customers. Non-value added activities have to detect and eliminate because the customers determine value of products or services. For value steam, all current activities need to be explored in detail because some activities not creating any value for the final product should be identified. For flow, the processes must flow continuously with waste eliminations. For pull, it means that companies should be responsive to demands from customers by producing at the right time. For perfection, it is continuous processes of removing wastes and improving performance to ensure optimisation (Dahlgaard and Dahlgaard-Park, 2006).

From the Lean philosophy, Kaizen is a subset of Lean philosophy and means “change for the better” in Japanese (Doria, 2003). The definition and scope of Kaizen is widely varied, since it evolves to suit each application and depends on its users. There are three perspectives of Kaizen. The first perspective is that it is a management philosophy through the maintenance and improvement of working standards. The second is that it is a part of Total Quality Management (TQM), linking with Continue Improvement (CI) of processes. The third perspective describes it as a theoretical principle for reducing waste by limiting the scope of activities, cutting time scales down and applying waste reduction across working structures (Suárez-Barraza et al., 2011). Therefore, the third is the most applicable perspective for this research because it is highly related to the waste of defects in processes.

From the suggestion, Figure 7 shows related principles and techniques under the third perspective. There are several suitable techniques such as process redesign, Value Stream Mapping (VSM), 5’S, and seven tools of Quality Control for this research. Process redesign is a methodology for decomposing processes to find possible improvement spots (Tibaduiza et al., 2012). Value Steam Mapping is a method to acquire an overview of all activities by tracking the flow of materials in processes (Kuhlang et al., 2014). 5’S and standardisation can be grouped as one technique since 5’S also includes standardisation and is a basic foundation of the production line in management systems (Gapp et al., 2008). Seven tools of Quality Control are for giving clearer understandings on current problems that trying to solve. The seven tools are process flow analysis, cause-effect diagram, run chart, control chart, scattergram, histogram and Pareto chart (Carter, 1992).

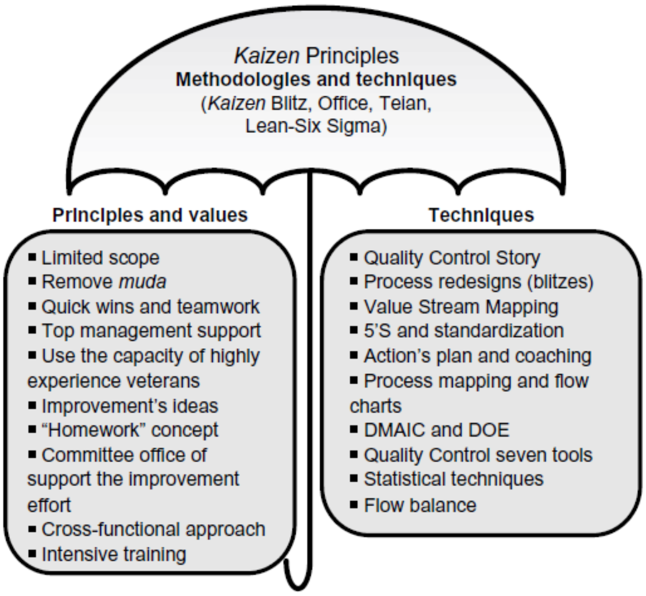
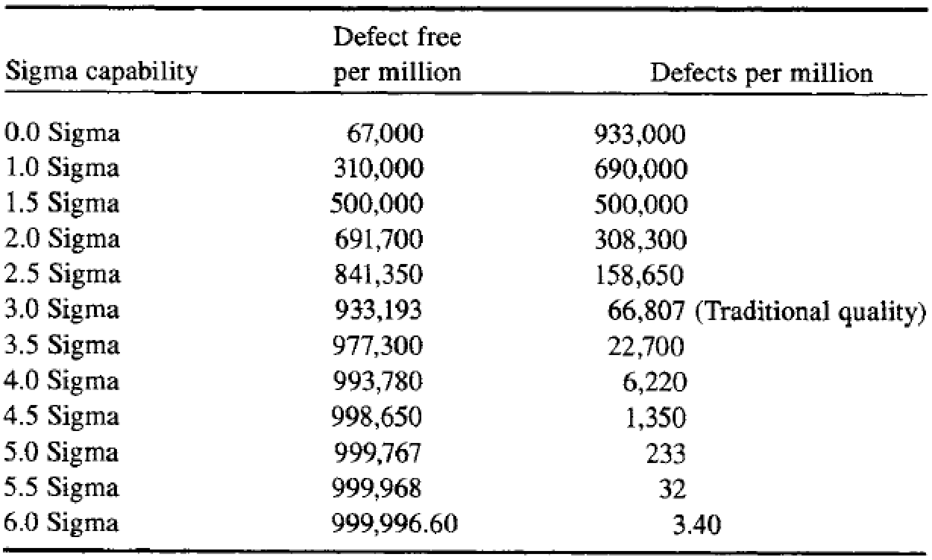


Figure 7: Kaizen as a theoretical principle (Tibaduiza et al., 2012)

2.1.2 Six Sigma

Six sigma is another knowledge that is also widely used for improving working performance by trying to identify and eliminate defects and failures in working processes (Jiju et al., 2005). This methodology was originated in the mid-1980 by Motorola and has become the standard for global businesses. The methodology has given unique benefits of cost reduction and customer satisfaction at the same time. It has various definitions, but the core value of Six Sigma remains the same. The name Six Sigma has stated its goal for lowering defect rates to as much as 0.0003% (Reosekar and Pohekar, 2014). However, Six Sigma is widely used in many large manufacturing companies because its implementation requires high investments that only large companies can afford (Adeyemi and Needy, 2006). Table 1 shows calculations of defects to be sigma capability by using 1.5σ to be off-set. This off-set is errors from operators and machines in long-term performance (statistical-theory-of-LSS).

Table 1: Estimation of Six Sigma from numbers of defects with 1.5σ off-set (statistical-theory-of-LSS)



Sigma capability	Defect free per million	Defects per million
0.0 Sigma	67,000	933,000
1.0 Sigma	310,000	690,000
1.5 Sigma	500,000	500,000
2.0 Sigma	691,700	308,300
2.5 Sigma	841,350	158,650
3.0 Sigma	933,193	66,807 (Traditional quality)
3.5 Sigma	977,300	22,700
4.0 Sigma	993,780	6,220
4.5 Sigma	998,650	1,350
5.0 Sigma	999,767	233
5.5 Sigma	999,968	32
6.0 Sigma	999,996.60	3.40

There is one tool commonly used as a problem-solving approach in Six Sigma called the ‘DMAIC method’ standing for ‘Define, Measure, Analyse, Improve and Control’. It shows steps to solve problems and suggests essential tools in each stage. However, it is a linear method enacted stage by stage. This generates specific requirements for the management team to achieve before going to the next stage. It is possible that the requirements are the same in every stage. Therefore, the team needs to achieve them repeatedly, which is time-consuming (Garza-Reyes et al., 2014).

The DMAIC method has the unique goal of preventing the defects from appearing rather than reducing and reworking these defects (Prashar, 2014). The method is a funnel approach, which moves from a wide to a narrow scope of problems. So, the final results have been through the tools and processes to be logical results from using this method (Lynch et al., 2003).

2.1.3 Lean Six Sigma

Lead Six Sigma (LSS) is the combination of the Lean management and Six Sigma approaches by using the advantages of each concept to compensate for the downsides of the other. There is still no absolute definition of LSS because it depends on each practitioner to implement it in their own way (Gershon and Rajashekharaiah, 2011). According to Gershon and Rajashekharaiah (2011), there are unclear depictions of LSS from articles and textbooks because most of them have low involvements of the lean management with Six Sigma in its methodology of DMAIC. Therefore, it is necessary to specifically form LSS suited to each application.

There are two objectives that will be achieved through LSS: quality improvement of products and cost reduction of productions (Dragulanescu and Popescu, 2015). Therefore, understanding of the Lean management in details is essential for absorbing the concept in order to think as the lean way. As suggested by Snee (2010), both Six Sigma and Lean share similar objectives to improve systems, as shown in Figure 8. This shows that they are perfectly suited to integration, thus benefiting the organisations.

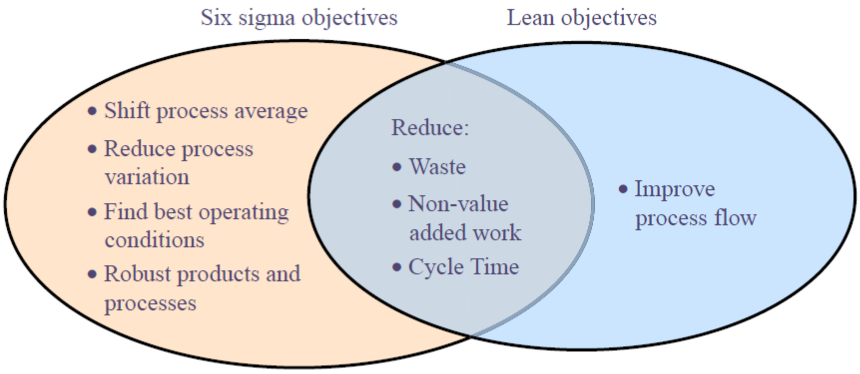


Figure 8: Objectives of improvements from Six Sigma and the Lean (Snee, 2010)

Lean management is the concept or philosophy of the lost reduction. Also, this concept can combine with DMAIC method of Six Sigma. Therefore, each stage of DMAIC method must incorporate Lean ways of thinking. There are six factors related to the successful implementation of LSS in systems (Hilton and Sohal, 2012):

1. the level of technical skill of implementers;
2. the level of corporative skill of implementers;
3. the level of influence from implementers;
4. the level of technical skill of the leaders of the project;
5. the level of corporative skill of the leaders of the project;
6. the ability and structure of organisations.

This shows that implementing LSS involves every single part of the organisations, from the top to the bottom of the organisational structure. This is because the lean concept needs to be embedded in organisational culture in order to implement it successfully.

There are several suggested processes in reforming LSS implementations to be more structural. Firstly, Snee (2010) suggested an integration between Six Sigma and the Lean concept into each step of processes, as shown in Figure 9. The main instance of performance being low is usually encountered when passing information and materials along the way of working processes. Thus, this cause of problems can be countered by using the Lean concept. For each value-adding step, it is the main cause of low performance during the step. Therefore, Six Sigma is commonly used to deal with low performance during value-adding processes.

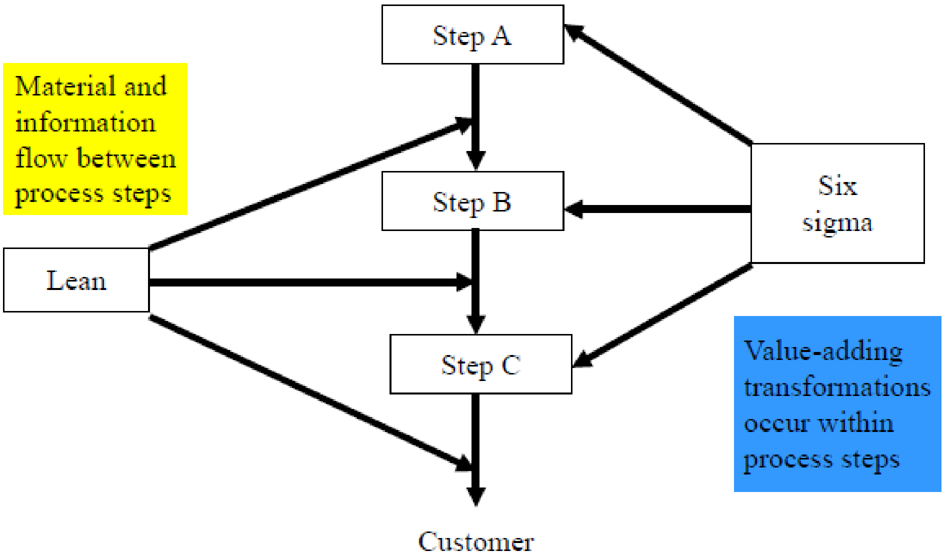


Figure 9: Working processes of combining Six Sigma and the Lean (Snee, 2010)

Secondly, a framework for project management improvement processes by using LSS is proposed. Figure 10 shows the integration of the DMAIC model of Six Sigma with the Lean concept (Tenera and Pinto, 2014). Furthermore, each phase of DMAIC is supported by selected methods and models as structural procedures in order to achieve desired improvements with continuity and sustainability. For the define phase, this usually describes the main problem relating to internal and external points of views from organisations and customers respectively. Expected targets are also defined in this phase. This phase is critical to the whole process because it defines directions and objectives of the project by gathering information and understanding current situations. For the measure phase, focused information and data are collected to compare with desired targets. In addition, selected metrics are used in this phase for being indicators of working performances.

For the analysis phase, the Lean tools are involved because they are key methods and models to improve the processes. There are two tools, Value Steam Mapping and Affinity Diagrams, for spotting opportunities for improvements in the processes and identifying root causes of problems respectively. After the root causes are identified, possible solutions are identified and prioritised using Prioritisation Root-causes matrix and Pugh matrix in the improve phase. The last phase is the control phase, for monitoring and sustaining the solutions of the improvements by involving periodic measurement, training processes, and updating procedures (Tenera and Pinto, 2014).

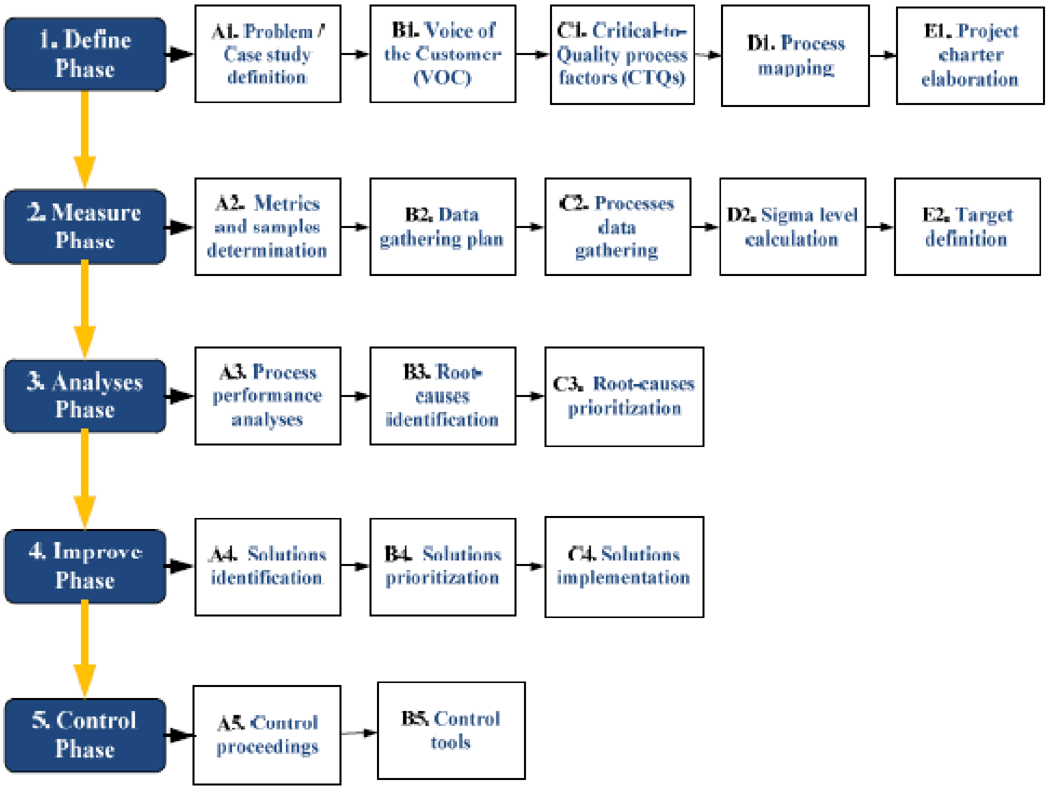


Figure 10: Structural processes of implementing the Lean Six Sigma (Tenera and Pinto, 2014)

2.2 DMAIC Methodology

After reviewing various methodologies of implementing LSS, the structure or framework of the implementation should be specified to each applying system. This is because each system has a different Define phase in terms of current problems, desired targets, and resources of organisations. Therefore, the framework for this case should be constructed based on this particular system, as shown in Table 2.

Table 2: The framework of implementing LSS in the manufacture

Define	Measure	Analyse	Improve	Control
-Descripting the current situation -Defining current problems and desired goals	-Measuring current levels of performances -Mapping out system flow of information and materials by using modified VSM -Identifying all the wastes in seven wastes of the Lean	- Applying cause-and-effect diagram -Using FMEA to ranking causes for solving in priority	-Forming solutions based on the lean tools -Implementing the solutions -Collecting outcomes and comparing them with the expectations	-Monitoring and controlling the improvements - Applying Continuous Improvement from the lean concept

Firstly, the Define phase is a defining phase for the current problems and the desired goals or objectives by using the lean concept to form definitions. Furthermore, the definitions should be based on both the views of organisations and those of customers. Furthermore, the expectations will be based on perfection (Kaizen) of the lean concept for eliminating the waste because the objective is reduction of the rate of defects. In the Measure phase, information of current performances (such as rates of defects, costs, and durations of the processes) are the key components for measurements. Based on the Lean, all wastes in the processes should be identified in terms of seven wastes. This can be done by using modified Value Steam Mapping (modified VSM) to combine two flows of materials and information together. This makes the processes become clearer and more adjustable by visual diagrams (Ortuño and Pérex, 2012).

For the Analyse phase, this involves the analysis of problems in detail. The cause-and-effect diagram or Ishikawa diagram is used for listing and identifying possible causes and effects of the problem by categorising the causes into several types of major causes, as the lean concept suggested (Ploytip et al., 2014). After identified root causes, all the causes are prioritised by using FMEA for solving the most impacts in orderings. This narrows problems down to find the root causes and makes solving them become easier from tackling them down one by one.

For the Improve phase, there are several lean tools that can be used to improve current processes and solve the problems. Firstly, standardised work is one of the lean tools for making working processes more effective and efficient by minimising variation and eliminating wastes during the processes (Whitmore, 2008). Secondly, just-in-time (JIT) is the concept of waste elimination during flows of information and materials with respect to time (Svensson, 2001).

The Control phase is designed to monitor and control the improvements from the previous phase by sustaining the implementation, integrating them into the processes and setting them as the standard for the future. Continuous improvement is another tool of the Lean that can be used in this phase for sustaining the implementations (Singh and Singh, 2015).

2.3 Related Tools

2.3.1 Sigma Metrics

There are several well-known metrics from Six Sigma used to measure the reliability of the production processes. Firstly, defects per million opportunities (DPMO) is a million multiplied by the number of defects, which is then divided by a multiplication of the number of units and the number of opportunities per unit. This gives a possible number of defects with the production of a million units. Secondly, defect rate is a percentage of defects in the production, giving a basic measurement calculated from total defect divided by total production. Thirdly, sigma level is commonly used to describe performance of the company compared to the average standards of the other performances shown in Figure 11 (Rudisill and Druley, 2004). Thus, an average company is expected to have a sigma level of 3, thus being a standard company but not a competitive company.

Furthermore, sigma level can be calculated easily by using an Excel spreadsheet's function with the calculation of probability value. This function is called NORMSINV in Excel. The probability value is calculated from [1 - (total defect/total opportunity)]. Thus, sigma level has an equation in Excel: '= (NORMSINV (1 - (total defect/total opportunity))) + 1.5' from a suggestion (Taghizadegan, 2006).

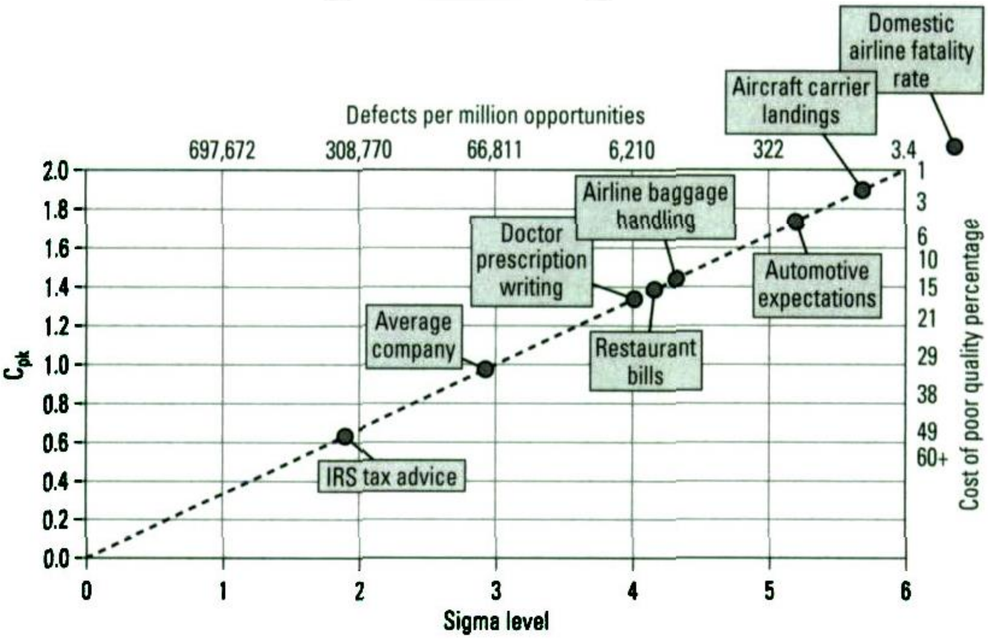


Figure 11: A monograph showing expectations of metrics in different businesses (Rudisill and Druley, 2004)

2.3.2 Seven Type of Wastes

According to Lewis and Jim, identifying and eliminating unnecessary activities is essential to the Lean for maximising full utilisation. These unnecessary activities can be presented as waste. There are seven types of waste, which are overproduction, waiting or idle time, transportation, defects, movement, inventory, and non-value adding activity (Lewis, 2005). Overproduction means production that creates units in excess of what is actually needed. Waiting is related to waiting time of machines and people. Transportation refers to unnecessary transport of units related to layout of the workplace. Defects refer to faulty units requiring more work and expense in correcting them. Movement means unnecessary movements of people in the production. Inventory means any type of storages such as raw material, work-in-process, and completed units. Finally, non-value adding activity can be described as any activity that adds no value to the product (Kuriger and Chen, 2010).

2.3.3 Causes-and-effects Diagram

This diagram is also known as an Ishikawa diagram, named for its creator. Furthermore, this diagram presents a general analysis of the impact causing the specific result for identifying the root causes. There is an example model of the diagram, as shown in Figure 12, to demonstrate a visual diagram of causes and effects (Stefanovic et al., 2014). Each diagram has differences depending on variations of problems and their causes. Therefore, this tool needs to adapt and adjust to suit each application.

