CONSTRUCTION OF FUZZY CONTROL CHARTS BY USING TRIANGULAR AND GAUSSIAN FUZZY NUMBERS FOR SOLDER PASTE THICKNESS

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ABSTRACT

Control chart is one of the seven problem solving tools in Statistical Process Control (SPC) and become a very popular technique in improving productivity, preventing defects and avoid purposeless process adjustment. Real data or problems nowadays are too complicated to handle and the difficulty involves with the level of uncertainty which might come from human, measurement devices or environmental conditions. This study aims to generate fuzzy numbers by using triangular and Gaussian approaches and to analyse the algorithm of fuzzy control charts by using α-cut and to analyse the algorithm of traditional control charts of $\bar{X}$-R and $\bar{X}$-S towards the solder paste thickness of integrated circuit data. The fuzzy numbers were generated by using random number between 0 to 1.2% for each observation. Next, performance of these control charts are compared by using average run length (ARL) to select the best chart to control the production process. Results showed that the new fuzzy control charts by using Gaussian fuzzy numbers are the best chart in monitoring the solder paste thickness showed by the lowest value of ARL compared to fuzzy control charts by using triangular fuzzy numbers and traditional control charts. Therefore, this fuzzy control charts by using Gaussian fuzzy numbers can be used to monitor the quality of a product.

ABSTRAK

Carta kawalan adalah salah satu daripada tujuh alat penyelesaian masalah dalam kawalan proses statistik (SPC) dan merupakan teknik yang sangat popular dalam meningkatkan produktiviti, mencegah kecacatan dan mengelakkan pelarasan proses yang tidak diperlukan. Data sebenar atau pelbagai masalah lain pada ketika ini adalah terlalu rumit untuk dikendalikan dan kerumitan itu melibatkan tahap ketidakpastian yang datangnya daripada manusia, peranti pengukuran atau keadaan alam sekitar. Kajian ini bertujuan untuk menjana nombor kabur dengan menggunakan pendekatan segi tiga dan Gaussian dan menganalisa algoritma carta kawalan kabur menggunakan "α-cut" dan menganalisa algoritma carta kawalan tradisional $\bar{X}$-R dan $\bar{X}$-S terhadap data ketebalan pes pateri untuk litar bersepadu. Nombor kabur dihasilkan dengan menggunakan nombor rawak antara 0 hingga 1.2% bagi setiap pemerhatian. Seterusnya, prestasi kesemua carta kawalan ini dibandingkan dengan menggunakan ARL untuk memilih carta kawalan yang terbaik untuk mengawal proses pengeluaran. Keputusan menunjukkan bahawa carta kawalan kabur baru yang menggunakan nombor kabur Gaussian adalah carta kawalan terbaik dalam memantau ketebalan pes pateri yang ditunjukkan oleh nilai ARL yang paling rendah berbanding carta kawalan kabur yang menggunakan nombor kabur segi tiga dan carta kawalan tradisional. Oleh itu, carta kawalan kabur Gaussian ini boleh digunakan untuk memantau kualiti produk.

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LIST OF ABBREVIATIONS AND SYMBOLS

$\bar{x}_p$	- Average of sample of x_g
$\bar{\bar{X}}$	- Process average of $\bar{x}_p$
$\bar{R}$	- Average of ranges
$\bar{S}$	- Average of standard deviations
ARL	- Average run length
SPC	- Statistical Process Control
EWMA	- Exponentially weighted moving average
CUSUM	- Cumulative sum
UCL	- Upper control limit
LCL	- Lower control limit
CL	- Centre line
IC	- Integrated circuit
PCB	- Printed circuit board

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter presents the introduction to this thesis. It begins by describing the overall research background followed by a brief history of integrated circuit (IC). Problem descriptions, research objectives, scope of the study which is divided into scope of data with scope of method and significance of study are also discussed. Finally, a brief description of each chapter is stated.