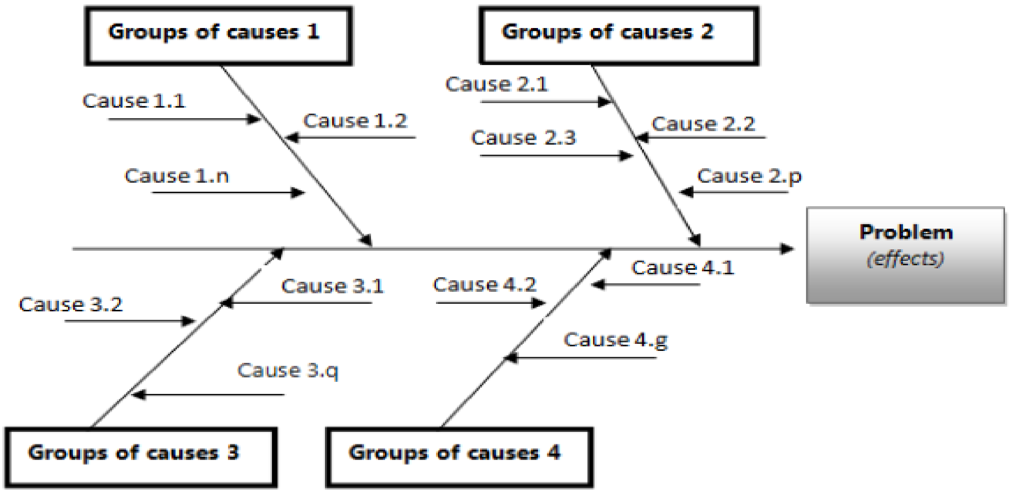


Figure 12: An example of causes-and-effects diagram (Stefanovic et al., 2014)

2.3.4 Modified Value Steam Mapping (modified VSM)

According to Ortuño and Pérex (2012), they combined the System Flow Diagram (SFD) and the Value Steam Mapping (VSM) together as modified VSM in order to save time of practitioners by selecting only necessary information. Modified VSM is less complicated because it only analyses selected processes in details. SFD illustrates the flow of activities in production, as shown in Figure 13. In addition, Figure 14 shows a simple example of a Value Stream Mapping, which contains details for every part of the processes.

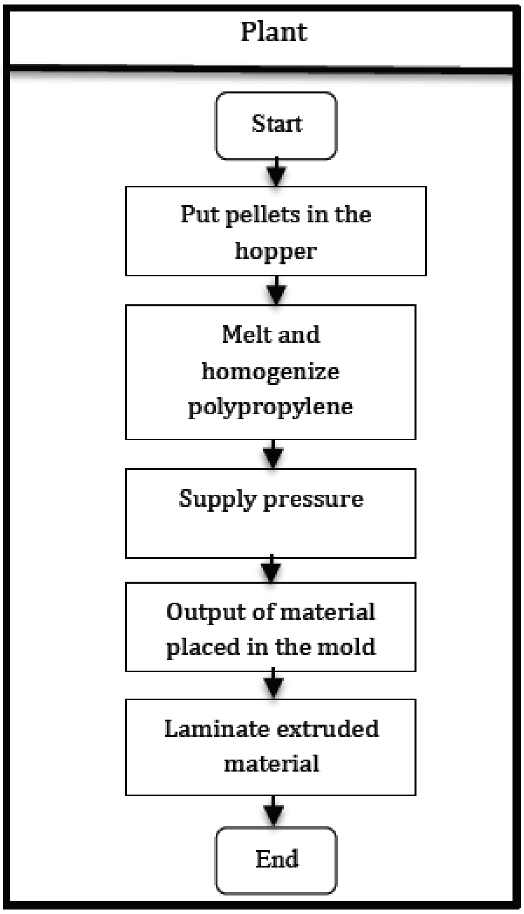


Figure 13: An example of the System Flow Diagram (Ortuño and Pérex, 2012)

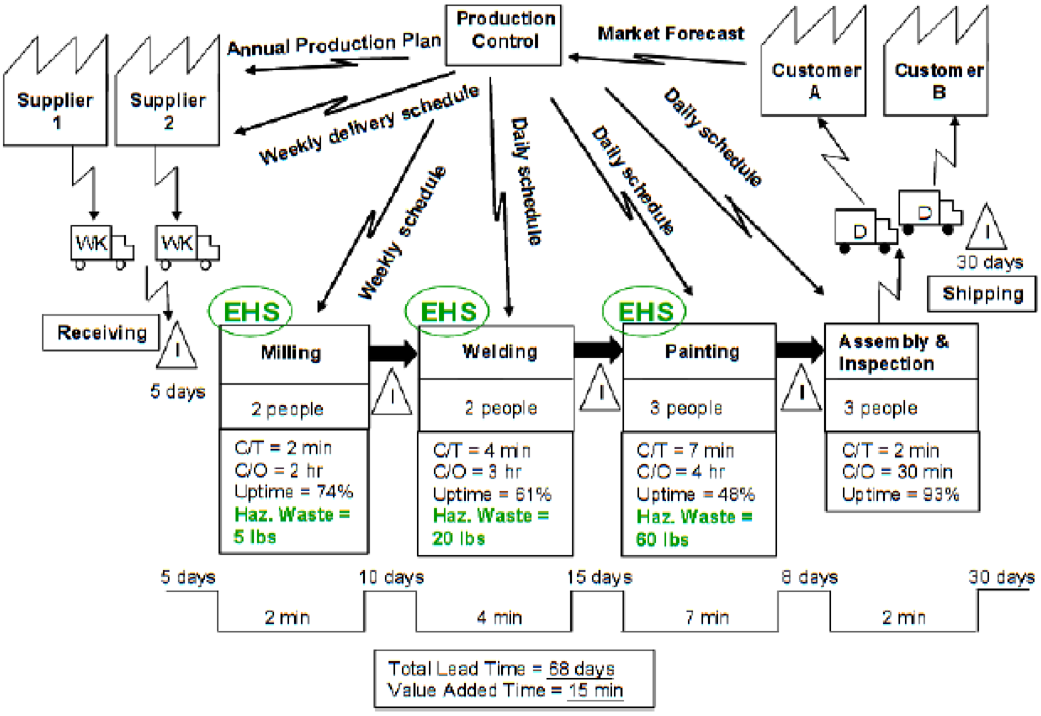


Figure 14: An example of the VSM (Ortuño and Pérex, 2012)

Modified VSM, as shown Figure 15, is a simpler visual diagram than the original one. In addition, Figure 16 show selected processes of the fourth process in detail by separating them from the main diagram of Figure 15. This makes applying the diagram easier, as well as making it understandable when presenting to other people. Table 3 shows examples of icons that using in Modified VSM.

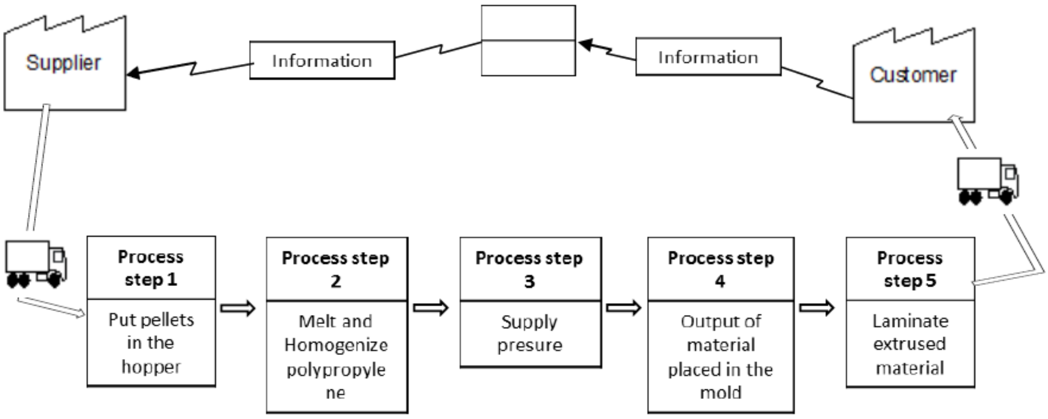


Figure 15: An example of the Modified VSM (Ortuño and Pérex, 2012)

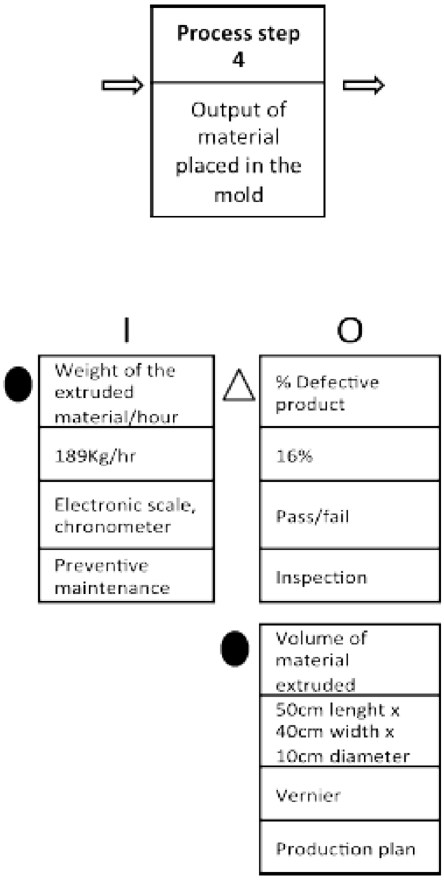


Figure 16: An example of the selected process from Modified VSM (Ortuño and Pérex, 2012)

Table 3: Examples of icons in Modified VSM

ICONS	ICON NAME	DESCRIPTION
▭	Process box	Describes an activity in the process.
🏭	Outside source	Indicates and identifies both customers and suppliers.
🚚	Truck	Indicates an outside delivery-either to a customer or from a supplier.
☰	Variable´s information	Describes: specification, Measurement System and Control of the variable if it exists.
↯	Electronic information	Indicates that the information is transmitted electronically.
→	Manual information	Indicates that the information is transmitted manually.
⇨	Finished good movement	Indicates when materials in a finished state are moved along the value stream. This can be a supplier moving it's a product to a company or a company moving its products to its customer.
●	Add value	Indicates that it is an add value variable.
△	Non-add value	Indicates that it is an non-add value variable.
◇	Decision	Indicates that it is a decision yes/no.

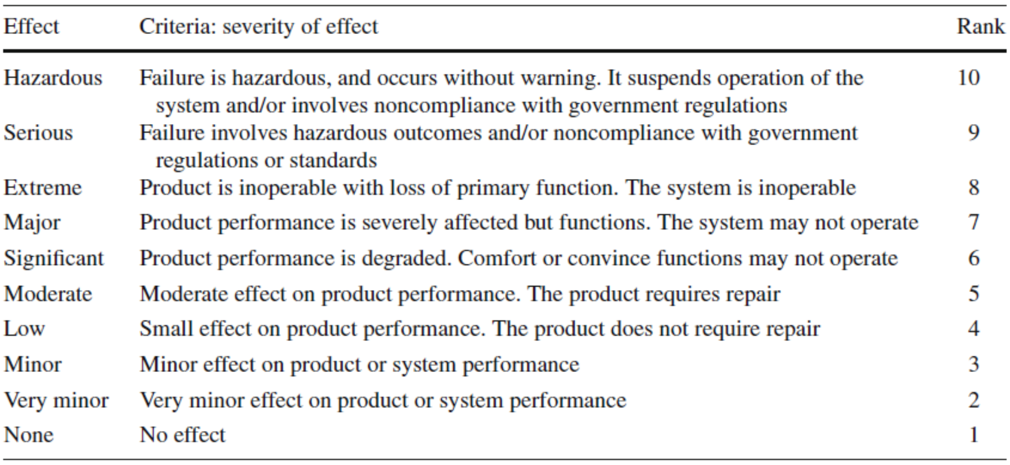
2.3.5 FMEA

Failure modes and effects analysis (FMEA) is a tool for evaluating failure events effecting on product operation by rankings. These ranks are calculation of risk priority number (RPN) giving impact rate of potential failure process to the operation. The RPN is calculated from multiplication of three criteria, which are severity, occurrence, and detection. It has ranges from 1 to 1000 because each of parameter has a rating from 1 to 10 where, 10 is the most of impact on each dimension of criteria to create problems to the system. The ranking scales of the three parameter have different terms, which are given from Table 4, Table 5 and Table 6 (applying-the-concept-of-exponential-approach).

Severity (S) is an effect on production system created from potential failure cause. Occurrence (O) is a likelihood of the failure occurring in the system. For Detection (D), it is a rating detection for failure process by the system. As a result, the higher numbers of ratings is the causing more damage to production system.

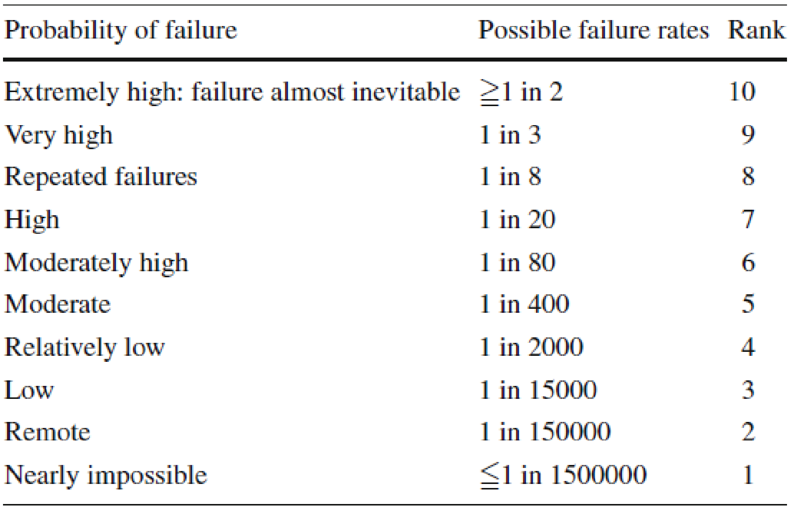
After calculation of RPNs, the highest RPN is the number one top priority that needed to be fixed and the priority starts from high to low RPNs.

Table 4: The ranking scales of severity (Ford Motor Ford Motor Company, 1988)



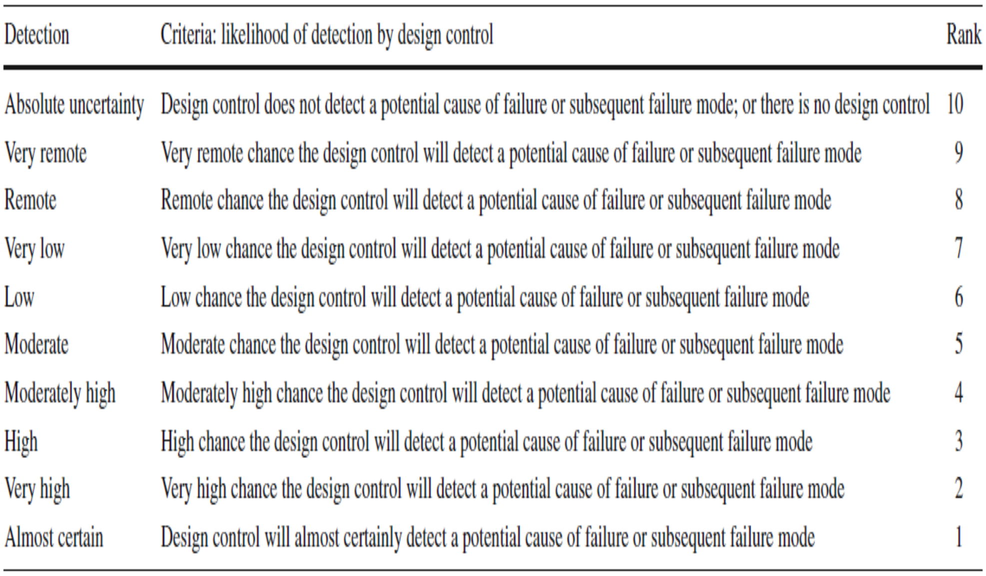
Effect	Criteria: severity of effect	Rank
Hazardous	Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations	10
Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards	9
Extreme	Product is inoperable with loss of primary function. The system is inoperable	8
Major	Product performance is severely affected but functions. The system may not operate	7
Significant	Product performance is degraded. Comfort or convince functions may not operate	6
Moderate	Moderate effect on product performance. The product requires repair	5
Low	Small effect on product performance. The product does not require repair	4
Minor	Minor effect on product or system performance	3
Very minor	Very minor effect on product or system performance	2
None	No effect	1

Table 5: The ranking scales of occurrence (Ford Motor Ford Motor Company, 1988)



Probability of failure	Possible failure rates	Rank
Extremely high: failure almost inevitable	≥1 in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2000	4
Low	1 in 15000	3
Remote	1 in 150000	2
Nearly impossible	≤1 in 1500000	1

Table 6: The ranking scales of detection (Ford Motor Ford Motor Company, 1988)



Detection	Criteria: likelihood of detection by design control	Rank
Absolute uncertainty	Design control does not detect a potential cause of failure or subsequent failure mode; or there is no design control	10
Very remote	Very remote chance the design control will detect a potential cause of failure or subsequent failure mode	9
Remote	Remote chance the design control will detect a potential cause of failure or subsequent failure mode	8
Very low	Very low chance the design control will detect a potential cause of failure or subsequent failure mode	7
Low	Low chance the design control will detect a potential cause of failure or subsequent failure mode	6
Moderate	Moderate chance the design control will detect a potential cause of failure or subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect a potential cause of failure or subsequent failure mode	4
High	High chance the design control will detect a potential cause of failure or subsequent failure mode	3
Very high	Very high chance the design control will detect a potential cause of failure or subsequent failure mode	2
Almost certain	Design control will almost certainly detect a potential cause of failure or subsequent failure mode	1

2.3.6 Control Charts

Based on Six Sigma, there is a powerful tool using to track and monitor improvement in Control phase. It is control charts, which have serval types based on data characteristics for demonstrating collected data in statistics approach. Two types of sample data are based on the Poisson distribution and the binomial distribution. The Poisson distribution has one point stating a term of defect as being errors on a production unit. Also, these errors do not mean that the unit cannot be unaccepted.

However, collected data in the term of binomial distribution have only defect or not defect meaning only two possible outcome from data. From these concepts, there are six types of control charts shown in Table 7 (Weinstein and Vokurka, 2006). For this case study, units are defined from inspection, which only have two outcomes. These two are passing or failing from the inspecting test. Therefore, Np char and P chart are suitable for this case.

Table 7: Types of control charts

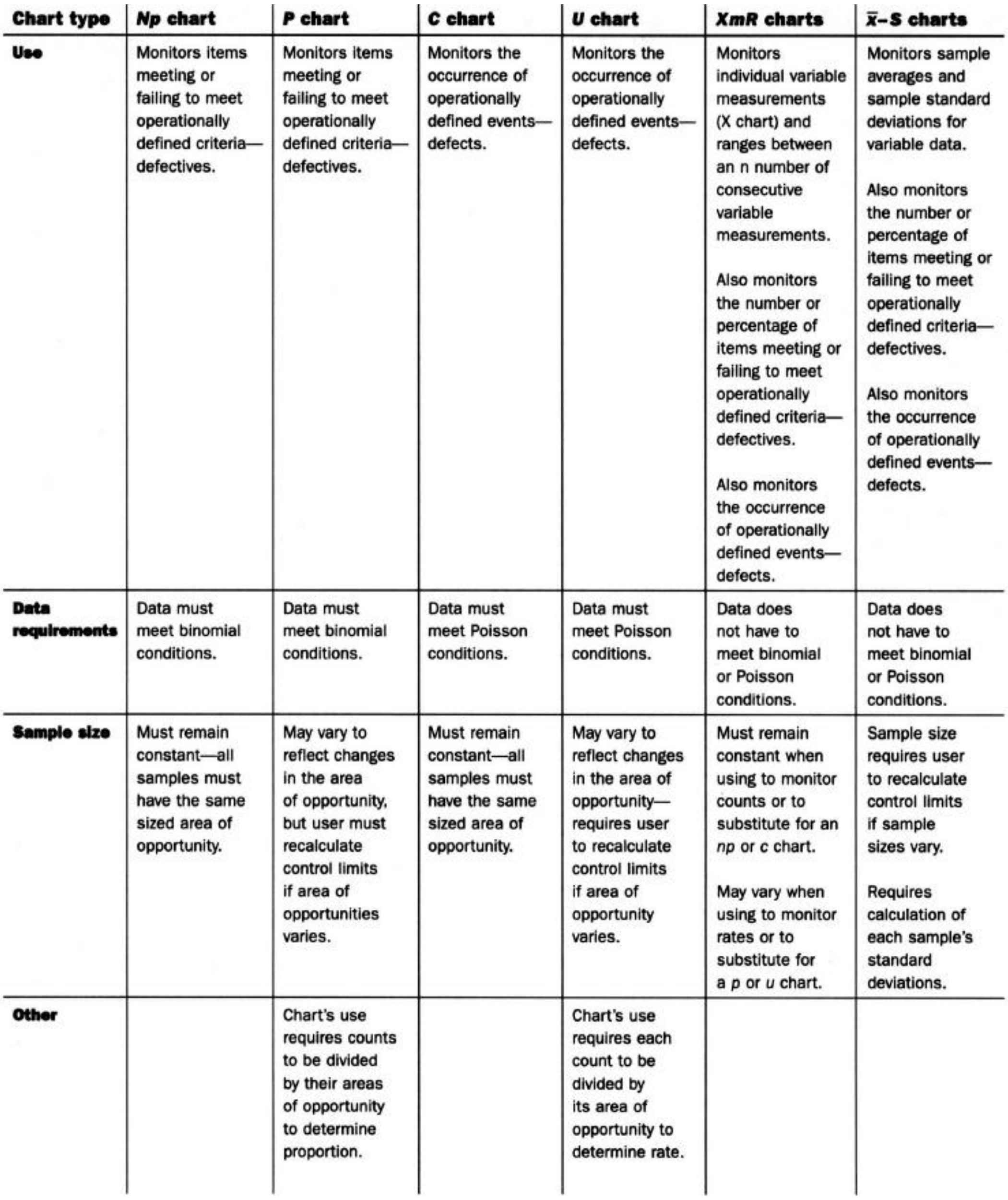


Chart type	***Np* chart**	***P* chart**	***C* chart**	***U* chart**	***XmR* charts**	**$\bar{x}$–*S* charts**
Use	Monitors items meeting or failing to meet operationally defined criteria—defectives.	Monitors items meeting or failing to meet operationally defined criteria—defectives.	Monitors the occurrence of operationally defined events—defects.	Monitors the occurrence of operationally defined events—defects.	Monitors individual variable measurements (X chart) and ranges between an n number of consecutive variable measurements. Also monitors the number or percentage of items meeting or failing to meet operationally defined criteria—defectives. Also monitors the occurrence of operationally defined events—defects.	Monitors sample averages and sample standard deviations for variable data. Also monitors the number or percentage of items meeting or failing to meet operationally defined criteria—defectives. Also monitors the occurrence of operationally defined events—defects.
Data requirements	Data must meet binomial conditions.	Data must meet binomial conditions.	Data must meet Poisson conditions.	Data must meet Poisson conditions.	Data does not have to meet binomial or Poisson conditions.	Data does not have to meet binomial or Poisson conditions.
Sample size	Must remain constant—all samples must have the same sized area of opportunity.	May vary to reflect changes in the area of opportunity, but user must recalculate control limits if area of opportunities varies.	Must remain constant—all samples must have the same sized area of opportunity.	May vary to reflect changes in the area of opportunity—requires user to recalculate control limits if area of opportunity varies.	Must remain constant when using to monitor counts or to substitute for an *np* or *c* chart. May vary when using to monitor rates or to substitute for a *p* or *u* chart.	Sample size requires user to recalculate control limits if sample sizes vary. Requires calculation of each sample's standard deviations.
Other		Chart's use requires counts to be divided by their areas of opportunity to determine proportion.		Chart's use requires each count to be divided by its area of opportunity to determine rate.		

2.4 Case Study Review

- A Framework and Case Study for Implementing Lean Six Sigma in Small Companies (Furterer and Smelcer, 2007)

This case study has one substantial difference from other articles, which is implementing the LSS in small companies as normally used in large organisations for the most effective improvements. This implementation to others is using the DMAIC approach as the main structure of its framework. Furthermore, there are stepping action plans, broken by 3-month intervals from three months to a year of planning. After the implementation, the company realised that simple tools can prevent defects and that production costs can be reduced by eliminating the defects.

From this article, it can be derived that basic lean tools such as the SIPOC, CTQ, 7 Wastes, and 5S are suitable for small companies because they are simple to use but require commitments to make successful implementations. This article provides great detail of tools and methods used in the framework for replication in other similar applications. Thus, other small companies can adjust and apply the framework as a useful guideline and problem-solving methodology.

- Reducing electronic component losses in lean electronics assembly with Six Sigma approach (Tan et al., 2012)

A case study of using Six Sigma in electronics assembly has the DMAIC approach as its main framework to reduce electronic component losses, which is similar to most of the Lean Six Sigma (LSS) implementation. Consequently, both Six Sigma and LSS share this similarity. This case demonstrates problems in electronic assembly, which is similar to this working project. This will help the project by sharing knowledge from common root causes of the problems. Furthermore, although this case uses practical solutions based on root causes, several causes have not been heavily investigated as critical causes to processes. Therefore, this study shows that the DMAIC approach can demonstrate the successful implementation of reducing the component losses, even if some parts are left unsolved.

The article shows that details of phases from DMAIC methodology are different in every application share the same structures. Also, it shows that all known causes have different priorities in solving them, while some of them can be improved using one solution. This case study suggests great value in using the lean concept as the core concept of any improvements, and that it also has more strength when working with Six Sigma's tools.

- Manufacturing Continuous Improvement Using Lean Six Sigma: An Iron Ores Industry Case Application (Indrawati and Ridwansyah, 2015)

A case application demonstrates usage of Lean Six Sigma to develop continuous improvement. DMAI cycle is used as a core processor to find problems, excluding C for the Control phase. There are several tools used in this case study, such as seven wastes, Process Activity Mapping (PAM), and Failure Mode and Effect Analysis (FMEA). This case study starts by identifying all types of waste and analysing them with FMEA to find root causes. After root causes are found, practical solutions are suggested in the Improve phase.

This case study shows that the author uses Lean Six Sigma as a guideline for finding root causes with systematic process. It combines concepts from Lean and Six Sigma. Thus, the application includes the concept of identifying and analysing problems from Lean and the concept of measurable indicators from Six Sigma. Moreover, practical solutions are based on the company's experience and expertise. This demonstrates that solutions for improving the working processes can be simple adjustments but serve the purpose of overcoming the problems.

- Implementation Analysis of Lean Sigma in IT Applications. A Multinational Oil Company Experience in Brazil (Filardi et al., 2015)

An article describes implementation of Lean Sigma methodology in an Oil Company to improve IT application. This implementation uses DMAIC approach as its main framework to improve existing processes while not aiming for Six Sigma level. The cost and time allocation process are measurable indicators for this improvement. The results after implementation show high improvements of cost and time. However, a potential weak point for the methodology is linked to people, as they cannot describe non-measurable indicators such as quality, effectiveness, efficiency, and customer satisfaction. Also, this implementation was delayed sixteen months from what was scheduled, showing that it is time consuming.

This article highlights key parts of improvements to other companies in the oil industry for giving opportunities of reusing the implementation. The key part is using Lean Sigma only in systems of production processes, which is not for improvements heavily related to people’s perspectives. It also demonstrates the existence of very specific tools and methods to each application inside the framework of DMAIC but also that it is able to replicate in other applications from shared problems.

- Implementing Lean Six Sigma to overcome the production challenges in an aerospace company (Thomas et al., 2016)

Lean Six Sigma (LSS) in this implementation is enchanting production of aerospace company. This case study fully brings fully potential usages of Lean and Six Sigma by integrating two well-known cycles from each of the methodologies, which are Lean cycle and DMAIC cycle. So, the integrated cycle starts with Specify value, Internal Value Stream, Create Flow, Pull on Demand, and Create Perfection from the Lean. Each of these five stages has its own DMAIC cycle. As a result, they use all potential strengths from the LSS by repeating the processes to pursue the perfection, a process called Strategic Lean Six Sigma Framework (SLSSF). This case looks at each stage of the cycle of the Lean and uses DMAIC cycle to develop improvements based on each stage characteristic.

This article introduces SLSSF to enhance production performance. However, this framework can only really be used in large organisations because implementing advanced techniques requires commitments from every member to develop themselves with the Lean and Six Sigma methods. Furthermore, the scale of the SLSSF is relatively large compared to other case studies since there are five cycles of the DMAIC approach. In contrast, other cases usually use only a single cycle of the approach. However, they share the common problems of engaging with members to fully follow the new systematic methodology.

To sum up, all suggested case studies share common problem-solving processes by using the DMAIC methodology. Each case study requires different methods for desired improvements, so all phases of the methodology may not be used, which commonly involves excluding the last phase of the Control phase. Furthermore, these case studies demonstrate successes in implementing the LSS. Despite this, some of the cases show no statistical data demonstrating improvement, as seen in articles by Furterer and Smelcer (2007) and Filardi et al. (2015). However, both articles show improvements as survey or action plan without statistical data. An article by Thomas et al. (2016) includes results of implementations in the form of measurable data: time reduction for building days to increase responsiveness and to reduce production cost. As a result, measurable data is more visible to justify results of problem-solving solutions, as shown in numeric results.

3 DMAIC Methodology Implementation

This chapter is the main part of the thesis by implementing DMAIC approach for reducing defect rates as following the proposed methodology after reviewing numerous literatures in previous chapter. For Define Phase, reviewing the production process gives clearer overviews of the process. Also, main problem and desired goal are defined in this phase (Furterer and Smelcer, 2007). For Measure Phase, data and information are transforming calculated metrics for being as indicators in this project. Modified VSM is used in this phase for separating non-added value and added value in each process. Additional information and evidences are collected to fill missing caps after reviewing the production process in details (Ortuño and Pérex, 2012).

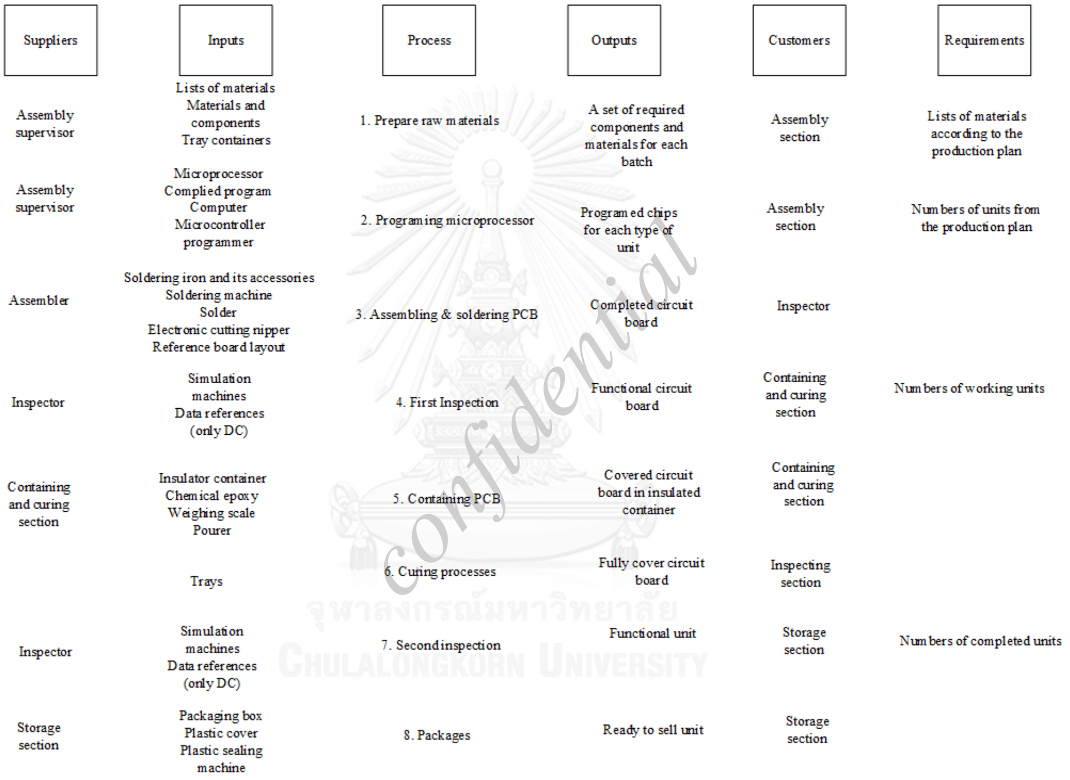
Next, Analysis Phase is for analysing all collected information for finding root causes of the problem by using seven wastes to identify all the waste in processes. Narrowing the waste down into defect type, collected defects are getting depth analysis for finding causes of each defect. After that, causes-and-effects diagram is used to find sub-root causes based on major causes. After identifying all sub-root causes, Improve Phase is taken place by using suitable solutions from both conceptual and practical solutions to solve the problem (Tenera and Pinto, 2014). The last phase is Control Phase, which monitoring improvements and creating systems to preserve the solutions.

3.1 Define Phase

The Define phase is for making a scope of the project by describing the current problem and target goals from its implementation. By refining information and adding details from the Introduction section, a visual diagram provides better perspectives to look at the project, as shown in Figure 17. From a suggestion, a SIPOC diagram is used in this phase for understanding requirements and preparing information for the next phase (Souraj et al., 2010). Moreover, the diagram integrates information and lays out a working flow capturing an overview of the processes. This SIPOC diagram views manufacturing processes from Introduction Chapter and add details into it. As a result, each process is defined in details knowing all variables that can cause problems. This makes clear picture of the processes before forming Modified Value Steam Mapping

(Modified VSM) in the Measure Phase. Also, it shows inputs and outputs of each process, which are linking to their next processes.

Considering the processes from the SIPOC diagram, this research only focuses on one assembly line of CDI units as having the most defect rate of all three product categories. Therefore, the goal is to reduce the defect rate of CDI units alone as stated at the Statement of Problem section. The company has a target defect rate of 1%. However, the problem, which this research is trying to resolve, has set the defect rate higher than the target collecting data from the year 2015.



Suppliers	Inputs	Process	Outputs	Customers	Requirements
Assembly supervisor	Lists of materials Materials and components Tray containers	1. Prepare raw materials	A set of required components and materials for each batch	Assembly section	Lists of materials according to the production plan
Assembly supervisor	Microprocessor Complied program Computer Microcontroller programmer	2. Programing microprocessor	Programed chips for each type of unit	Assembly section	Numbers of units from the production plan
Assembler	Soldering iron and its accessories Soldering machine Solder Electronic cutting nipper Reference board layout	3. Assembling & soldering PCB	Completed circuit board	Inspector	
Inspector	Simulation machines Data references (only DC)	4. First Inspection	Functional circuit board	Containing and curing section	Numbers of working units
Containing and curing section	Insulator container Chemical epoxy Weighing scale Pourer	5. Containing PCB	Covered circuit board in insulated container	Containing and curing section	
	Trays	6. Curing processes	Fully cover circuit board	Inspecting section	
Inspector	Simulation machines Data references (only DC)	7. Second inspection	Functional unit	Storage section	Numbers of completed units
Storage section	Packaging box Plastic cover Plastic sealing machine	8. Packages	Ready to sell unit	Storage section	

Figure 17: A SIPOC diagram (confidential)

After process mapping was identified, Critical to Quality (CTQ) is formed to identify factors, which are relating to defect reduction. Production quality, unit quality and overall production are the main three CTQs of defect reduction. Thus, these three are considered main indicators to evaluate overall production after implementation.

Table 8: CTQ for the defect reduction

CTQ	Metrics
Production quality	Defect rate of the production in percentage
Unit quality	Rate of failed components
Overall production	Compare sigma level with average standard level

3.2 Measure Phase

Following the DMAIC method, the Measure phase follows the definition. This phase will continue the processes of problem-solving by gathering data and information that indicate current performance (Mehrjerdi, 2011).

Focusing on defects from the CDI units, Six Sigma has its indicator of variation called sigma level. This variation has an ideal value of 6σ or 3.4 defects per million opportunities (DPMO). It shows that there is a very low chance of defects appearing in production processes if the production line is able to maintain high-quality standards. Thus, a higher sigma level is the better because it will keep the number of defects low and provide a competitive advantage (Samuels and Adomitis, 2003). There are four basic indicators of production performance: DPMO, percentages of defects, yield level, and sigma level (Adeyemi, 2014). Using sigma level as additional indicator is for comparing production system with standard quality from other companies.

3.2.1 Sigma Level

By calculating raw data to be in the form of these indicators, Table 9 shows the results of the calculations from 2015. The Sigma level of pre-improvement performance is 3.48σ. Normally, it is ideal to achieve a sigma level of 6σ because it requires high commitment and working standards from the whole organisation as being world-class manufacturing. For an industrial level, the sigma level would typically be 4σ, as this is the industry average (Lucas, 2002). This case is thus below the industry average. Therefore, pushing the company to the average standard of the industry would reduce the costs of poor quality for the company using the average sigma level as one of indicator. This indicator is able to compare overall production with other companies.

Table 9: Performance metrics before improvements (confidential)

Sigma level	
Defect (%)	2.37
Yield (%)	97.63
DPMO	23,698
Sigma level	3.48

3.2.2 Modified Value Steam Mapping

The production processes are roughly defined by using SFD and SIPOC diagrams. However, those diagrams show basic production processes without any details on each stage of the production. Value Steam Mapping (VSM) is one of the lean tools which details the overview and each production stage by examining them from the lean perspective. Identifying waste in the production for elimination is one of many perspectives from the lean perspective. VSM incorporates this concept in its diagram by identifying which activities are either value adding or non-value adding activities (Manos, 2006).

To present the VSM in a well-understood form, Modified VSM has been introduced by Ortuño and Pérex (2012). This modification slices one complex diagram into smaller simple pieces. This aids the implementer in observing and focusing on each single process. Figure 18, Figure 19 and Figure 20 show the Modified VSM for the processes. It is divided into two sections: the first describes the overall processes and the second shows details of each process.

Figure 18 shows the overview of the processes to see flows of material and information flows. These eight main processes are a pathway to follow in order to find causes of the defect problem by tracking from material flow as defects appear inside this pathway. This diagram shows a cycle starting from customers in order to create production plan.

From Figure 19 and Figure 20, Process 1 has only non-value added activities. If it cannot be removed, it should be reduced spending time on this process. For Process 2, it is value added activity because it gives an output of programmed microprocessor. For Process 3, it is also value added activity from assembling and soldering circuit boards. For Process 4, it is inspection for completed circuit boards, which is non-value added activity but it is essential for detecting defects before passing through other processes. Process 5 is for covering PCB with case and epoxy for shock and moisture resistances, which does not add value until curing process finishing. For Process 6, it give an output of completed unit as added value. Process 7 is second inspection, which is also essential to the production since Process 6 causes unit to fail. The last process is Process 8, which getting added value output from packed products.

Figure 19 and Figure 20 describe each process in depth by identifying inputs and outputs from each one and then classifying them into non-value or value adding activities and items. In addition, some of the processes show only non-value adding activities, such as preparing raw materials and inspection. Materials passing through these processes are not increasing value but are still important to the production. From a lean thinking point of view, these activities should be eliminated and removed as waste.

However, not all wastes can be removed as they are often essential parts of the processes. Therefore, they should be reduced instead by keeping consumption as low as possible. For example, the two non-value adding activities cannot be removed immediately from the whole process because these support others to prepare working units for the next one. For the preparation process, every unit needs a list of materials and components with specific quantities.

Other processes in the assembly line cannot be performed without the preparation because an assembler needs to know the exact numbers of components in order to create requested batches of finished units. For the inspection, it is a process checking on qualities of units and separating defects before going through to the next processes. Therefore, the defect units affect production costs in smaller amounts before adding more values to them in the next processes. However, this process has not prevented the defect problem but has removed defects from the processes. Therefore, this research is about finding the causes of the problem and forming solutions to prevent them from happening.

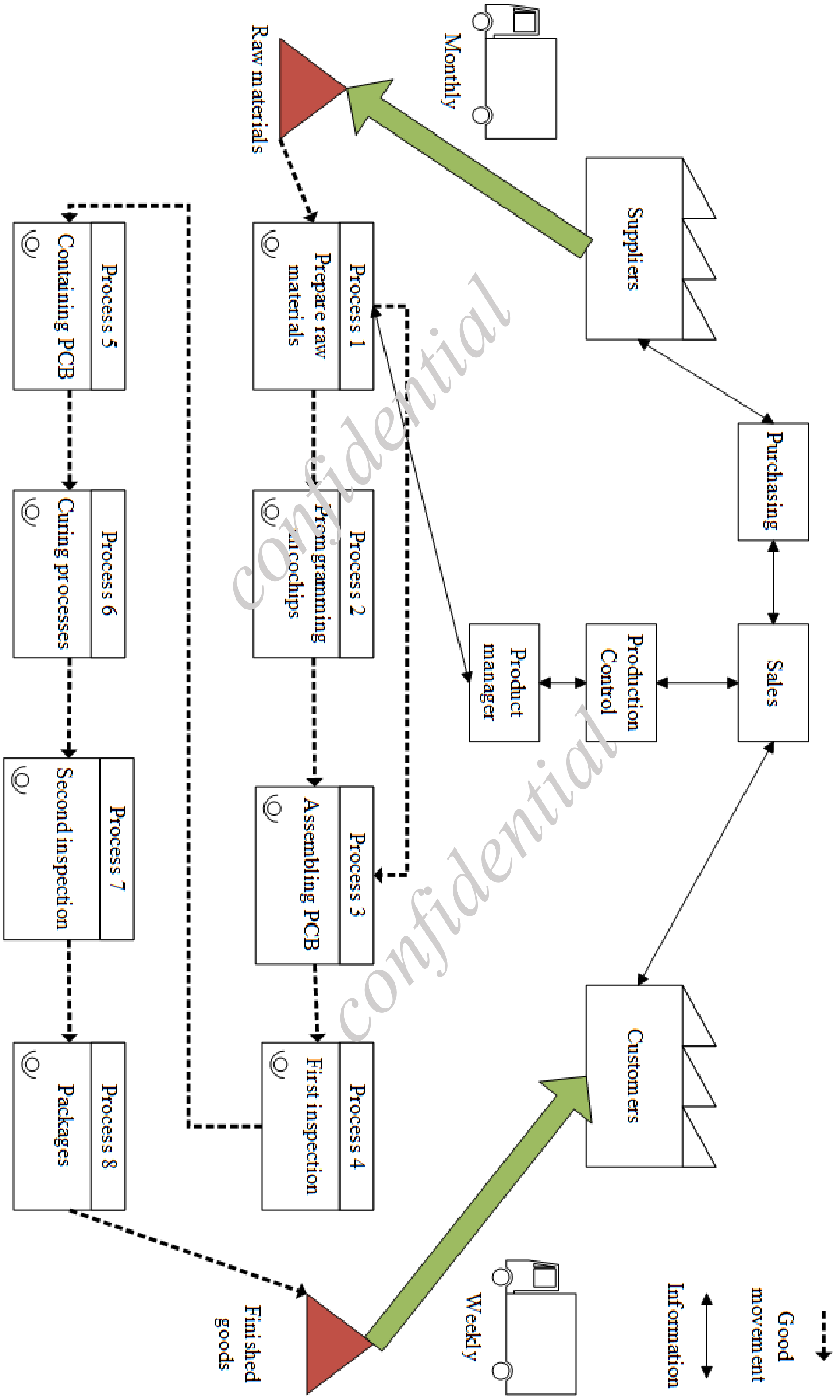


Figure 18: Modified VSM for the overview of the processes (confidential)