1.2 Background of Study

Control chart was first discovered by Walter A. Shewhart in 1920s. Control charts are the most important management tools for cost control and material control. It is also one of the tools used in determining whether production or business process is in statistical control condition and was designed to monitor a process for shifts in the mean and variance of a single quality characteristic (Senturk & Erginel, 2009). It is a very popular tool used to solve problems as it has been proved in improving productivity, preventing defects and avoids purposeless process adjustment (Montgomery, 2009). Besides, control chart shows diagnostic information to allow modification in the process that can improve performance and information of process capability.

Control chart is also a quality characteristic's graphic presentation that was calculated or computed from a sample against the sample number of time (Montgomery, 2009). It is a graph used to study how a process is changing from time to time and data are plotted in time sequence. It has a centre line and two horizontal lines which are upper control limit and lower control limit (Saravanan & Nagarajan, 2012). These limits are chosen to see whether a process is in stable condition or not. If the analysis of the control chart indicates that the process is currently under control, for example, it is stable with variation only coming from sources common to the process or all the sample points fall between the control limits, then no corrections or changes to process control parameters are needed or desired (Montgomery, 2009).

However, if the chart shows that the monitored process is out of control, where there is a point that is not in the control limits, detailed analysis of the chart may assist in determining the sources of variation and boost process performance. A process that is stable, but operating outside the desired limits such as scrap rates may be in statistical control, but needs to be improved through a deliberate effort to understand the causes of current performance and fundamentally improve the process. Corrective actions are also required in finding and eliminating the assignable causes responsible for that behaviour (Montgomery, 2009). It can also be considered to make sure the process is stable. It means that the process shows sign of in statistical control state. In manufacturing, the major objective in using a control chart is to reduce the percentage of faulty products that are produced before a shift in the process mean can be attained (Guldner, 1887). Therefore, identifying and understanding the methods that might help in increasing the power of control chart is important so that shifts in a process able to be detected faster.

The fuzzy theory was first proposed by Zadeh (1965). The development of fuzzy theory as an independent area is mainly because of enthusiasm and excellent work of Zadeh. It is a mathematical tool that dealt with uncertainty which comes from a shortage of information, incompleteness, vagueness and inaccurate measurements. Fuzzy theory provides a mechanism in representing linguistic construct (Sivanandam *et al*., 2007). For example, heavy, hot, old, tall and others which are true and false to some level or something that within the category to some extent but also outside the category to some extent. These concepts can be referred as fuzziness or vague concepts.

Fuzzy theory and probability theory are both belong to information theory in mathematics and knowledge representations in computer science. Both represent uncertainty and include sets, intervals, measures and analysis. The difference between these two theories is both addressed different forms of uncertainty (Singpurwalla & Booker, 2004). Probability statements are more on the likelihoods of outcomes whether a situation is happening or not, such as how probable is it that a variable is in a set. In contrast, fuzziness used the concept of levels of truth that ones can not choose and say clearly either a situation happened or not such as how much variable is in a set. Besides, fuzzy set theory utilizes fuzzy set membership's concept, whereas probability uses the concept of subjective probability.

Kosko (1990) discussed the traditional binary set theory which describes the uncertainty of situation occurrences in which situation that happens or not happens. It uses probability theory where the chance is measured to explain if a situation will happen with given a situation is expected to happen. The fuzzy logic theory is based on the notion of relative graded membership. It describes the ambiguity of a situation. It counts the level to which a situation is happening or not. This can be said that, either a situation happens is "random" whereas to what level it happens is fuzzy.

Real world data or problems are too complicated to handle and the complication involves with the level of uncertainty. Fuzzy data is a natural kind of data, such as inaccurate data or data with a source of uncertainty that is not due to randomness. This type of data is easy to find in natural language, social science, psychometric, environments, econometrics and others (Yang & Ko, 1996). Fuzzy numbers have been used to represent fuzzy data and to model fuzziness of the data. Fuzzy theory uses the entire interval between 0 and 1 to reflect mankind reasoning (Werro, 2015).