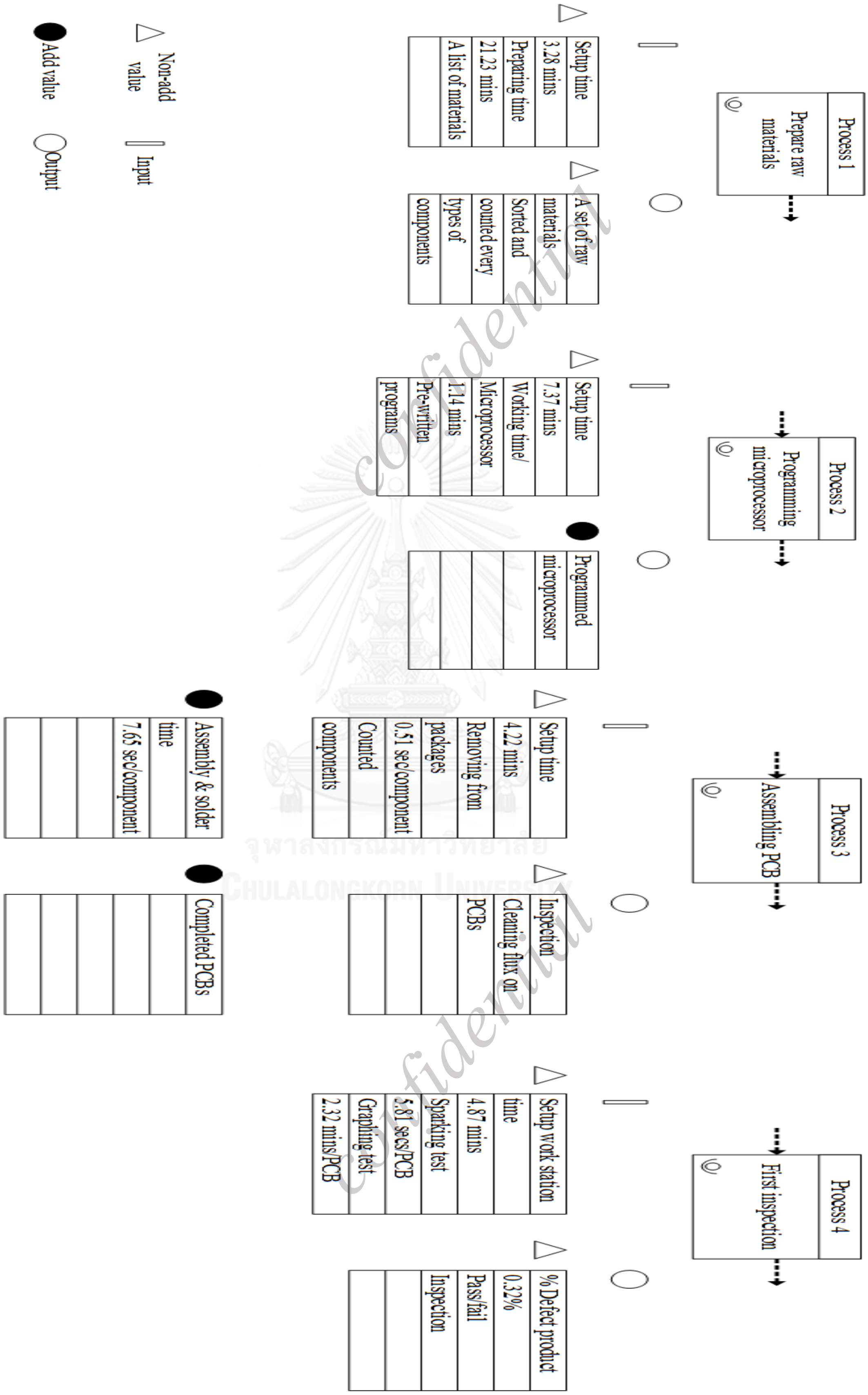


Figure 19: Modified VSM for each process (confidential)

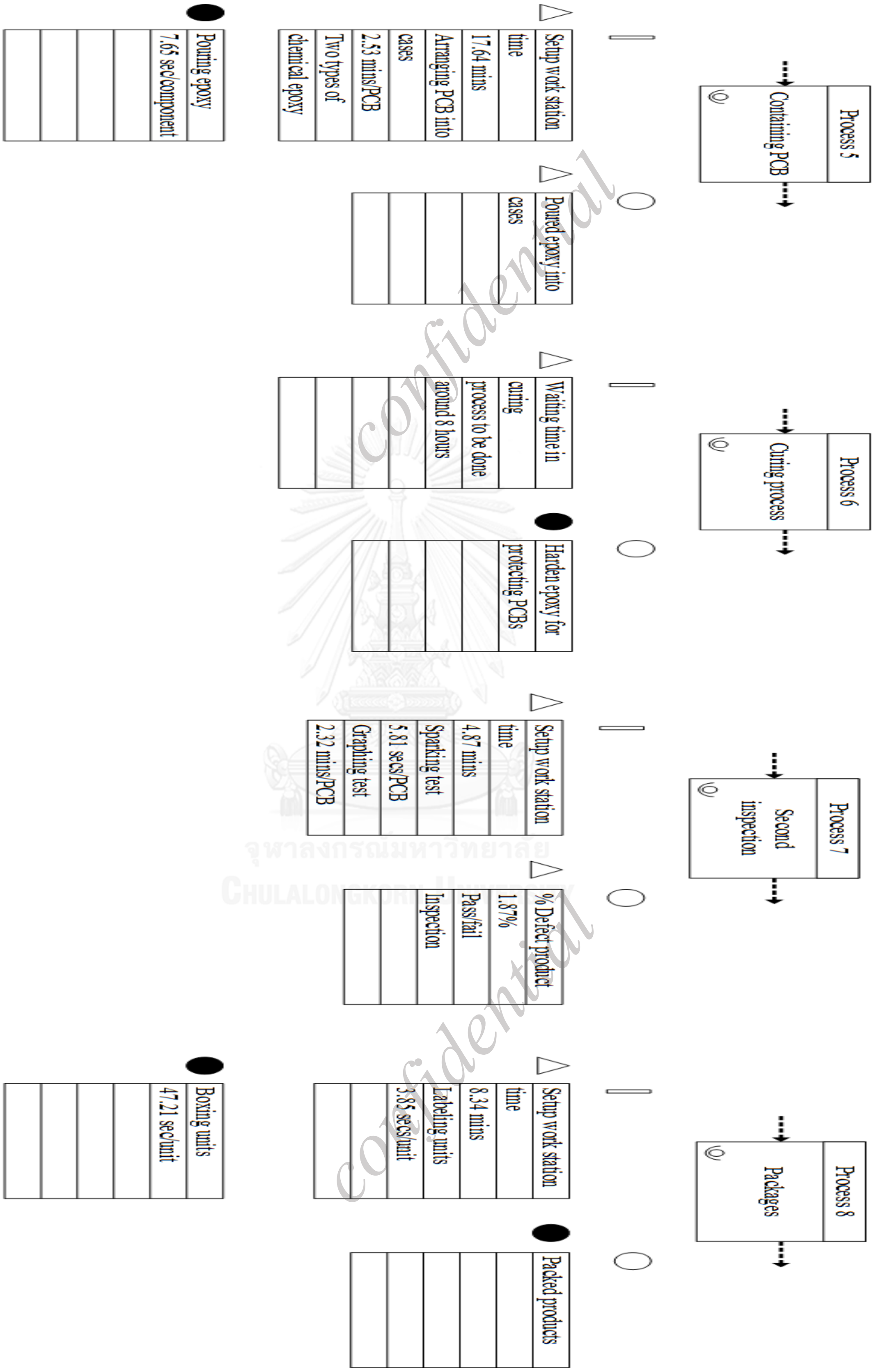


Figure 20: Modified VSM for each process (continue, confidential)

3.2.3 Defects

By gathering new information concerning defects from both AC and DC units, the data was collected from one selected model from each type of units, since the past records of defects did not specific defects in sufficient detail for solving the problem. Thus, two models for gathering missing evidences are selected based on the most frequently produced model from each type. Model A is the AC unit, which has higher manufacturing volumes with few components and materials. Model B is the DC unit, which has the opposite characteristics to the model A. Figure 21 shows Model A on the left and Model B on the right.

Figure 21: Model A and Model B (confidential)

One batch of Model A contains a thousand units but model B has only 200 per batch. On average, three to four batches of Model A are per month, whereas only two to three batches of Model B are produced. Moreover, Model A needs components to assemble one unit less than Model B's around three times Therefore, Model B requires more experience and skills from assemblers since it has many more components with similar dimensions of circuit boards.

Therefore, seven batches of Model A and five batches of Model B were collected as new evidence over two months of March and April. From the collected data, Figure 22 shows percentages of average defects per batch for these two models.

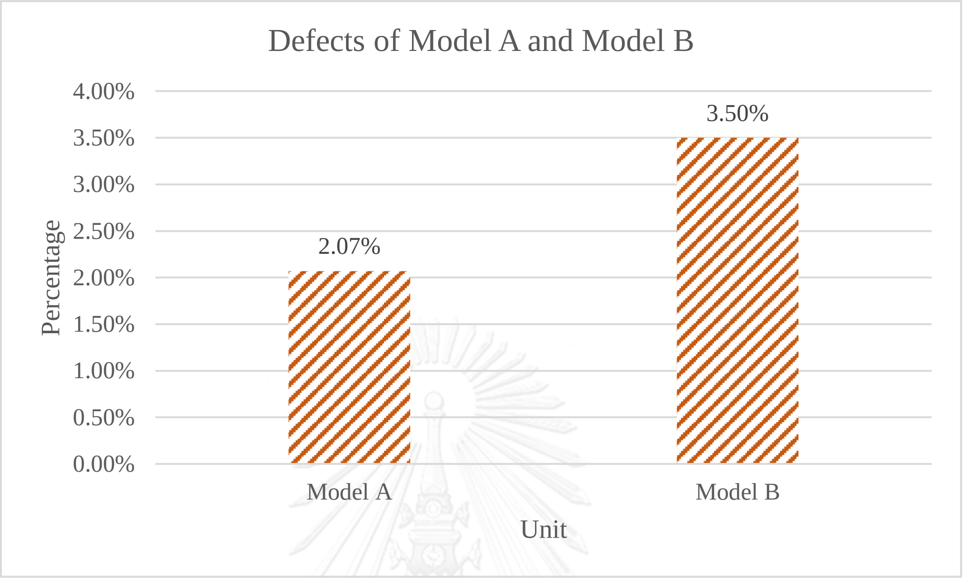


Figure 22: Defects of Model A and Model B

Model B has an average rate of defects per batch of 3.5%, which is slightly higher than Model A's 2.07%. High defect rates make the cost of production of Model B much higher because of reworks, scrapes, and materials. This is because Model B contains many more components than Model A, which makes it more complex to locate failed components to be replaced with new ones. These numbers are presenting portions of the whole defects occurring in the production. However, they are solid evidences and other models share the same production processes, which cause defects. Furthermore, they are approximately the same as the total percentages of defects for CDI units.

Looking at both models using the Six Sigma indicator, Table 10 shows that both models have a sigma level lower than the average industrial target of 4σ. Model B has a sigma level lower than Model A, even though it has a smaller batch size. Thus, high numbers of manufacturing units per batch does not mean that rates of defects will correspond accordingly.

Table 10: Performance metrics before improvements for Model A and Model B

Sigma level		
Metrics	Model A	Model B
Defect (%)	2.07	3.5
Yield (%)	97.93	96.5
DPMO	20,714	35,000
Sigma level	3.54	3.31

3.3 Analysis phase

In this phase, information and evidences from the Measure phase are pulled apart into small pieces to spot every important details and then analysing them by the lean thinking. There are many angles and dimensions to analysis the same problem for finding solutions. Thus, this phase will discuss various options for finding root causes of the problem.

3.3.1 Seven Wastes

The Modified VSM shows details of every activity in the production processes. From the lean, the concept of seven wastes identifies wastes in the production by categorising wastes into seven types, which are all mentioned in the previous chapter. An eighth waste is added to the traditional seven wastes, which is related to humans being an important part of production processes. Human resources drive flows of the production, which can be any parts of the production from creating systems to implementing them. Hence, unutilised human resource is one of the wastes in the production since it covers various activities (Smith, 2014).

Based on the concept of seven wastes, some activities are identified as wastes. Firstly, processes 1, 4, 6, and 7 are clearly non-value added activities that should be reduced, if they cannot be removed. Waiting time occurred when work-in-process (W.I.P.) unit is transferring through each process. Secondly, defects are mostly found at Process 7. After investigating processes 4 to 7, several issues were found. For example, in Process 4, an inspector re-tested samples of tested W.I.P. units. The result showed that some of them are faulty units (mostly AC units) even though, they passed the sparking test. In processes 5 and 6, during containing and curing processes, chemical reactions release heat energy to the atmosphere. The heat is a major issue for electronic components, which depend on heating durations and heat temperatures. Hence, heat is a factor in causing faulty units, making completed units needing reworking, which generates further costs.

Since heat is the influential factor, working stations for steps 5 and 6 are located in another area at the back of the factory, having better air-flow and spaces. However, this creates transportation waste. Meanwhile, most of the processes are located in the same area, excluding working stations for processes 5, 6, and 8. In addition, the soldering process for AC units is done in another area by using soldering machines for multiple tasks at a time. Distances between the stations should be re-adjusted to keep the waste at a minimum level.

Fourthly, waiting in curing process for many hours is another waste, which should be reduced. It also takes up spaces for laying units in the curing process. On a particular day, only certain numbers of units are in the processes. This part may reduce the rate of production.

As a result, three issues are focused on, which are based on seven wastes: testing processes at inspection, heat at curing process, and production flows such as material flow and work instruction. While the first two are related to factors with defects, the last one directly effects costs of production. These issues provides useful information that can be used later in identifying root cause of defect.

3.3.2 Analysing Defects

From the Measure phase, those defect samples are taken for further investigation. This identifies causes of the defects because every defect is caused by different reasons. Thus, separating the samples into smaller pieces of evidence can locate failed components in each defect unit. Most of the samples are collected from Process 7 in Figure 18, which involves a hard coating on top of the unit to cover electronic components.

Unpacking the finished unit requires substantial skills to avoid creating more damage to the components. Therefore, only portions of defect samples are torn apart to find new evidences. After removing the cover, sensitive components such as capacitor and transistor at high-voltage part are firstly checked by measuring their electronic capabilities. If they are no longer acting according to their electronic functions, they are taken out and replaced with new ones. This is a part of the reworking processes, which adds further cost to the unit. Thus, finding causes of the problem to prevent this from happening is essential.

As seen in Figure 23, some of the samples have more than one failed component in the same unit, because some of components cannot be checked an inspection is conducted. Furthermore, they are energized by an electricity from the simulation machines. If one component malfunctions, it may cause other components to fail since a short circuit makes high voltages able to pass through components that cannot survive them. This normally damages components relating to the voltages, such as the capacitor and transistor. Both capacitor and transistor damaged at different rates. Thus, Model A has only these two types of failed components from the samples because its circuit is not complex. Meanwhile, Model B has many critical components, so it has five common defect components and still shares a trend with Model A.

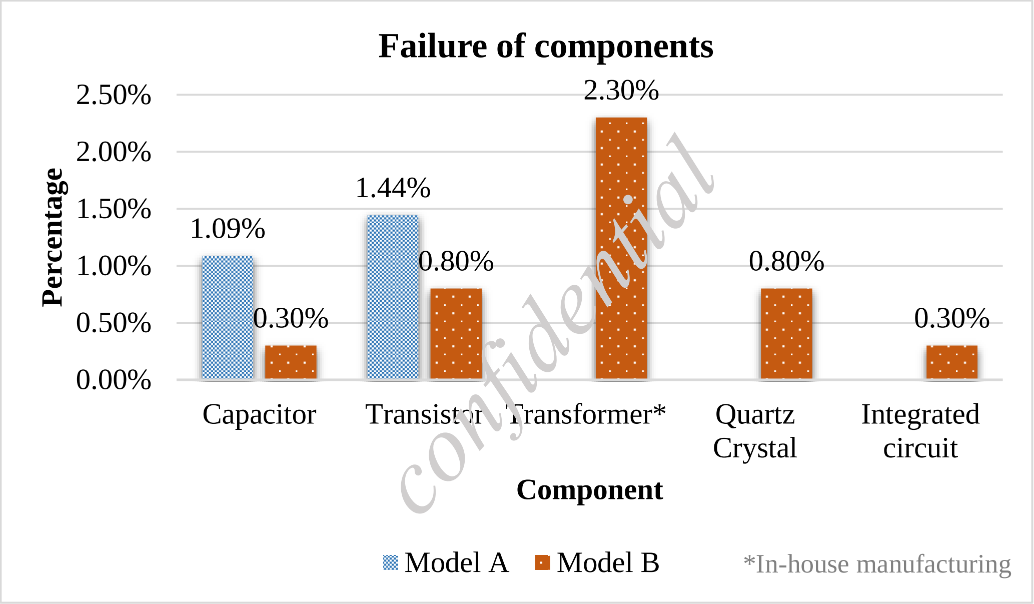


Figure 23: Failure of components (confidential)

Figure 23 shows that transformers have the highest rates of the five regarding both models. The transformer is directly related to high voltages and is also manufactured by the company. Hence, there is a chance that a failed transformer was caused by its manufacturing processes and its in-house manufacturing. Moreover, both models share the common damaged components of the capacitor and transistor. Both components are related to high voltages, which may be caused by the inspection processes. Therefore, tracing the processes back is necessary to find root causes of the problems.

After analysing key information, KPOV (Key Process Output Variables) and KPIV (Key Process Input Variables) are defined by gathering information from the MVSM. Also, they are factors may cause defects in processes. Two KPOVs that are related to the defect rate are short circuits and failed components. Furthermore, the two are located in different sections of the processes separated by the first and second inspections. The short circuit is found in processes 3 and 4. Yet after these processes, the failed component appears in processes 5, 6, and 7.

Figure 24 shows the first KPOV, containing three KPIVs: electronic components, assembling and soldering, and testing steps. Figure 25 shows the second KPOV having one same KPIV as the first one, which is testing steps. As a result, the testing steps are of more value in finding countermeasures or solutions than others since they appeared in both KPOVs. Another important KPIV is the heat in curing process, causing electronic components to fail during the processes. Therefore, these two KPIVs are considered to be causes of defects, which are taken into account in finding root causes.

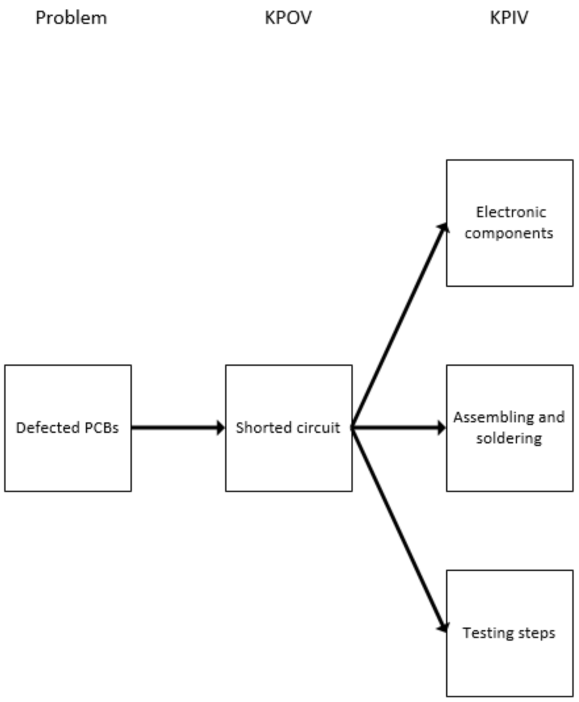


Figure 24: The first KPOV

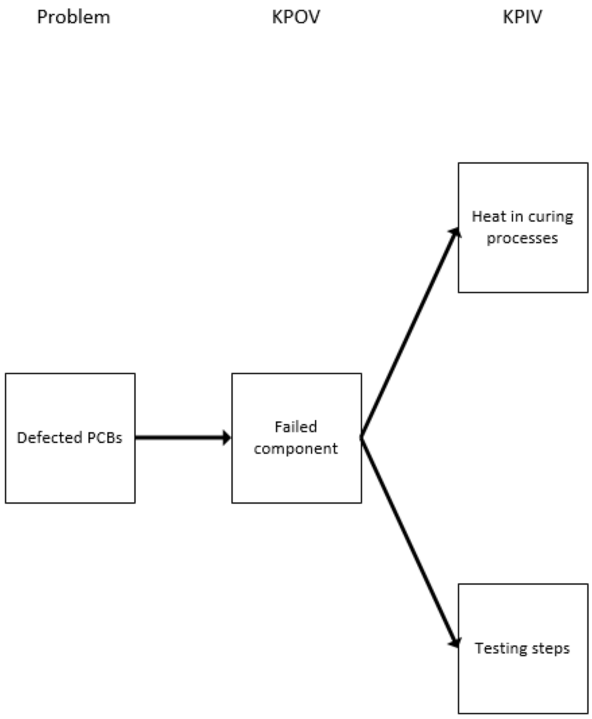


Figure 25: The second KPOV

3.3.3 Causes-and-effects Diagram

By taking those damaged components to further investigation, a causes-and-effects diagram is used to group root causes into four dimensions: material, manpower, method, and machine and tool (Ploytip et al., 2014). These four dimensions are common causes across industries. Each dimension provides a unique aspect in examining causes of the defect so, making it easier to detect actual causes and acting similarly to a funnel by narrowing the causes down.

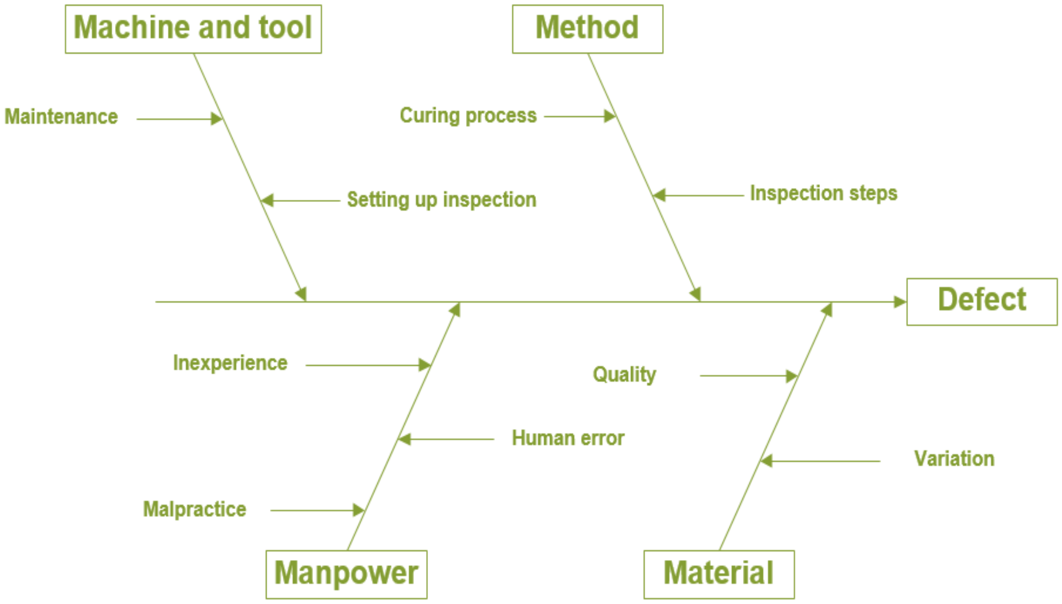


Figure 26: Causes-and-effects diagram

As Figure 26 illustrates, each dimension has several sub-root causes specifying actual causes and taking identified wastes from seven wastes into consideration. The sub-root causes were gathered based on defect samples in the previous section. Starting from Machine and Tool, it describes causes created from faults in how workers use these machines as two aspects of maintenance and setting up inspection. Next, the Method looks at each instruction and step of the processes that cause the defect. Curing process and inspection steps are sub-causes of the Method. Manpower refers to causes directly created by humans, including inexperience, human error, and malpractice. Finally, Material is a group of causes from raw materials and components causing working units to be faulty in the assembly line. As a result, the quality and variation of materials belong to this group.