Fuzzy theory or fuzzy logic often plays an important role in order to form new concepts creatively to understand something. There are numerous applications and usage of fuzzy logic in our everyday life which can be found such as in commercial products and in various fields like in engineering applications, industry of automation and optimization (Singh *et al.*, 2013). For example, Singh *et al.*, (2013) mentioned that we can see real life applications of fuzzy logic in home air conditioners, washing machines, vacuum cleaners, facial pattern recognition, antiskid braking systems, transmission systems, control of subway systems and unmanned helicopters.

There are many significant advantages of fuzzy logic that has been applied as a solution to combine mathematical concept with linguistic variables to many complex problems that not be able to describe precisely. Fuzzy logic allows people to communicate easily with an automated system than in the common way as it is conceptually easy to understand (Sivanandam *et al*., 2007). In addition, it is very flexible and able to compromise with imprecise data (Nandu *et al*., 2016). Fuzzy logic can blend with standard control techniques. Fuzzy logic does not necessarily substitute the standard control methods, however, in most cases, fuzzy logic reinforce them and ease their implementation. Werro (2015) believes that fuzzy logic also represents natural language such as young, high, small, thick which is the basis for human communication. Hence, it is easy to be used since it is created upon the structures of qualitative description that were used in everyday language.

Askerbeyli & Gedik (2011) reveals that fuzzy logic has broad application areas. Statistical process control (SPC) is one of the area that develops solutions with fuzzy theory, such as fuzzy control charts. The advantage of using fuzzy control chart is that it does not need to fulfil assumption of normality, differs from a traditional control chart which needs typical assumption where observations or measurements must follow the normal distribution to build a control chart. Other than that, fuzzy control chart is useful in monitoring process when vagueness and uncertainty arise since the concept of fuzzy theory can deals with uncertainty data.

1.3 Solder Paste Thickness of Integrated Circuit

Integrated circuit (IC) was invented by Jack Kilby in September 1958. It is a set of electronic circuits on a small plate of semiconductor material. The integrated circuit is a very advanced electric circuit that is made compactly from various active and passive devices interconnected by single or multilevel metallization on a piece of single crystal silicon (Saxena, 2009). An IC consists of different electronic components that are connected to each other, such as transistors, resistors, capacitors, diodes and other electronic components in size of a human fingernail (Chattopadhyay & Rakshit, 2006). Each component plays a different behaviour. An IC also resembles the heart and brains of most circuits. It is the little black “chips” that can be found on every circuit board or that were embedded in electronics

An IC has two main advantages over the individual electronic components or discrete circuit. The first advantage is in terms of cost (Carr, 1996). The cost of an IC is low because it is printed as a unit with all their components rather than being constructed as one transistor at a time. For simple circuits, the cost per component is nearly inversely proportional to the number of components (Moore, 1998). Packaged ICs also use less material than the individual electronic components. The second advantage of integrated circuit is in terms of performance where the performance of integrated circuit is high. This is because the components of an IC can switch quickly and consume less power than the discrete circuit as it has a smaller size and close proximity of the components (Moore, 1998).

Furthermore, ICs are usually be determined by the amount of transistors and other electronic components. They can be classified into five types which are small-scale integration, medium-scale integration, large-scale integration, very large-scale integration and ultra large-scale integration (Carr, 1996). IC can also be divided into linear IC and digital IC. Linear IC has continuously signals which are free to vary between the limits imposed by power supply voltage and circuit resistances. In contrast, the digital IC operates at a few defined levels or states rather than over a continuous range of signal amplitudes. Linear ICs are used as audio-frequency amplifier and radio-frequency amplifier whereas digital ICs are used in computers, computer networks, modems and frequency counters (Chattopadhyay & Rakshit, 2006).