3.3.3.1 Machine and tool

After discussing an overview of the causes-and-effects diagram, details of every sub-cause must be well described in order to understand each of them for improvements. From machine and tool, maintenance is related to maintaining tools such as soldering equipment and simulation tools. From an observation, some soldering irons have unclear nips, making heats from them release unstably and unevenly. This means that the solder may not melt down easily, so it takes longer than it should, which may damage components. Moreover, crystal is a very sensitive component to the heat, so heating for too long damages the crystals and replacement units are needed during the inspection if they are completely destroyed. Next, a fixed voltage display is in setting up inspection at the short length of the cap between the terminal on the left and that on the right, as well as motor speed for testing only AC units, as shown in Figure 27. However, the long length of the cap and variations of motor speeds are important to the inspection process because they provide better views for the inspector when separating defects.

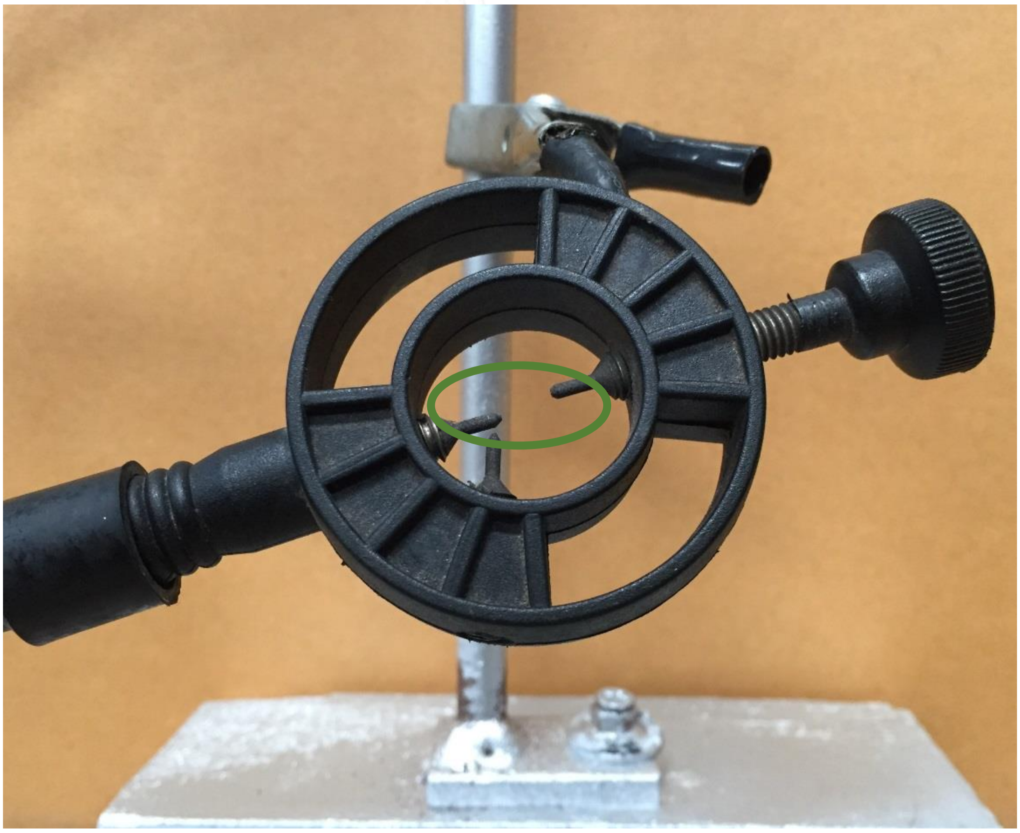


Figure 27: A sparking display from the physical simulation

3.3.3.2 Method

- Curing process

Moving to the Method phase, the observation shows that there is no airspace between each unit, as shown in Figure 28. This causes some components to break down during the curing process. The curing process is one of the sub-processes of covering PCBs by using chemical epoxy to fill up spaces after the units are placed in containers. Every electronic circuit board needs some sorts of protections because they are very sensitive to environments and have electricity running across them, which is harmful to humans. Therefore, units require protections for themselves and their users.

Heat from chemical reactions is released during this process from epoxy and its adhesive, and they start to rise up at high temperatures and subsequently cool down (Gibson, 2017). During the high-temperature, the heat is released from the units to cooler environments, making heat transfer from one to another if they are connected to each other (Smith et al., 2013).

Figure 28: An example of placing units without any space between them (confidential)

Normally, air surrounds any objects in the Earth’s atmosphere, so the unit is in contact with the air. However, if there is no space between the units, heats can transfer from one to another, meaning that cooled units can be heated by others and that heat will escape to the air slower because of small contact areas between the unit and the air. This fact that components will take a longer time to cool down leads to them being damaged.

- Inspection

For inspection steps, one important step is missing when using simulations, which is discharging electricity from electronic circuits in every units at Process 4. During the first inspection, PCBs without any cover are tested by energising them with electricity from the simulations. This creates possibilities that inspected units still have electricity in them because the capacitor can store an electric change. Hence, the electricity can transfer to any other areas of the unit itself or of other units if they are in contact with each other or are in the same conducting medium. This cause leads to higher defect rates in the second inspection, as seen in Figure 19 and Figure 20, and this is verified by rechecking the inspected units during the first inspection. When this is done, it becomes clear that there are some defects occurring after the first inspection, which are potentially caused by the inspection itself.

Another point about inspection steps is that inspection changes from detecting to neglecting the defect, which is failed to do its job, because it cannot detect defects in some cases. From this, voltage output from the AC simulation is displayed on a spark-display, as shown as Figure 27. This display can be adjusted lengths of sparking output by turning an adjusting knot that attached on the display. Furthermore, the length of the spark is a distance of electric charge travelling from one place to another, resulting a further distance showing the strength of charge to travel. From the observation, a setup of the AC simulation has not set distances long enough to separate a weak and discontinued spark from a strong and acceptable spark. Hence, the adjustment of the display is critical to locate detects during the inspection.

3.3.3.3 Manpower

- Inexperience

Currently, employees tend to change their jobs more frequently, creating problems for the company in training new employees and resetting the associated learning curve for employees to be familiar with electronic assembly. Therefore, inexperience is one cause of the defects, since this working type is very specific and electronic components may look similar in shape but be different in value. This means that workers who are unfamiliar with electronic components need to take time to get used to working processes.

In addition, there are many areas of caution when manufacturing electronic components. Some components are very sensitive to electricity, which cannot be seen by human eyes. Therefore, measurement tools such as digital multimeters and oscilloscopes are required to check component capabilities after components have been assembled in the production line. Electronic components can be damaged easily and in a manner that is invisible until they are measured. Hence, one mistake spot caused by inexperience may cause more than one component to fail, because they are connected in circuits.

- Human error

At the moment, the assembly line is done mostly by humans. It cannot be denied that humans are imperfect and prone to error. Thus, human error is another cause of defect problems. In the assembly line, many electronic components have the same shapes and sizes but have small marks to indicate their values, which humans easily mistake by taking the wrong values of the components. Therefore, errors in assembly usually come from humans themselves. Based on the observation, an opposite direction of placing components in a circuit board is one of the common errors appearing in the assembly line. Components such as diodes, transistors and polar capacitors have specific directions that must be followed when placing them in their footprints. Hence, placing them in the wrong direction may allow electricity to damage the components during the inspection. This is because electricity is running into the units and passing through the components in opposite direction. Moreover, it may affect other components that connect to the damaged one since they are all linked in the same circuit.

Another common error made by assemblers is creating an excessive amount of solder linking nearby connections, creating short circuits. This may lead to damaged components. For an example, a polar capacitor usually has two terminals, so if excessive solder connects two terminals together, this will damage the component when electricity passes through. This is because each terminal of the component should not interfere with each other, since they have polarities. In this part, assemblers will inspect their own working units before placing a tray and transferring to the next processes. Furthermore, DC units mostly have small circuit boards with many components making each solder point being close to another. Thus, assemblers can easily solder connections in wrong places and miss the mistakes without fixing them.

- Malpractice

In the assembly line, malpractice greatly impacts defect rates, as it can be defined as not following the correct processes by skipping some sub-processes. Some working processes have more sub-working activities than others. This creates more complexities for workers, which the lean thinking tries to get rid of by using work standardization (Ingvaldsen et al., 2013). Inspection process and sub-manufacture of transformers are two major areas where some sub-processes are missed. This creates incorrect working processes among other workers, as others follow the example of malpractice. This would encourage the whole company to create defects, which may lead to the worst-case scenario of claims from end customers when these defects had reached them.

By starting off with the inspection process, where the whole unit is powered by electricity so, one small mistake may cause the unit to fail, which cannot be undone. This is because electricity will easily damage some very sensitive components when it passes through areas it is not meant to. Therefore, the inspection process by using simulations is critical to the whole manufacturing process being both detector and creator of the defects. This is because of improper ways to do the inspection leading to damage the unit.

Performing a closer analysis of testing steps, these can be divided into main two parts: sparking tests and graphing tests. A sparking test is done by simulating motorcycle ignitions from physical and digital simulations. However, a graphing test is used only for DC units and uses digital simulation to show different position of ignitions, specific to each model of motorcycles.

Physical simulation of a sparking test is a simulation using a motor to turn a motorcycle rotor, generating signals to be inputs, which is similar in mechanism to an actual motorcycle, as shown in Figure 29. For digital simulation, this generates digital signals of motorcycles instead of the actual mechanism and transmits them to the control units, as shown in Figure 30. These two simulations give different forms of sparking results. The physical one gives the output of the actual sparking voltage but the digital one gives the digital sound of sparking voltage.

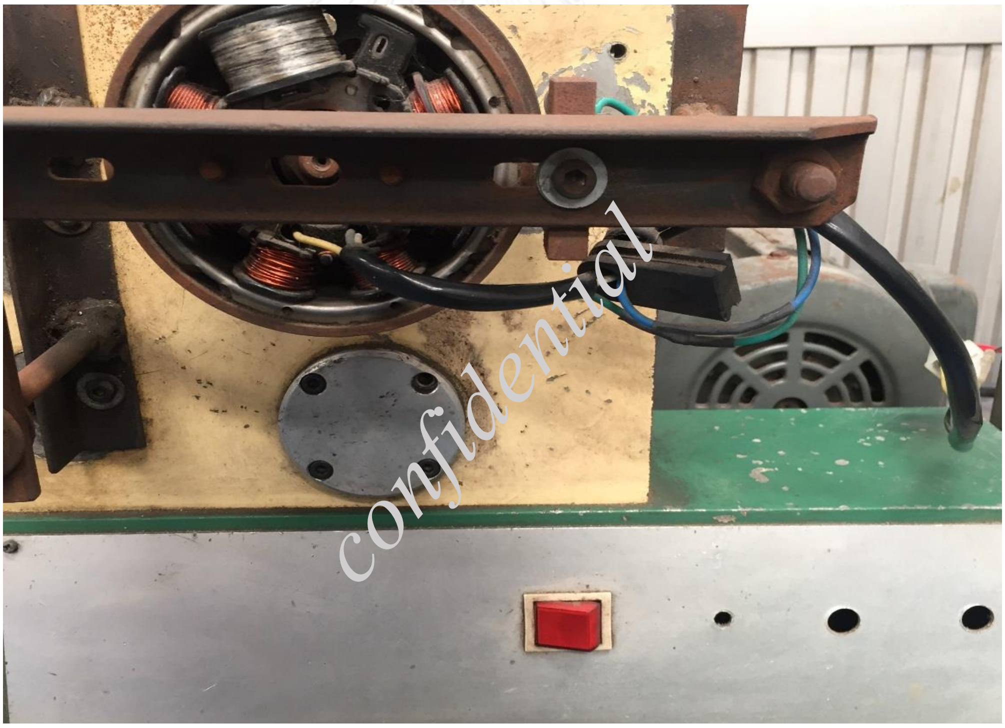


Figure 29: A motor in physical simulation for the sparking test (confidential)

Figure 30: The digital simulation for the sparking test (confidential)

The graphing test uses a similar method as the digital test of sparking. It is additional data, according to each motorcycle model, which is converted into digital signals giving different positions of the ignition, resulting in a graph format shown in Figure 31.

Figure 31: The graphing test in digital simulation (confidential)

The physical simulation is used in large quantities of AC units and few defects were discovered by using this method from re-testing units that had passed the first test. After performing analysis on the test, an inspection of sparking output was found to be a main reason of the defects after the test. The sparking output is inspected by its visibility and the sound of voltage's sparking. A problem occurred when inspectors spent too little time observing the sparking output in closer detail. A thickness, sound, and duration of the spark are key criteria of the inspection. For the inspection to be conducted correctly, the thicknesses need to be similar so inspectors can see the spark clearly in every unit. Moreover, the sound should be evenly loud, simulating the same motor speed. In every period of time, the output must have the same characteristics of thickness, sound and duration. Figure 32 shows a good-condition unit, with a thick and clear output.

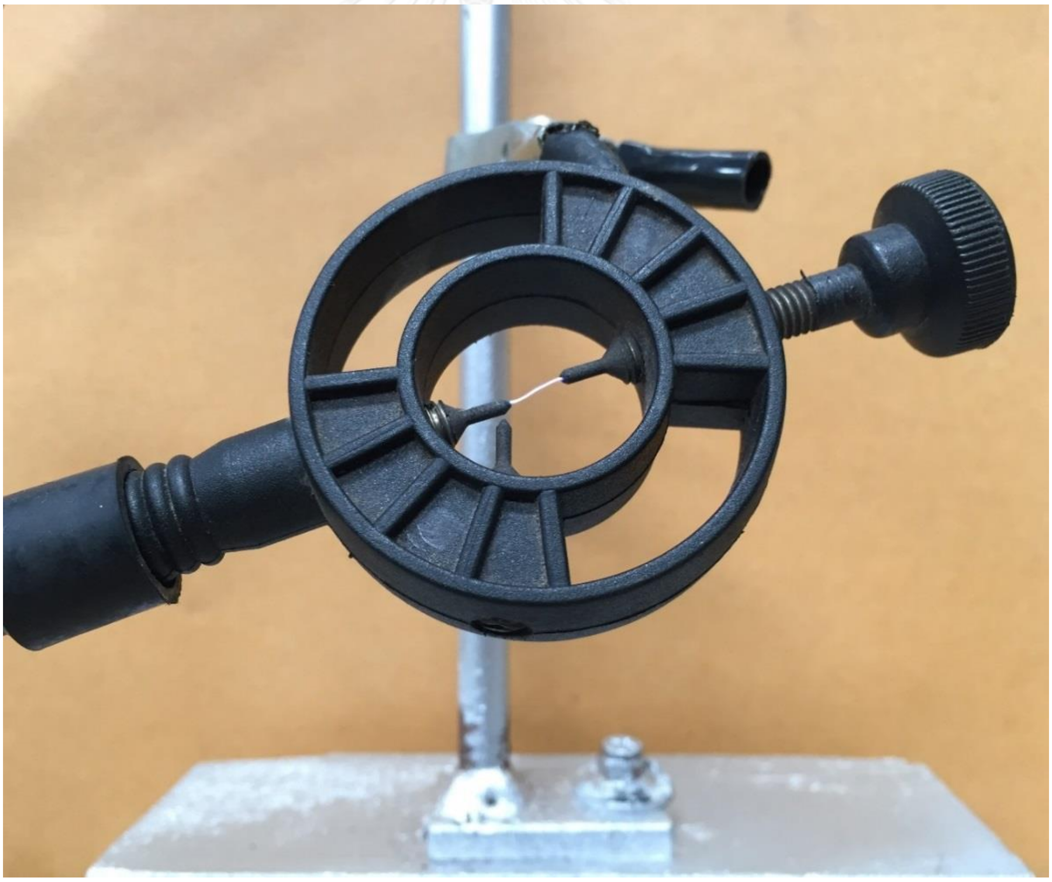


Figure 32: The correct display output

In the failure cases, the first point is inspectors taking only few seconds to inspect the sparking output for each unit, meaning they may not see a periodic sparking voltage as it should be since there is a short window of inspection between each unit. The second point is inspectors only listening the sound of the spark to be only criterion of the inspection. This leads to the test being passed with defects if the thickness is not thick evenly in periodic duration. Thirdly, after the test uses electricity in each unit, some circuit boards retain the electricity. However, circuit boards did not discharge the electricity properly, which may lead to shorted circuits if the boards are connected to each other on the right spots as voltages transfer from one to another.

The digital simulation, even though it does not show physical evidence, gives straight-forward criteria and instructions of the inspection. This is because it shows digital results as sound and graphic display. Therefore, inspectors can easily separate defects from others with minimal human errors. However, using the digital simulation has some drawbacks. The device cannot show the thickness of sparking results, which refers to output voltages. Therefore, one key factor in identifying defects is missing, since there is an evidence of defects resulting in weak and thin output voltages.

As a result, the simulations for the inspection are very critical to the manufacturing processes because they ensure sufficient qualities of the products in order to satisfy customers. If defects are missed by the second inspection from operators or the inspection systems, they would seriously damage the company in terms of manufacturing cost, reputation, and competitiveness. Moreover, instructions in the inspection have weak details and few questionable steps for operators to follow. Therefore, they may not follow every instruction during their workings. In addition, some instructions with little explanations are done in a slightly different way than how they should be.

The operators may change these instructions and begin to inspect in their own way, slightly different to the original instructions. This is the case for employees who have been working in the company and have become used to the processes. They start to change their working activities. For example, in the inspection, a visual inspection to check correction based on referenced units is not fully committed to by operators. Also, operators assume that incorrect assembled units can pass the testing simulation, including cases of missing components and incorrect directions of the components.

Therefore, operators usually use only the simulations to reject defects from the batches rather than use their visual inspection before testing the units. This means they are skipping one simple instruction but being useful to the quality of the product.

Moving to the sub-manufacturing of transformers as an essential component of the units, breaking the process of manufacturing transformers down into six key stages provides an overview of the process. Firstly, a plastic core of the transformer with terminals is formed by using an injection-moulding machine. Secondly, the core is wired with copper wires in specific rounds of wirings and each end of the wire is attached with each specific terminal by soldering. Thirdly, a specific type of duct tape is used to separate each layer of the copper wires from other ones. Fourthly, the second and third stages are repeated twice more with different numbers of wiring rounds. Fifthly, the core is assembled with magnetic metals and the duct tape is used to secure the attachment. Sixthly, an inspection for measuring electronic values of each terminal is the last stage, ensuring the quality and connectivity between wirings and output terminals.

Figure 33 illustrates three units in different stages of transformer production. Starting from the left, first displayed is a product from the third stage, which has one layer of copper wires and one layer of insulated duct tape. The example in the middle is from the fourth stage, which has one more round of the tape wrapping left. The right one is a completed unit ready for inspection by measuring ohms and connection of wirings

Figure 33: Three examples in different stages of manufacturing transformers (confidential)

From the analysis of the processes, malpractice and variation of materials are combined to create defects in the assembly line of the transformer. Thus, this section will describe malpractice and its link with the variation. Based on the processes, wiring numbers of the copper wires are fixed by using wiring machines with digital counters. However, the duct tape to create separated layers of wiring rounds is counted by workers. By comparing the original specification of how many rounds of duct tape are required on the first and second layers with currently manufactured units, a difference can be seen in rounds of each layer for the duct tape, leading to inconsistency in insulator thickness. Thus, fewer rounds of duct tape increase a chance of failure from because of the layers being less separated.

This links to variation in the duct tape, which recently has come with a smaller size than the specification of fully covering areas on the core. The smaller size of the duct tape increases the chance of copper wires from one layer making contact with other ones, as the tape does not fully cover a previous layer. This ensures that the transformer does not work as it should, because the reason for separation is to create different numbers of wiring and thus different voltages by creating ratios (Sekaran, 2016). Therefore, an insulation to keep each layer separated is necessary for this type of the transformer for getting different voltages scaled by the pre-set ratios from wiring rounds. Skipping a few rounds of duct tape may cause failures of the transformer.

From the discussion of the analysis of malpractice, two sub-causes share common problems of poorly-defined instructions and lacking explanations behind each instruction and working process. They create a huge gap between employees and the company, so building a strong culture and good relationships in workplaces can reduce this gap (Timme, 2015). These shared sub-causes show that the lean thinking has not been embedded to the company because it also includes employees' perspectives by approaching and recognizing them as parts of the company. Therefore, each instruction should be explained so that employees can obtain a better understanding of their activities.

3.3.3.4 Material

- Quality

The quality of raw materials and components has a greater impact on the defect rate. Many electronic components come with large quantities in one set of packages. These components are taken from their packages and used in assembly lines without checking the electronic qualities of every single component. They are more likely to be checked based on their physical appearances when forming batches for assemblers and during the assembly processes. Thus, some faulty components would be accidentally assembled in the units until the inspection by simulations. These components may also cause other components to fail when applying electricity to circuits, especially relating to high-voltage parts of the circuits. This also links with the sub-manufacturing line of transformers, which creates a chain effect to the defect rate. The transformer is an example of components that are used in assembly without proper quality checking, because it is only its electronic value but not working capability that is checked by measurement. In addition, components from suppliers are found as the cause of the defects, which mostly applies to transistors and capacitors.

This section will focus only on qualities of materials and components that cannot be directly controlled by the company. The collected data show that some batches of electronic components contain faulty components, unable to perform their electronic characteristics. So, when they are assembled and used in the units which are ready for test by the simulations, they usually show up as defects during the first inspection and are taken out for replacements. This leads to additional costs to the company because of scrap and reworking. Also, the cost is higher when these defects pass the first inspection because some of them cannot tolerate the heat from the curing process since their working capabilities are different to their manufactured specifications.

From the analysis, the quality of materials and components is a foundation of the sub-cause linking directly to the defect problem. It is a base of the whole processes to build on. In a manner that is similar to construct building, if the base is not fully secured enough, it is easily collapses during the construction. Therefore, checking the quality of raw materials should be considered a top priority before checking other causes of the problem. Even though it may have little effect in this case, it is still worth it to fully eliminate issues and to pursue the perfection of lean thinking.

- Variation

Two main variations of raw materials occur in the processes increasing chances of creating fault and error in the assembly line. These variations further increase complexities for human as an operator, since the operator is the one who runs in many activities and instructions. Component packages have many forms and types, so they increase complexities to assemblers because of unpacking various types of components. Another variation is that the sizes of the duct tape used in the sub-manufacturing line of the transformer have been different to their original specifications. This makes working conditions more difficult for the operators.