Nowadays, there are many places that the IC could be found. It is used in almost all electronic equipments and has transformed the world of electronics, computers, mobile phones, audio, video equipments, automobiles and other digital appliances. It is also being used in switching telephone circuits and data processing (Irvine, 2001). Besides, it is can also be found in military equipments. The most common application of integrated circuit is in digital watch and a scientific calculator.

A studied by Thakur *et al.* (2015) presents that all electronic components including IC are mounted on a board by using an adhesive material which is known as solder. Solder paste plays important role in joining electronic components onto printed circuit board (PCB). It is composed from metal powder particles in a thickened flux vehicle. It serves as both mechanical and electrical means of connection where the small amount of solder attaches the surface mount component to the circuit. If the correct amount of solder paste is not applied at the solder paste stencil printing stage, this situation can not be corrected at the next process stages. This can effect the quality of finished PCB. Hence, the thickness of solder paste should be carefully controlled to give the best results in making of electronic equipments (Lotfi & Howarth, 1998).

1.4 Problem Statement

In statistical process control (SPC), an early assumption such as sample observation must be independent and process observation must follow a normal distribution need to be fulfilled. However, precise data are not always available and in real data, shifted of standard deviation may occur which cause the observation shifted to non normal distribution. Uncertainty could come from human judgement, measurement devices or environment conditions and these can create vagueness in measurement. The problems in using traditional control charts arise when uncertain data or non normal data are exist. Hence, fuzzification method is needed to overcome this uncertain data or non normal that occurred during the implementation of the control chart.

Furthermore, quality has become one of the most vital factors for consumers in choosing many competing goods and services that indeed need to be controlled, for example, solder paste that used to join the integrated circuits onto printed circuit boards (PCBs). The thickness of the solder paste could affect the quality of finished PCBs where only small amount of solder paste is needed to join the integrated circuit onto PCBs. Hence, it is important to monitor and control the solder paste thickness in order to reduce number of failure PCBs, costs and improve the production outcome, so that manufacturers are able to meet their quotas and satisfy their customers. In addition, normally traditional control charts of $\bar{X} - R$ or $\bar{X} - S$ were used by manufacturers to control the thickness of solder paste. There is not many manufacturer that used other method to monitor the thickness of solder paste.

1.5 Research Objectives

The objectives of this research are detailed as follows;

1. To generate fuzzy numbers by using triangular and Gaussian approaches for solder paste thickness of integrated circuit data.

2. To analyse the algorithm of traditional control charts of $\bar{X}$ chart based on range with R chart ($\bar{X}$-R) and $\bar{X}$ chart based on standard deviation with S chart ($\bar{X}$-S) towards the solder paste thickness of integrated circuit data.
3. To analyse the algorithm of fuzzy control charts by using α-cut towards the solder paste thickness of integrated circuit data.
4. To measure the performance of fuzzy control charts compared to traditional control charts by using average run length to select the best chart to control the production process.

1.6 Scope of the Study

The data for this study was obtained from one of manufacturing industry in Johor, Malaysia. Manufacturing industry is where the goods or items or products are produced and manufactured from raw materials and commodities for use or sale by using labour, machines, tools, chemical and biological processing or formulation. During the production process, it may involve with different kind of sub-process that the quality of the production process and product need to be controlled.

The data is about the solder paste thickness of an integrated circuit where integrated circuit is one of the smallest components used in printed circuit board (PCB) in mobile phone or audio. There were 50 sets of sample for each contains 5 observations on the chosen quality characteristic which is the solder paste thickness of integrated circuit. In reality, these 50 sets of sample are fairly enough since the sampling cost and cost of inspection related to variables measurements are normally large.

Furthermore, the method used for this research is fuzzy control charts by using α-cuts where α-cuts method is used to convert fuzzy sets into scalar value. α-Level fuzzy midrange transformation technique is used to retain the standard format of control chart. Microsoft Excel software and Minitab software were used in developing the control charts. Traditional control charts of $\bar{X}$-R and $\bar{X}$-S were applied to compare with fuzzy control charts by using average run length (ARL).

1.7 Significance of Study

There are many advantages could be obtained from this research. Firstly, many aspects of production could be controlled by using the control charts to ensure the production process is effectively controlled. Besides, the cost of the production could be reduced due to the lower rejection of lots or badges and defective rate could be narrow down and profit gained by the factory might be increased by having continuous monitoring. Furthermore, the data that were gathered in manufacturing industry are not necessarily normal and might be uncertain due to vagueness in measurements. Hence, by applying fuzzy control charts, this non normal or uncertain data can be used to monitor a production process in manufacturing industry.

In addition, there were only a few studies on fuzzy control charts by using fuzzy numbers approach. Hence, this research continued the construction of fuzzy control charts by using Gaussian fuzzy numbers approach. The existing fuzzy control charts were modified by using Gaussian fuzzy numbers approach. Gaussian fuzzy numbers and triangular fuzzy numbers for solder paste thickness of integrated circuit data were also generated throughout this research.

1.8 Structure of Thesis

This thesis consists of five chapters. Chapter 1 introduces the background of study on control charts and fuzzy set theory. A brief history of solder paste thickness of integrated circuit, discussion of problems, the objectives of this research, research scope or limitation on the method and data, and structure of the thesis were also discussed in chapter 1.

Chapter 2 is the literature reviews to review the previous and current research. The reviews on the traditional control charts in production and manufacturing and applications of fuzzy theory in control charts were also included. Then, previous studies on solder paste thickness with integrated circuit have been discussed.

Chapter 3 presents the methodology used in this study. A detailed steps and techniques of traditional control chart, fuzzy control charts by using triangular and Gaussian fuzzy numbers approaches were also discussed. Besides, average run length method to compare traditional and fuzzy control charts based on triangular and Gaussian approaches were also presented in this chapter.

In chapter 4, results and discussion from the research findings were given. This chapter discussed the analysis of the proposed fuzzy control charts by using solder paste thickness of integrated circuit data together with comparison between fuzzy control charts using Gaussian and triangular fuzzy number and traditional control charts.

Chapter 5 is about conclusions and recommendations of the study. The summarizations and results of the study were listed clearly. Lastly the related and potential recommendations based on the limitations of the study were also presented.

1.9 Summary

This chapter reviewed the background of the study. It covers the background of control charts and fuzzy theory as the head of the chapter. This chapter also gave a brief history of solder paste thickness of integrated circuits. Moreover, this chapter also revealed the problems occurred in the production process where precise or normal data were not always available. The research objectives were identified together with the scope of the study. The structure of thesis was also been summarized. The next chapter will be literature reviews. It is based on previous research on this topic.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The goal of this chapter is to clearly discuss the significance theories behind the use of control charts in production and manufacturing company. The applications of fuzzy logic in control charts are also presents and previous studies on solder paste thickness together with integrated circuit in various fields are clearly presents.

2.2 Traditional Control Charts

Control chart is one of the tools used in statistical process control where it helps practitioners in monitoring production processes. Walter A. Shewhart of the Bell telephone Industries is the first person who developed the concept of statistical control chart in 1920s (Shewhart, 1931). A typical control chart consists of a centre line that represents the mean value of the chosen quality characteristic. There are two other horizontal lines of control chart known as upper control limit and lower control limit (Montgomery, 2009).

Woodall (2000) reveals the basic Shewhart type control chart with no additional law is a process considered to be under control if the plotted sample falls within the control limits, otherwise, it is considered to be out of control. Besides, under normality assumption, the standard Shewhart control chart has an in control ARL of 370.4 where the control limits have a probability of false alarm (α) equal to 0.0027 (Antzoulakos & Rakitzis, 2010). Here, α is the probability of Type I error according to 3-sigma limits of normal distribution.