Types of packages depend on component types. For example, resistors and small capacitors usually come with reels. Packages of transistors and integrated circuits containing the components are in a tube form because they have many component terminals close together, so tubes will secure all the terminals by covering the components as their original shapes. It is also very easy to unpack the components in tube’s packages. However, a downside of reels is that sticky tapes are used to hold and secure the terminals, so a specific way is required to unpack the components without damaging electronic terminals. Hence, some package types make working processes of assemblers smoother but some require skills from assemblers to unpack without damaging the terminals.

The duct tape used in the manufacturing transformer as an in-house component currently comes in a smaller size than the standard size from a supplier. The smaller size of the duct tape reduces the area that can be covered as an insulation layer, as opposed to the smaller width of the tape shown in Figure 34. As can be seen in Figure 35, the tape on the left is an incorrect width, which is slightly smaller than the correct specification on the right.

This adds more difficulty for operators when trying to warp around the transformer core to create the insulation layer between each different wiring round of copper wires. Therefore, operators should add more rounds to ensure the coverage. However, the current manufacturing line still uses the same specific rounds and focuses on securing the magnets to the core by using the tape. Furthermore, tit can easily be seen whether or not the magnets are secured and hold because they exhibit visible properties. However, this is unlike layers because they are not visible to the operators.

Figure 34: A cover area of the smaller width of the tape (confidential)

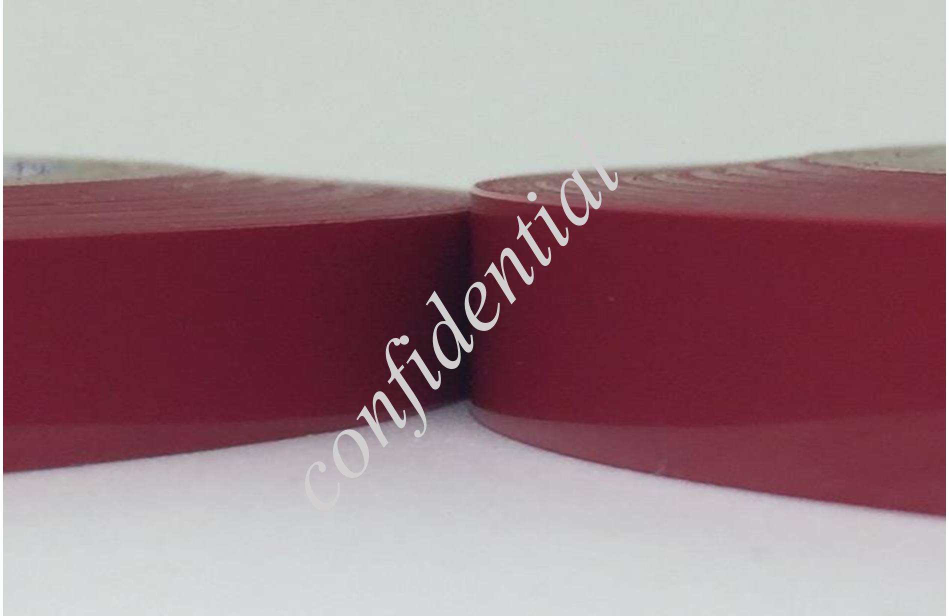


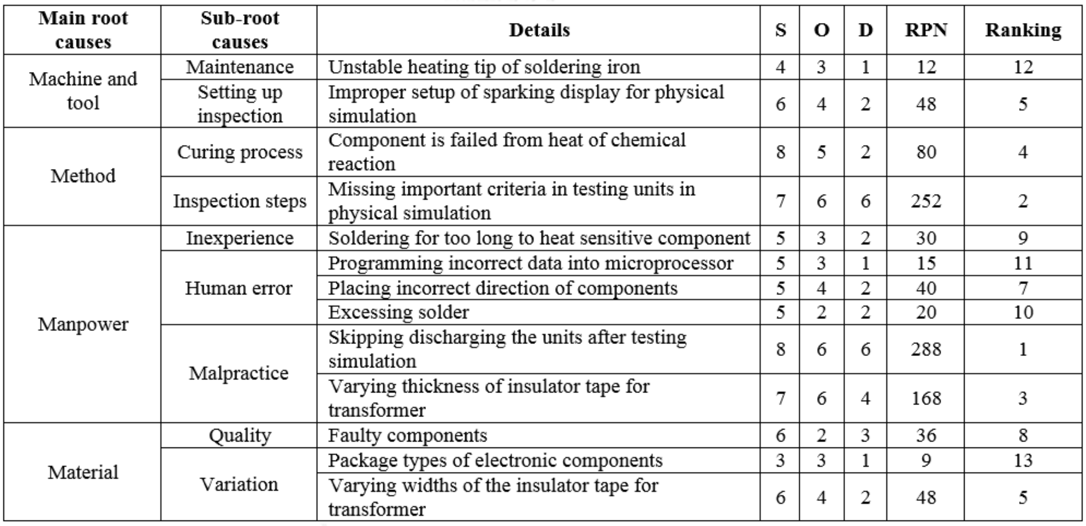
Figure 35: Two different width sizes of the tape (confidential)

Despite this, every transformer is inspected by multimeters to ensure the ohms of each terminal are the same as manufacturing specifications. There are some units which have the correct ohms but that are failed when they are assembled in circuits and supplied with electricity by the simulations for inspecting completed circuits. Furthermore, the tape that creates the insulation layer is not recognised and considered by the inspectors because it does not show any physical and measurement evidences. Thus, this problem is overseen because it exhibits minimal physical evidence, which requires detailed analysis to appear as solid evidence and provoke a search for the best solution.

3.3.3.5 FMEA

Using collected defects from previous section of analysing defects, these defects can be presented in portions of each sub-cause since each defect may have its own causing impact to production system. FMEA is a tool for rating impacts of the sub-cause to the system. First of all, a team for creating accurate results is formed by production supervisors along with product manager. This team has five people in total to discuss and rate each found cause in three dimensions. These dimensions are severity (S), occurrence (O) and detection (D). A multinational result of these three is risk priority number (RPN). By ranking all sub-root causes, Table 11 shows a FMEA of this problem. Selecting top five highest RPNs, there are two from malpractice, one from inspection steps, one from curing process, one from setting up inspection, and one from variation in total of six causes. Also, some of them can be grouped together. For inspection, inspection steps and setting up inspection are grouped as inspection process. For malpractice, it is a blur area between system and implementer. So, they can be fixed by practical solutions throughout adjusting production process and conceptual solutions by building good behaviours at personal level of employees.

Table 11: FMEA



Main root causes	**Sub-root causes**	**Details**	**S**	**O**	**D**	**RPN**	**Ranking**
Machine and tool	Maintenance	Unstable heating tip of soldering iron	4	3	1	12	12
	Setting up inspection	Improper setup of sparking display for physical simulation	6	4	2	48	5
Method	Curing process	Component is failed from heat of chemical reaction	8	5	2	80	4
	Inspection steps	Missing important criteria in testing units in physical simulation	7	6	6	252	2
Manpower	Inexperience	Soldering for too long to heat sensitive component	5	3	2	30	9
	Human error	Programming incorrect data into microprocessor	5	3	1	15	11
		Placing incorrect direction of components	5	4	2	40	7
		Excessing solder	5	2	2	20	10
	Malpractice	Skipping discharging the units after testing simulation	8	6	6	288	1
		Varying thickness of insulator tape for transformer	7	6	4	168	3
Material	Quality	Faulty components	6	2	3	36	8
	Variation	Package types of electronic components	3	3	1	9	13
		Varying widths of the insulator tape for transformer	6	4	2	48	5

3.4 Improve Phase

After analysis of the causes was defined in the previous phase, this phase will take the analysis and merge it with lean thinking to obtain the best solution. There are numerous tools and concepts from lean thinking that can improve simple solutions to pursue perfections. This phase will combine practical solutions based on technical experience and knowledge with lean thinking to enhance their performances. Moreover, lean is a conceptual tool, so to make the most of it should act as a sharpener that allows simple solutions to be more powerful from being systematic solutions. In addition, this makes them easier to continuously improve by embedding the lean into the culture of the company.

This phase will try to find solutions to the causes of the previous section, based on the FMEA. The six causes of the top five highest RPNs will be the top priority tasks. Malpractice need solutions from both sides of practical and conceptual solutions because it mainly involves users as they misuse systems. So, practical solutions will be systematic processes trying to prevent the users from misusing the processes. Conceptual solutions for this cause will be considered as understanding and recognising the perspectives of users. Both inspection steps and setting up inspection share common linkages because both of them are located in the inspection section. Also, transformer of main component in DC unit is needed to adjust its production process. Thus, they can be improved alongside each other in order to get the most effective solutions as adjusting production process. For the last major cause, curing process needs more practical than conceptual solutions because during this process operators are not involved. This also links to working space, which is one constraint of this process.

3.4.1 Malpractice

After the analysis, there are two cleanly visible loopholes that need to be fixed immediately, which are linked to inspection of completed circuits and manufacturing transformers. Improvements of this cause can be divided into two parts, as they not only improve working systems or instructions but also improve the culture and behaviour of the company through employee acceptance of the lean (Shetty et al., 2010). This is because of the employee being the main part of this cause and directly increasing a change of the defects. This problem is linked to the control phase because they share many similarities in stabilising the systems after implementations.

Firstly, improving systems and instructions to prevent malpractice from easily occurring are very important. A strong system can reduce a chance of malpractice by employees. Thus, creating detailed data loggers for every major process is necessary for the company to track every detail of the processes. Doing this allows the company to locate the causes in early processes before adding more cost and damage to the company. This data logger has a form used across the production line, an example of which is shown in Appendix A. It also records details of defects, which have four types of information to give key information of the record. Unit model with lot number, defects per batch along with total units per batch, and causes of defects such as breakdown and missing components are information that should be recorded. The last one is which process number that is creating defects.

Every record is conducted by supervisors who have experience and responsibilities for getting replacements of raw materials and components from the inventory so that the numbers of used materials should be matched up with records from the inventory. This allows the system to be more stable by rechecking with another working section for obtaining correct numbers of the replacements. Toyota’s system, as the origin of the lean, has one concept that influenced this system. This concept is a synchronising production, which shares information across the production (Arya and Jain, 2014). Hence, this adapts the lean for suiting this particular situation to pursue the perfection, as suggested by one of the key elements from the lean.

Adding new instructions of the transformer inspection is another improvement of the system. Doubling rounds of insulated layers between each ratio wiring is done to reduce the chance of connected wires between layers. These rounds have exact numbers in every unit to create standards of the process. Another instruction is to be aware of smaller width of the duct tape, which is one of the causes. This instruction is a suggestion to assemblers that adding details of covering each layer is very important to the processes. This will give better understandings to the assemblers of the need for caution when adding insulated layers.

Secondly, this part links to the control phase, which is to ensure implemented improvements remain in the system. However, this improvement is related to understanding employees and then embedding this knowledge to the system. Employees as users of the system are not following it properly. Trainings with well-explained instructions give employees more than instructions because they also give understandings to employees behind every working activities.

3.4.2 Adjusting Production Process

Two improvements are construed to solve problems creating from this cause. Both of them are adjusting instructions of the inspections, which are for fully assembled units and transformers as in-house manufacturing components. From the analysis phase, current instructions are not fully proper instructed and needed clearly definitions because some of defects are created from the inspections.

- Inspection process for fully assembled units

Two improvements are construed to solve problems created by this cause. Both adjust instructions of the inspections, which are for fully assembled units and transformers as in-house manufacturing components. As seen in the analysis phase, current instructions are not fully and properly instructed and needed clear definitions because some defects are created by the inspections.

For fully assembled units, the inspection of the AC Unit uses a physical simulator, which has a display output, as shown in Figure 32. Adjusted instructions for this inspection are listed in a simple flow diagram, as shown in Figure 36. Three things used to separate defects are the sound, the strength, and the duration between each spark. The strength of the spark can be shown by image but sound cannot. Hence, Figure 37 and Figure 38 show the difference in output sparks between accepted and unaccepted spark strength.

For Figure 37, this output spark is from a defected unit, which is unacceptable because it is less bright and thick when comparing to the spark from Figure 38. Using these two figures as references for inspectors serves as visual aids for them. For the sound and duration, a referenced unit is needed during the inspection. This unit is used to give the correct sound and duration between each spark to inspectors at the beginning of the inspection processes or during the processes to ensure specifications are reached.

Furthermore, every unit must be discharged to get the electricity out when circuit boards are not fully covered by its protections during Process 4 of the First inspection in Figure 19.

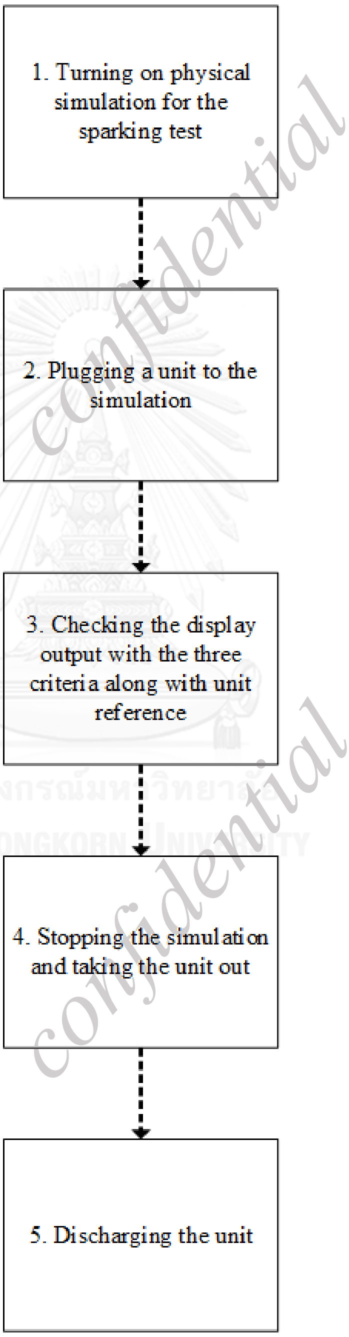


Figure 36: A flow diagram of the sparking test by the physical simulation (confidential)

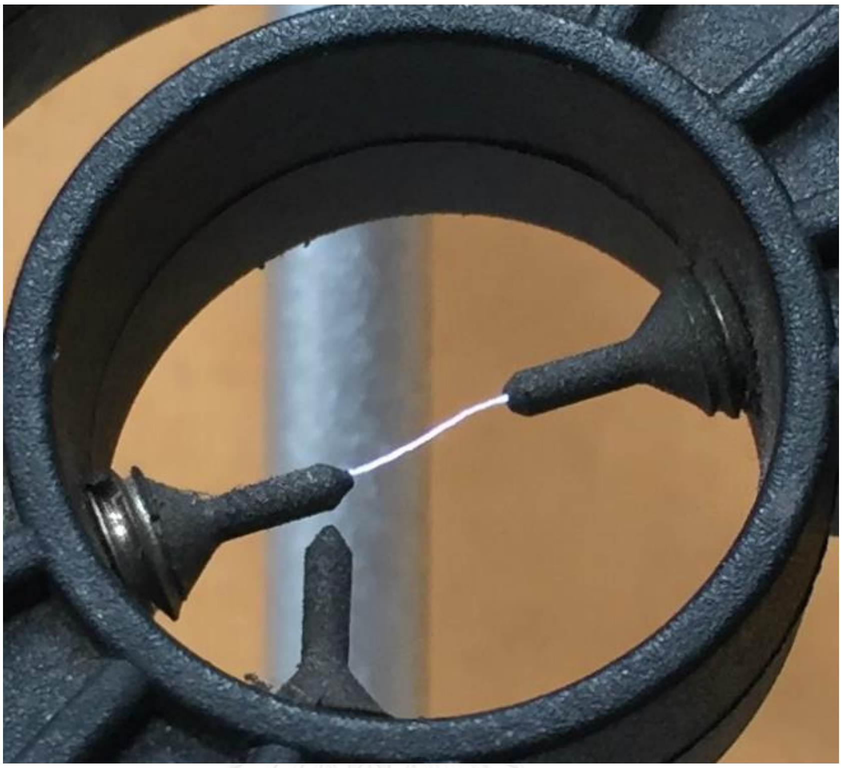


Figure 37: A sparking output from a defect unit

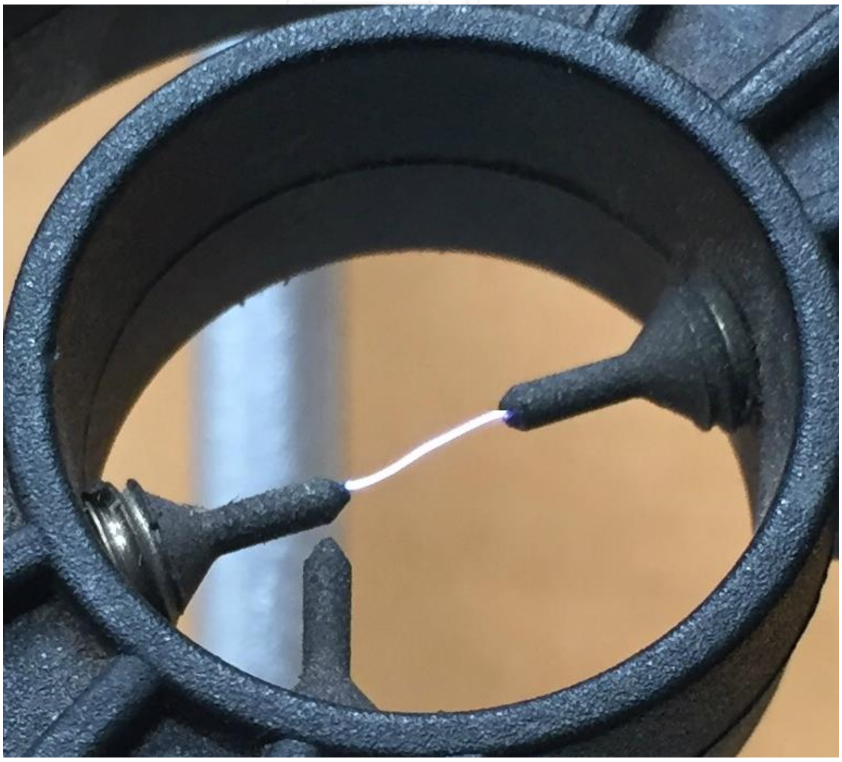


Figure 38: A sparking output from a good-quality unit

- Transformer

For transformers, another testing method to inspect completed transformers before assembling with other components is added to the processes. This method is testing transformers by using a completed circuit as a demo board to test transformers before assembly and soldering. This demo board is a functional unit but with a slot for testing only transformers. Also, this demo board is tested by using digital simulation for the sparking test. Hence, all completed transformers have to be passed by two different inspection methods before being able to be assembled to circuit boards. These methods have different areas of inspections. Measuring by multimeter is for inspecting connectivity and it filters defects that could damage the demo board when testing them with electricity out by a simple measurement.

Despite this, they require more work and add cost to the manufacturer as non-value adding activities. They are still important parts of the processes that prevent defected components from affecting subsequent production processes. Assembling defected components in the circuits are added even more cost for reworking in further processes. Moreover, they may cause other components to fail when electricity runs through them.

Therefore, a simple flow diagram in Figure 39 shows improved manufacturing instructions for the transformers. Adding known problems to the lists of instructions creates greater caution among implementers. These known problems, such as varying sizes of the wrapping tape and less thickness of insulated layers, are well explained for reducing the possibility of unexpected failures.

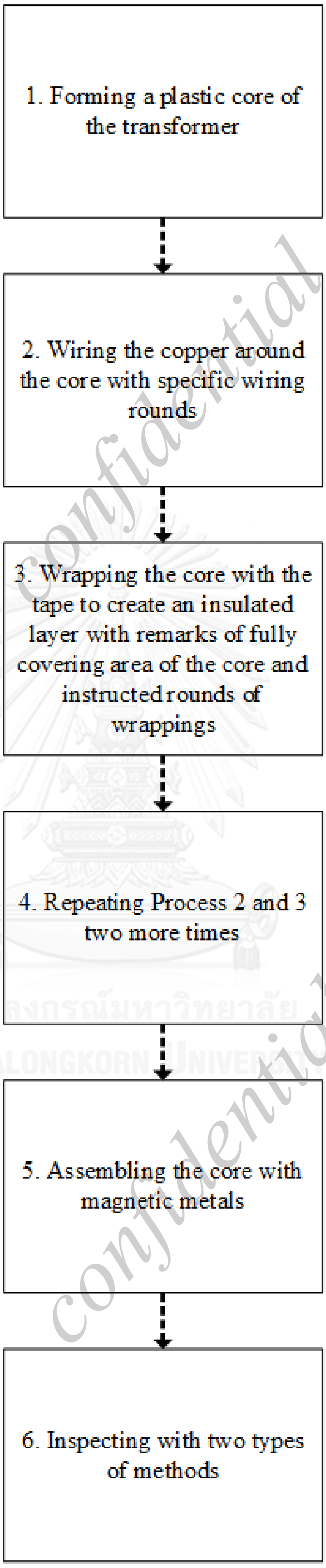


Figure 39: A flow diagram of improved instruction of manufacturing transformers (confidential)

3.4.3 The Curing Process

As discussed in the Analysis stage, air gaps are essential to transfer the heat from the chemical reaction out from the units. So, creating air gaps between each unit is a simple improvement but it is useful and effective. These gaps create a room for the heat to release out to the air, even though they are small gaps. This allows higher temperature to move to a lower temperature, which is similar to the heats from the curing process and the room temperature (Smith et al., 2013).

Figure 40 shows the improvement of arranging units during the curing process to get air gaps between every unit. This allows the heat from the units to be better released from the air gaps since a greater surface area makes contact with the air.

Figure 40: Arranging units with spaces between them (confidential)

3.4.4 Results of the Improvements

After implementing these improvements in the production, defect data of the selected two models were collected with the same number of batches to make comparisons between before and after improvements accurately in around two months of June and July. From Figure 41, after the implementations, the numbers of detects were significantly reduced in both models. Model B still has a higher defect rate than Model A because more components create more potential for problems, requiring different approaches to solve them. Many other minorities of causes are taking more time to adjust, such as the quality of material and human error, which could further reduce the rates of both models.

Looking at each model in detail, failures of components for both models are reduced, as shown in Figure 42 and Figure 43. For Model A, the capacitor and transistor rates were lowered more than half of their pre-improvement levels. Discharging units in proper ways and being cautious in inspection procedures significantly lower the rate of failed components thanks to inspection. However, Model B does not show a significant decrease of both components, since the major problem of Model B is not those components but the transformer. Therefore, the rate of failed transformers was dramatically decreased by adjusting the transformers' production.

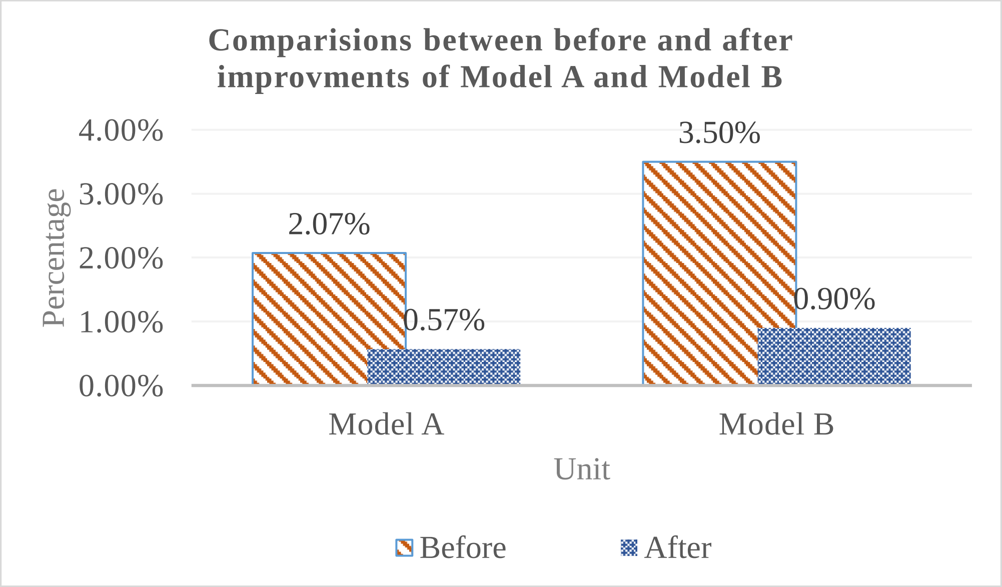


Figure 41: Comparisons of before and after implemented improvements

Despite the fact that there are still defects occurring in the processes, this implementation reduced most of defects, which reached the target of defect rates at 1%. Only four causes were solved and implemented in the new system, so to reduce the rates more can be done by tackling remaining causes. This is because the four causes created the majority of the defects.

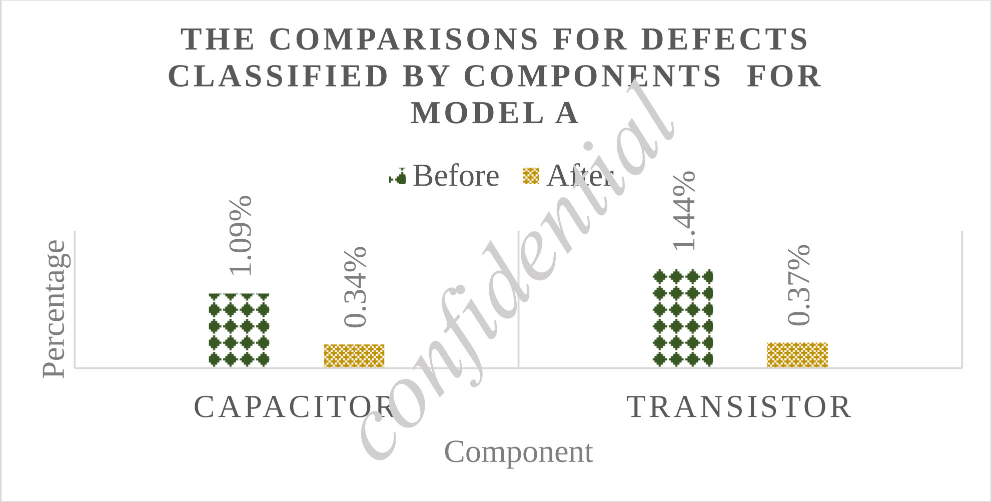


Figure 42: The comparisons for Model A (confidential)

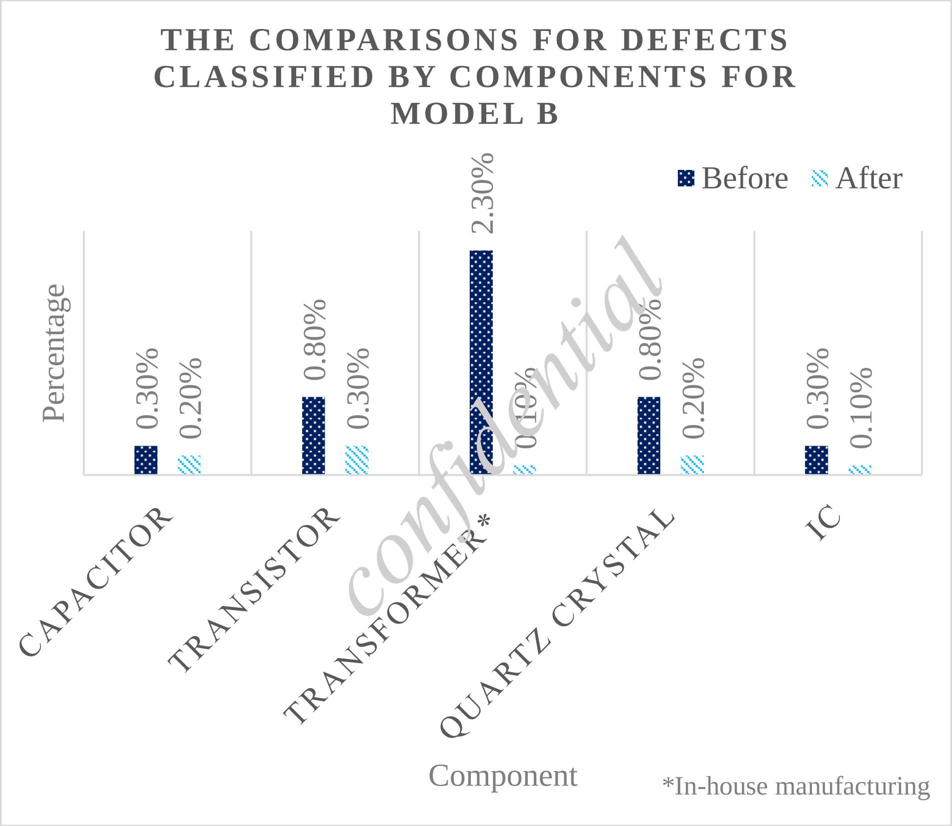


Figure 43: The comparisons for Model B (confidential)

- Hypotheses tests for two samples

A statistical tool is used to validate the results as to whether there is any significant reduction of defects by comparing before and after implementations for both models. This statistical tool is derived from statistical inference for two samples. Thus, hypotheses tests on the difference in mean with variances unknown is the tool with which to validate the decrease of the two results from normal distributions. There is a case study that using paired test to test difference in mean under same conditions (Suwannarit, 2010). However, for this case, both before and after implementation samples are not under the same conditions. There are varying factors such as different assemblers, inspectors and machines.

Therefore, the pooled t-test for used in this case, which two samples are independent. This is because variances of both samples are unknown since the numbers of batches vary. Furthermore, the numbers of samples are small: fewer than 40 samples. However, there are two cases of the mean test which assume that the variances of the two are equal for the first case but not for the second. Thus, an F-test needs to be used to test the ratio of two variances in order to create a hypothesis as to whether two sample variances are equal or not (Montgomery, 2010). These two tests are calculated by using integrated functions from an Excel spreadsheet. Data are assumed as normal distribution by using normal probability plot in Appendix D. Also, this case is considered only defect numbers from each batch. So, Model A has seven samples and Model has five samples from each record of before and after implementation.

- To test whether there has been a change in population variances of defects from Model A

Where, σ_{Before}^2 is variance of defects from Model A before the implementation,

σ_{After}^2 is variance of defects from Model A after the implementation.

By using F-test in a one–tailed test since either direction is possible with 95% confidence intervals.

Formulating the Null and Alternative hypotheses (H_0 and H_1) as the following;

H_0: $\sigma^2_{After} = \sigma^2_{Before}$

H_1:$\sigma^2_{After} \neq \sigma^2_{Before}$

F-Test Two-Sample for Variances

Table 12: Calculations of F-test for Model A

	Before implementation (Model A)	*After implementation (Model A)*
Mean	20.71429	5.714286
Variance	21.2381	1.238095
Observations	7	7
df	6	6
F	**17.15385**	
P(F<=f) one-tail	0.001536	
F Critical one-tail	**4.283866**	

From Table 12, $F_{calc} \approx 17.15\ and\ F_{cri} \approx 4.28$. Therefore, $F_{calc} > F_{cri}$ meaning that H_0 is rejected. The variances of defects from Model A are not equal.

- To test whether there has been a reduction in population means of defects from Model A

Where, μ_{After} is mean of defects from Model A before the implementation,

μ_{Before} is mean of defects from Model A after the implementation.

By using t-test in a one–tailed test for investing a change of reduction with 95% confidence interval.

Assuming $\sigma^2_{After} \neq \sigma^2_{Before}$

Formulating the Null and Alternative hypotheses (H_0 and H_1) as the following;

H_0: $\mu_{After} \geq \mu_{Before}$ (No reduction)

H_1: $\mu_{After} < \mu_{Before}$

t-Test: Two-Sample Assuming Unequal Variances

Table 13: Calculations of t-test for Model A

	Before implementation (Model A)	*After implementation (Model A)*
Mean	20.71429	5.714286
Variance	21.2381	1.238095
Observations	7	7
Hypothesized Mean Difference	0	
df	7	
t Stat	**8.371**	
P(T<=t) one-tail	3.41E-05	
t Critical one-tail	**1.8946**	
P(T<=t) two-tail	6.82E-05	
t Critical two-tail	2.364624	

From Table 13, $t_{calc} \approx 8.37\ and\ t_{cri} \approx 1.89$. Therefore, $|t_{calc}| > |t_{cri}|$ meaning that H_0 is rejected. The means of defects of Model A are statistically significant differences between before and after the implementation.

- To test whether there has been a change in two population variances of defects from Model B

Where, σ^2_{Before} is variance of defects from Model B before the implementation,

σ^2_{After} is variance of defects from Model B after the implementation.

By using F-test in a one–tailed test since either direction is possible with 95% confidence intervals.

Formulating the Null and Alternative hypotheses (H_0 and H_1) as the following;

$$H_0: \sigma^2_{After} = \sigma^2_{Before}$$

$$H_1: \sigma^2_{After} \neq \sigma^2_{Before}$$

F-Test Two-Sample for Variances

Table 14: Calculations of F-test for Model B

	Before implementation (Model B)	*After implementation (Model B)*
Mean	7	1.8
Variance	7.5	1.7
Observations	5	5
df	4	4
F	**4.4118**	
P(F<=f) one-tail	0.089815	
F Critical one-tail	**6.3882**	

From Table 14, $F_{calc} \approx 4.41\, and\, F_{cri} \approx 6.39$. Therefore, $F_{calc} < F_{cri}$ meaning that H_0 is accepted. The variances of defects from Model B are equal.

- To test whether there has been a reduction in population means of defects from Model B

Where, μ_{After} is mean of defects from Model A before the implementation,

μ_{Before} is mean of defects from Model A after the implementation.

By using t-test in a one–tailed test for investing a change of reduction with 95% confidence interval.

Assuming $\sigma^2_{After} = \sigma^2_{Before}$

Formulating the Null and Alternative hypotheses (H_0 and H_1) as the following;

H_0: $\mu_{After} \geq \mu_{Before}$ (No reduction)

H_1: $\mu_{After} < \mu_{Before}$

t-Test: Two-Sample Assuming Equal Variances

Table 15: Calculations of t-test for Model B

	Before implementation (Model B)	*After implementation (Model B)*
Mean	7	1.8
Variance	7.5	1.7
Observations	5	5
Pooled Variance	4.6	
Hypothesized Mean Difference	0	
df	8	
t Stat	**3.8335**	
P(T<=t) one-tail	0.002497	
t Critical one-tail	**1.8595**	
P(T<=t) two-tail	0.004993	
t Critical two-tail	2.306004	

From Table 15, $t_{calc} \approx 3.83 \; and \; t_{cri} \approx 1.86$. Therefore, $|t_{calc}| > |t_{cri}|$ meaning that H_0 is rejected. The means of defects of Model B are statistically significant differences between before and after the implementation.

As a result, it is accepted that results from Model A and Model B in statistical tests are differences in defect rates from the implementation by using the hypotheses tests to verify the results. Moreover, the tests show trends of reduction in means for both models after the implementation.

- Sigma level

By calculating new metrics based on Sigma level to indicate performance of the improvements, Table 16 shows current performances being improved from the implementations since defect rates for both models are below the target level of one percent. However, only Model A has reached the targeted sigma level of 4σ, with 4.03σ placing it at the industrial level. Model B requires more skills for assembly, since it has a complexity of circuits for assembling and soldering components in complex patterns. This links to human error as more components trending to increase higher errors. Also, adjusting transformer process is required time for employees to get used to new process.

Hence, the sigma level of Model B is below the target of 4σ from higher defect rates. In order to increase the sigma level of Model B, the remaining causes from Table 11 can be solved. Furthermore, Model B requires more time for employees to get used to adjusted instructions because of its complexity and the variation of components.

Improving these two models also improves the whole system since each model represents two major groups of products. Thus, similar approaches can be adjusted and applied to other product models based on the two selected models. This is because they share similar manufacturing processes and improvements are only related to the processes and not involved in individual product models.

Table 16: Performance metrics after improvements for Model A and Model B

Sigma level		
Metrics	Model A	Model B
Defect (%)	0.57	0.9
Yield (%)	99.43	99.1
DPMO	5,714	9,000
Sigma level	4.03	3.87

3.5 Control Phase

Satisfied with the results of the improvements, this phase is designed for stabilising and maintaining these improvements to remain in the system, and then continuing improvements to obtain the perfect system. This also links to the previous phase of improvement as conceptual solutions. These conceptual solutions are directly related to employees that need to be controlled in order to maintain the improvements. Even though the instructions, processes, and systems are well-designed, they cannot be excused or processed by themselves and are required to have implementers, which in this case is employees. Thus, the Control phase not only controls but also guides implementers of the system through to new transformations and improvements.

- Control guidelines

Five ways to embed the lean thinking and improvements into the organisation are education, participation, facilitation, negotiation, and coercion. In a real-world application, the first three are more applicable (Eaton, 2010). There are two main suggestions to control the improvements: well-defined trainings and adapting tool concepts from the lean into the organisation. Well-defined trainings are a combination of education and facilitation. This combination is member training with teaching skills and acknowledging understandings behind their working processes. Tool concepts are mostly involved with building a good working culture among employees.

Trainings with giving explanations for every caution in steps or processes are not only for training employees to work in the correct way but also for providing tips. These explanations are parts of learning that make employees understand the reasons behind very strict instructions, which must be carried out in very specific ways. As a result, they will understand the importance of doing them right at the first time. These trainings are conducted from the management level but are supervised by the heads of each process.

Hand-outs of visual cautious instructions for each process are given to new employees in order to view remarks and cautions. These hand-outs are references, guiding employees when they encounter unclear situations. For an example, two different sparking outputs are presented in hand-outs for new employees beginning the process of inspection. Using visual images of the spark outputs allows for the justification and differentiation of the two characteristics of acceptable and unacceptable outputs.

From lean thinking, there are tool concepts that help control systems become smoother by understanding employees before creating the system. These concepts are employee acceptance and employee recognition and reward (Shetty et al., 2010). Employee recognition and reward provide new perspectives, showing that working culture and a positive working environment are related to contributions from employees for the company (Timme, 2015).

Employee acceptance is very critical as being one of the factors that affect successful implementations and improvements. New systems and technologies need to be used by employees because there is no point for the organisation to be heavily invested in the systems if nobody uses them. To build the employee acceptance is from highlighting good usages of using new systems. This makes employees actually realising that these systems are enhancing working abilities of users. To make it clearer, every new instructions and system should be introduced with how it make users more comfortable with their workings (Totty, 2008).

This can be applied to the new improvements. For example, inspections of circuit boards and transformers are actually adjusted systems that are newly introduced from the solutions. By guiding workers through instructions, reasons for adjustment are given by suggesting that doing this extra step once is better than reworking the processes from defected units.

Employee recognition and reward involves showing gratitude to employees and creating bonds with them by saying a meaningful “thank-you.” There are three elements to thanking employees: saying it expressly, letting them know what they are being thanked for, and combining acknowledgement of this with the company’s values. Saying “thank-you” is a simple method to create a good environment in the workplace and also it is a skill showing leadership (Kruse, 2013). This becomes useful when trying to influence a strong working culture from the created system. To embed this concept into the organisation, a workshop for leader members such as supervisors, department heads, and managers is created to emphasize the importance of recognizing other members’ work.

From the employee recognition concept, a new reward system is created for recognising hard work from employees and also motivating them to continue their efforts. This new reward is creating the employee of the month based on hard work with the least error. This employee will gain recognition from the whole organisation for his/her top performance and this also motivates others to do the same. The criteria for this reward are judged by mistakes, productivities, and performances collected from each employee during one month. The reward are gifts and a hall of fame to show that the organisation recognises good performances from its members. The hall of fame will be located near the punch attendance machine, so every member will see it clearly. This reward will be given to those members who did their best for the overall benefit of the organisation.

- Control charts

Since collected data are interested only being pass or fail, they can be considered as binomial data, which only have two outcomes. Np chart is suitable for this case because the data have constant sample sizes for each model (Weinstein and Vokurka, 2006). For Np chart, p equals to numbers of defects divided by sample size (n). For average of proportion numbers of defects, it can be represented average numbers of p ($\bar{p}$) and also, average line (AVG) is $n\bar{p}$. Using the “3-sigma” control limits, lower and upper control limits have equations as the following;

$$LCL = n\bar{p} - 3\sqrt{n\bar{p}(1-\bar{p})}\ and$$

$$UCL = n\bar{p} + 3\sqrt{n\bar{p}(1-\bar{p})}.$$

There is a case that LCL has negative meaning that there is no LCL in statistical terms (Saniga et al., 2009). However, for this case, if LCL is negative, it will be represented as zero instead for being in realistic case.

As a result, Figure 44 and Figure 45 show Np control charts for Model A and Model B respectively. These charts show all collected data from before and after implementation to Control phase. In Control phase, there were three batches each for both models in the following month of August. Data from before and after implementation are represented with circle and triangle symbol respectively. For Control Phase, square symbol represents for data collected from this phase.

For defects before implementation, upper and lower control limits have a large differences between them. However, for after implementation and Control Phase, differences of between the control limits are reduced because improvements controlling variations with systematic approaches. Also, comparing average defects (AVG) between before and after implementation, there is a large reduction after implementation for both models. During Control Phase, the averages for both models are slightly decreased so, these make upper control limits decrease as well. Both charts show that defects and their variations are reduced from implementations. Thus, these charts are used to monitor and control defect rates in desired numbers by comparing new collected data with previous ones. If there are numerous defects rising out from upper limits, these mean that production system is needed to readjust to control defects inside control limits from Control Phase.

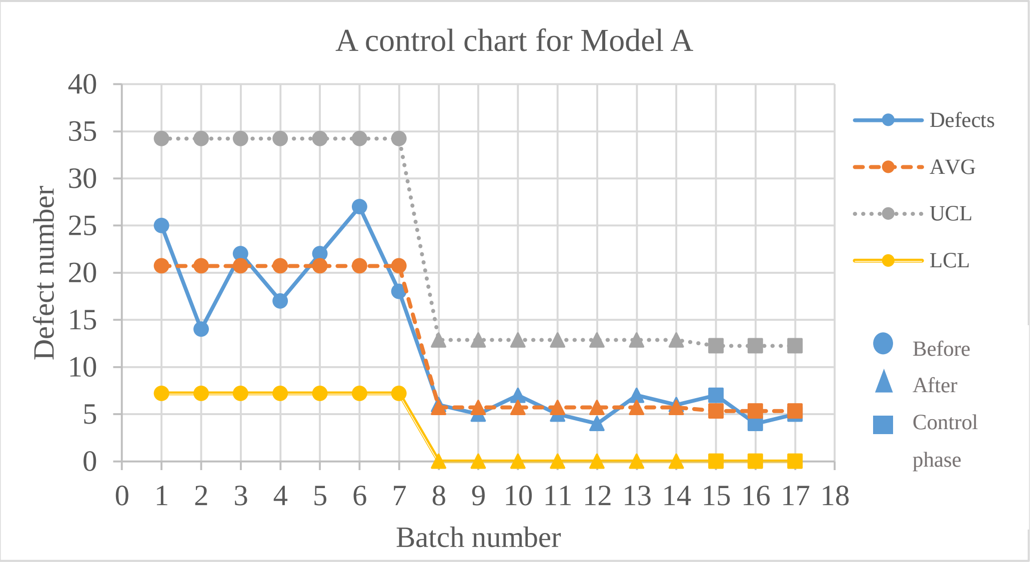


Figure 44: Np control chart for Model A

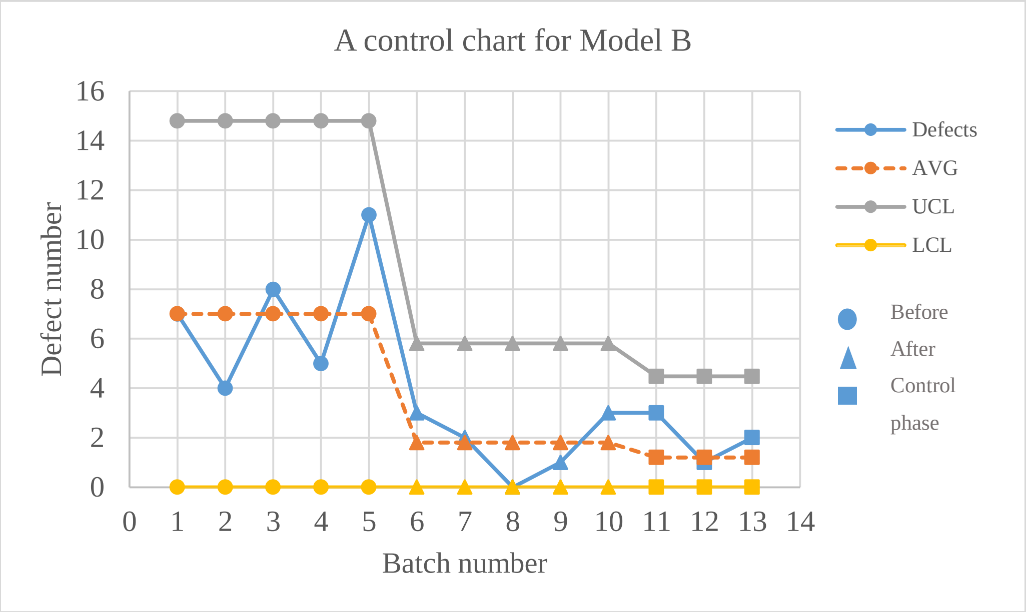


Figure 45: Np control chart for Model B

To conclude for Control Phase, after implementation, production system is needed adjustments to merge proposed implementation with realistic system in order to make the production running smooth. For this case, working culture is main focus for this case to ensure stable implementation from the Lean thinking. Also, using control charts are for monitoring defects in order to adjust production system. This creates continue improvements for the company.