In calculating the control limits of a control chart and its sample standard deviation, the subgroup size, *n* is used where it is one of the elements that have a significant influence on the power of a control chart. Hence, when the subgroup size is increased, the power of a control chart will be also increased (Khoo, 2013). Manyele (2017) had analyzed the effect of subgroup size on $\bar{X}$ control chart characteristics which are changes in out-of-control points, upper control limit and zonal demarcations. He presented a new criterion to choose a proper subgroup sizes and examined the effect of the subgroup sizes on the performance of the control charts. he claimed that with a proper choice of subgroup sizes, $\bar{X}$ control chart is capable to indentify uncommon changes in the sample. The rational subgroup sizes were suggested to be $4 \leq k \geq 20$.

In addition, the control charting system has two distinct stages which are phase I and phase II. Phase I is known as the retrospective phase where trial control limits is set up as well as estimation of parameters and phase II is known as the prospective phase where the control chart is used to monitor the process on line to detect any shift that occurred in the process so that corrective measures could be taken quickly (Nazir *et al.*, 2013). Montgomery (2009) found that a control chart falls into two general types of quality characteristics which are variable and attribute. The difference between these two is, variables quality characteristic is from the data that can be measured on a continuous scale, whereas the attribute quality characteristics is from the data that are counted.

Subramani & Balamurali (2012) proposed a control chart for variables with specified process capability indices in order to predict future performance of the process. In their study, the manufacturing process compatibility and the performance were assessed in two stages of process which are in terms of control charts and process capability indices. The relative performance of the proposed control charts for variables could be measured with existing variable control charts that are $\bar{X}$-chart and *R*-chart. The proposed control charts shows that it can be simply applied and without any tedious computations for both control charts and process capability indices.

Furthermore, Ahmad *et al.* (2013) have designed another $\bar{X}$ control charts based on process capability index under repetitive sampling scheme. The performance of the proposed control charts were compared by using ARL approach. Results show that the suggested repetitive sampling scheme is better than traditional single sampling in detecting shift in the process mean. Meanwhile, Aslam *et al.* (2014) continued the study by Ahmad *et al.* (2013) in constructing new attributes and variables control charts under repetitive sampling. They proposed the np control chart and X-bar control chart by using repetitive sampling and compared these control charts with existing control charts by using ARL approach. The ARLs analysis presents that the proposed control charts perform better than existing control charts.

Control charts are mainly classified into two categories known as memoryless (Shewhart type control chart) and memory control charts (contains CUSUM control chart and EWMA control chart). These two control charts of CUSUM and EWMA are effective alternatives to the Shewhart control chart if practitioners are interested in detecting small shifts (Montgomery, 2009). The control structure of these control charts is designed such that because instead of ignoring the past information like Shewhart-type charts, they utilize the previous information along with the current information to present a better performance for small and moderate shifts (Abbas *et al.*, 2014).

Ryu *et al*. (2010) conducted a study on optimal design of a cumulative sum (CUSUM) control chart for a mean shift of unknown size. They assigned a probability distribution to the size of the mean shift to describe the lack of knowledge. They used performance measure based on ARL, which is expected weighted run length (EWRL) since it could be considered as a more suitable measure when the mean shift from a certain probability distribution is assumed. They also proposed a method to optimally design a CUSUM chart based on EWRL. The numerical results show that the CUSUM or the CUSUM-based chart can be improved by their proposed optimization model with different environmental settings in terms of EWRL.

Moreover, Patel & Divecha (2011) have done a research on exponentially weighted moving average (EWMA) control chart that were modified using an analytical process data. The proposed approach is very effective to detect small and abrupt shifts in monitoring the process average. According to the same study, they claimed that the proposed chart has good performance for observations that are autocorrelated or distributed normally and independently. They also compared the performance of the modified EWMA chart with the traditional EWMA chart in terms of average run length (ARL). Furthermore, their proposed approach can be used in

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