4 Discussion, Recommendation and Conclusion

This chapter will discuss the overview of this project and its results from implementing the Lean Six Sigma (LSS) to eliminate causes of defects. By using a simple framework from the LSS, the DMIAC is the best tool for solving a problem by following it through its different phases from defining the problem to ensuring solutions remain in the system. This creates a clear structure to find the best solutions and also to preserve them for further continuing improvements. Furthermore, adjusting the structure based on each application makes the DMIAC a unique and flexible tool when to combine with lean thinking.

Hence, each phase should be discussed to see the uniqueness of this tool, starting with the first phase. The Define phase collects information of problems that are to be solved with target goals. For this project, defect rates in manufacturing processes for CDI units were higher than the target of one percent, which was unacceptable for the company. So, the problem was high defect rates and the goal as to reduce the rates to the acceptable level.

The next phase, Measure, is designed to collect information in more depth by gathering data to calculate metrics of the Sigma level. These metrics are indicators of the project, which are defect rate, yield, DPOM, and Sigma level. However, there was not enough information in the past records, so new evidences and records were collected during this phase. Two models were selected based on their different characteristics of materials and production processes. Therefore, pre-improvement Sigma levels for Model A is 3.54σ with defect rates of 2.07% and for Model B is 3.31σ with defect rates of 3.5%. Both of them had Sigma levels below the average standard of the industry, which is 4σ. In this phase, the similarities and differences between the two models were also discussed.

The Analysis phase is the core process to find root-causes of the problem using the lean tools to analysis the evidences and information. Therefore, defected units of the two models were removed from their covers and disassembled circuit boards to find defected or failed components in order to identify more evidences of the causes. From the investigation, capacitors, transistors, and transformers were identified as the three main defect components, leading to four groups of the causes. Method, manpower, materials, and machine and tool are the four groups and they share related causes. Six chosen sub-root causes based on their contributions to affecting the defect rates were discussed to find improvements for eliminating the causes.

The Improve phase is the implementation of those suggestions from the Analysis phase by applying them to processes. After knowing the real causes, adjustments and improvements of production processes are created and applied to the processes. The results of the improvements were collected during this phase, which reached the company's target of one percent of the defect rate. Model A's defect rate is at 0.57% with a Sigma level of 4.03σ. Model B has the defect rate of 0.9% with a Sigma level of 3.87σ. Model B has a Sigma level lower than Model A because of its complexity and component variation. Therefore, these add more factors to the defect rate and Sigma level, requiring further improvements by solving minority causes.

The last phase is the control phase for stabilising and preserving the improvements to remain in the systems for long time. This phase is more focused on conceptual solutions, because it focuses on the users of the system: people. Consequently, it introduces the creation of good relations and recognition between members in order to build a strong culture for the organisation, as suggested by lean thinking.

For recommendations in future work, there are three areas that can be an extension from this project. Firstly, spending more time on the Control would ensure that the system would be stable by collecting feedbacks from members after the implementation. This is for receiving perspectives from working grounds and then adjusting the system accordingly. Secondly, solving the remaining minority causes decrease levels of defects even further. These causes can be used in the well-known lean tools such as 5S, TQM, and JIT to increase overall production performance. Thirdly, this project mainly focuses on one type of the seven wastes from the lean, which is defect. There are other types for the company to reduce for pursuing the perfection as suggested from the lean. This is listed as continued improvements for creating no waste in the system.

There is one critical limitation to this scheduled time frame for the implementation, which is full cooperation in a short period of time from every member in the organisation to follow suggested systems. It is difficult to obtain this cooperation from every level of members because this is more than regular working processes. This is extra to some people since it relates to social and cultural developments for embedding the lean culture. Also, this process requires a long length of time before getting excepted result. Some information and data cannot be collected, since the company does not keep past records in some cases. As a result, it is unable to obtain these data for the implementation within the schedule.

To conclude, the Lean Six Sigma for this project is the combination of the lean thinking and the DMIAC structure to solve the problem. It gives structural guidance for finding the root causes and then creating solutions based on lean thinking. Even though the outer surface of the structure looks similar to other applications, the inside of the structure is unique to each single application, as suggested by the case studies in the Literature Review.

Contributions for this project are giving example of implementing concept of Lean Six Sigma into actual application, suggesting tools and methods that can be used in other similar applications, and combining tools from other case studies to construct unique stricture. Also, this project includes similar cases and highlights similarities and differences. This makes comparisons more visible for other implementers to construct their own structures.

As suggested by Filardi et al. (2015) and Thomas et al. (2016), the weakness of the implementation is how to get every member committing to follow new improvements and working concepts. Thus, the Control phase for this project is aiming to solve this problem by integrating concepts for building better social environments in the workplace. Reviewing case studies by Furterer and Smelcer (2007) and Tan et al. (2012) guides the project in the right direction by demonstrating common problems from the perspective of small companies and electronic assembly companies implementing the Lean Six Sigma, which relates directly to this project.

By reviewing these case studies, it becomes clear that they share a common problem of commitment from members in organisations using suggested lean concepts. Thus, this project adjusts the problem by focusing on members of organisations in the Control phase for building working culture.

For this project, there are both practical and conceptual solutions. Practical solutions are formed by technical experiences and conceptual solutions are constructed based on tools from the lean. The lean is a concept integrating related tools and concepts to pursue perfection without any wastes in production processes.

As a result, this project was a successful solution for the company because it reduced the defect rates to the targeted goal. However, the project is not as fully integrated with the lean as the case study by Thomas et al. (2016), which has five DMAIC cycles for each lean aspect. Therefore, the project still has room for further improvement by using the suggested tools and methods.

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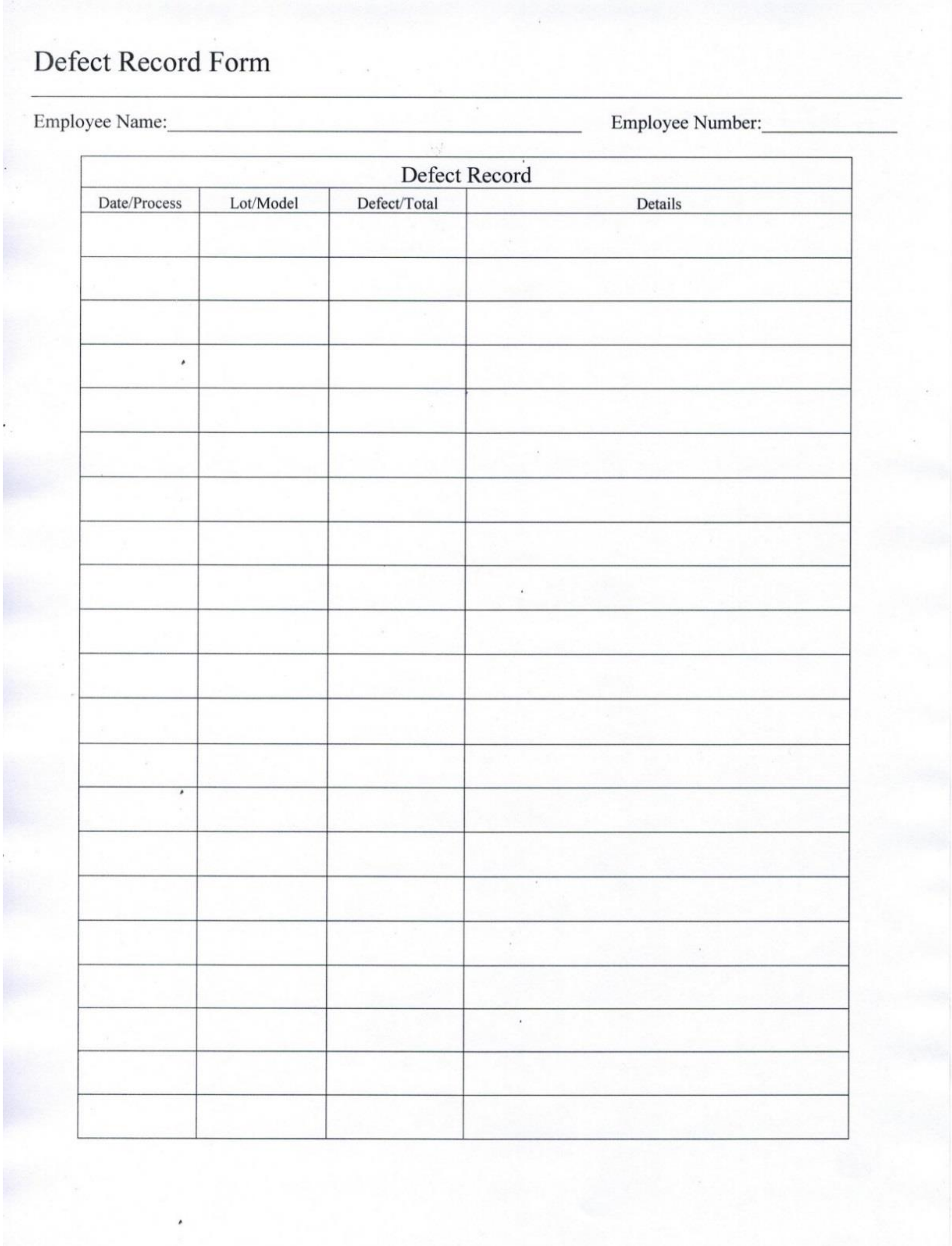
APPENDIX A



Defect Record Form

Employee Name:______________________________________ Employee Number:_____________

Defect Record			
Date/Process	Lot/Model	Defect/Total	Details

APPENDIX B

Model A and Model B collected data before the implementation

Table B.1 (confidential)

Model A (pre-implementation)			
1000 units per batch			
Number of batch	Capacitor	Transistor	Total defects
1	7	16	25
2	4	12	14
3	10	17	22
4	12	14	17
5	11	15	22
6	23	16	27
7	9	11	18
Sum of 7 batches	76	101	145
Standard Deviation	5.98	2.23	4.61
Average defects per batch	10.86	14.43	20.71
Percentage of defects	1.09%	1.44%	2.07%
Yield (100 - %defect)	98.91%	98.56%	97.93%
DPMO	10,857.14	14,428.57	20,714.29
Sigma level	3.80	3.69	3.54

Table B.2 (confidential)

<table>
<tr><th colspan="7">Model B (pre-implementation)</th></tr>
<tr><th colspan="7">200 units per batch</th></tr>
<tr><th>Number of batch</th><th>Capacitor</th><th>Transistor</th><th>Transformer</th><th>Quartz Crystal</th><th>IC</th><th>Total defects</th></tr>
<tr><td>1</td><td>2</td><td>2</td><td>5</td><td>0</td><td>0</td><td>7</td></tr>
<tr><td>2</td><td>0</td><td>0</td><td>3</td><td>2</td><td>0</td><td>4</td></tr>
<tr><td>3</td><td>1</td><td>3</td><td>6</td><td>1</td><td>2</td><td>8</td></tr>
<tr><td>4</td><td>0</td><td>1</td><td>2</td><td>2</td><td>1</td><td>5</td></tr>
<tr><td>5</td><td>0</td><td>2</td><td>7</td><td>3</td><td>0</td><td>11</td></tr>
<tr><td>Sum of 5 batches</td><td>3</td><td>8</td><td>23</td><td>8</td><td>3</td><td>35</td></tr>
<tr><td>Standard Deviation</td><td>0.89</td><td>1.14</td><td>2.07</td><td>1.14</td><td>0.89</td><td>2.74</td></tr>
<tr><td>Average defects per batch</td><td>0.6</td><td>1.6</td><td>4.6</td><td>1.6</td><td>0.6</td><td>7</td></tr>
<tr><td>Percentage of defects</td><td>0.30%</td><td>0.80%</td><td>2.30%</td><td>0.80%</td><td>0.30%</td><td>3.50%</td></tr>
<tr><td>Yield (100 - %defect)</td><td>99.70%</td><td>99.20%</td><td>97.70%</td><td>99.20%</td><td>99.70%</td><td>96.50%</td></tr>
<tr><td>DPMO</td><td>3,000</td><td>8,000</td><td>23,000</td><td>8,000</td><td>3,000</td><td>35,000</td></tr>
<tr><td>Sigma level</td><td>4.25</td><td>3.91</td><td>3.50</td><td>3.91</td><td>4.25</td><td>3.31</td></tr>
</table>

APPENDIX C

Model A and Model B collected data after the implementation

Table C.1 (confidential)

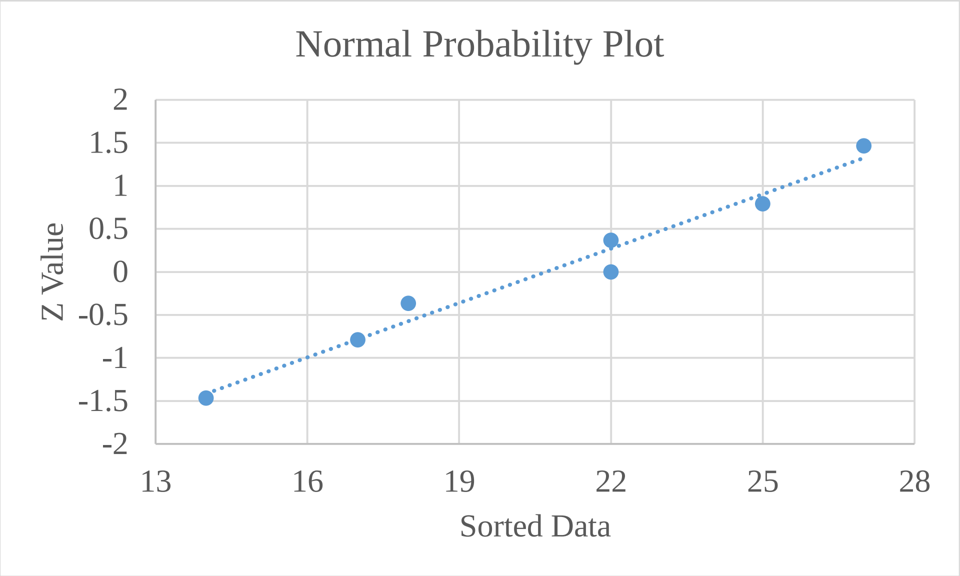
Model A (post-implementation)			
1000 units per batch			
Number of batch	Capacitor	Transistor	Total defects
1	4	5	6
2	2	4	5
3	5	3	7
4	5	1	5
5	2	3	4
6	3	5	7
7	3	5	6
Sum of 7 batches	24	26	40
Standard Deviation	1.27	1.50	1.11
Average defects per batch	3.43	3.71	5.71
Percentage of defects	0.34%	0.37%	0.57%
Yield (100 - %defect)	99.66%	99.63%	99.43%
DPMO	3,428.57	3,714.29	5,714.29
Sigma level	4.20	4.18	4.03

Table C.2 (confidential)

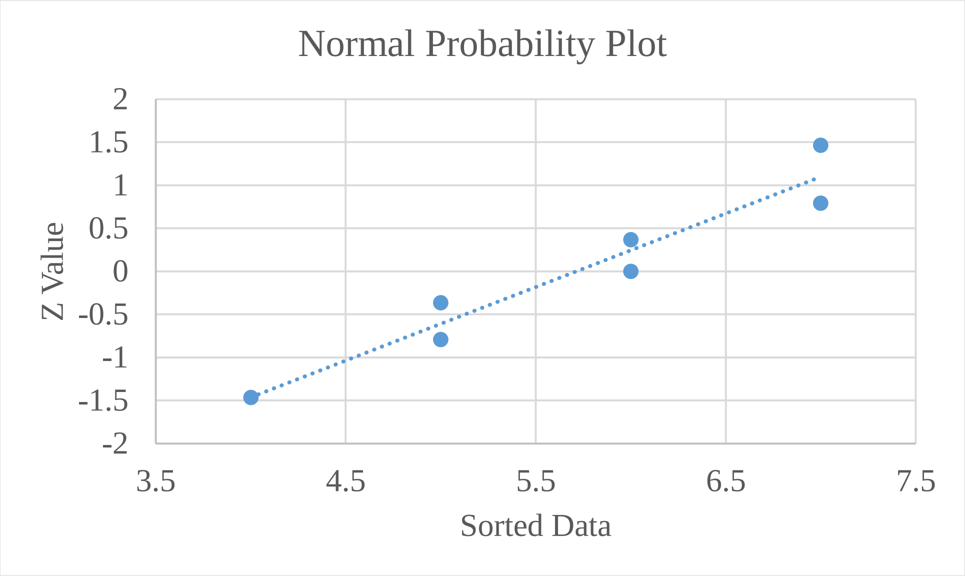
Model B (post-implementation)						
200 units per batch						
Number of batch	Capacitor	Transistor	Transformer	Quartz Crystal	IC	Total defects
1	1	0	1	0	1	3
2	1	1	0	0	0	2
3	0	0	0	0	0	0
4	0	0	0	1	0	1
5	0	2	0	1	0	3
Sum of 5 batches	2	3	1	2	1	9
Standard Deviation	0.55	0.89	0.45	0.55	0.45	1.30
Average defects per batch	0.4	0.6	0.2	0.4	0.2	1.8
Percentage of defects	0.20%	0.30%	0.10%	0.20%	0.10%	0.90%
Yield (100 - %defect)	99.80%	99.70%	99.90%	99.80%	99.90%	99.10%
DPMO	2,000	3,000	1,000	2,000	1,000	9,000
Sigma level	4.38	4.25	4.59	4.38	4.59	3.87

APPENDIX D

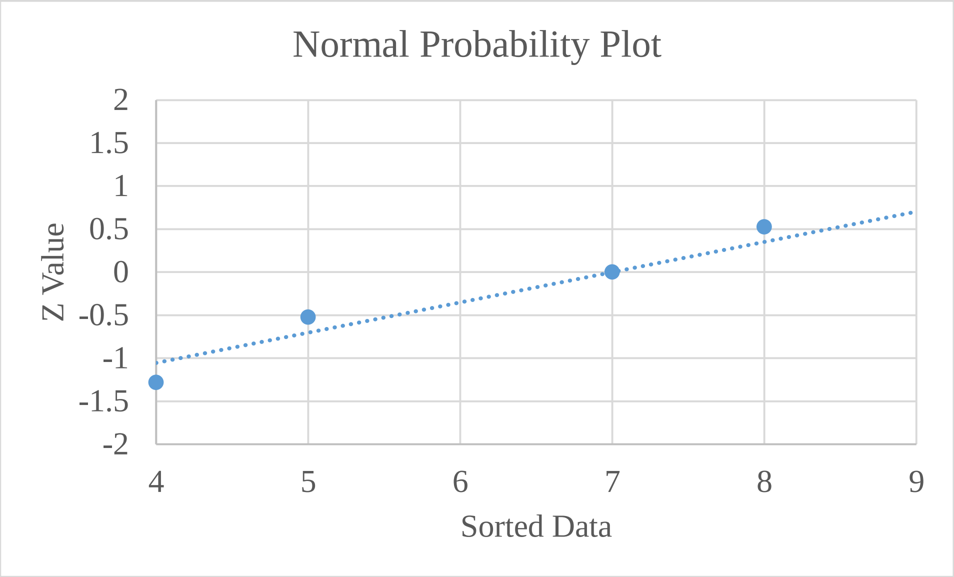
Normal Probability Plot for Model A and Model B



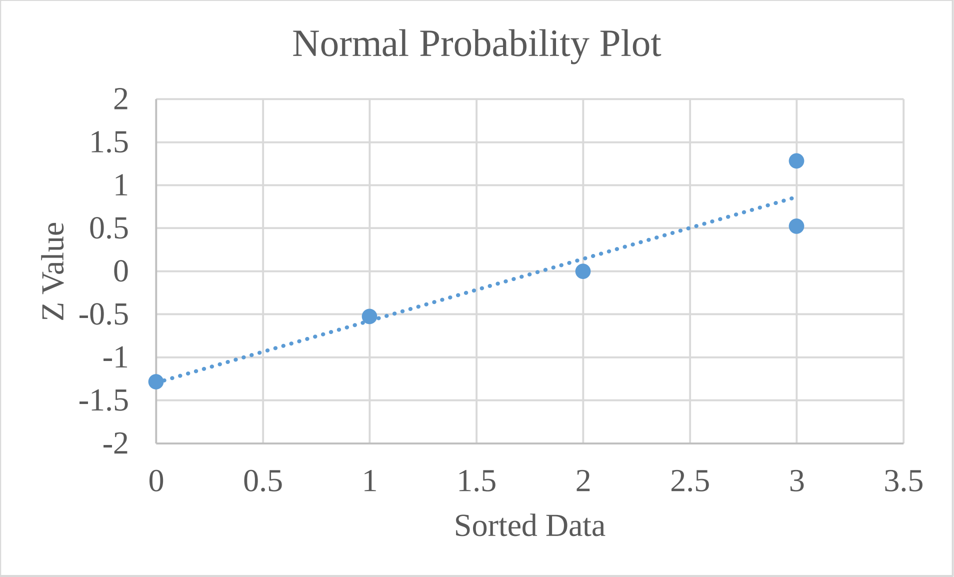
D.1: Mode A before implementation



D.2: Mode A after implementation



D.3: Mode B before implementation



D.4: Mode B after implementation

APPENDIX F

Model A and Model B collected data in Control phase

Table F.1

Model A (at Control Phase)			
1000 units per batch			
Number of batch	Capacitor	Transistor	Total defects
1	3	5	7
2	3	2	4
3	2	3	5

Table F.2

Model B (at Control Phase)						
200 units per batch						
Number of batch	Capacitor	Transistor	Transformer	Quartz Crystal	IC	Total defects
1	1	1	2	0	0	3
2	1	1	0	0	0	1
3	0	0	1	1	0	2

VITA

Mr. Phataraphat Kittijetsada was born in Bangkok, Thailand in 1990. He graduated from University of Nottingham with a bachelor degree in Electrical and Computer Engineering in 2014. After that, he decided to continue his study for Master of Engineering and Master of Science in Engineering Management offered by Chulalongkorn University and Warwick University from part-time dual degree program at the Regional Centre for Manufacturing Systems Engineering. He was enrolled this program since 2014.