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DEVELOPMENT OF FUZZY CONTROL CHARTS FOR MONITORING MANUFACTURING PROCESS WITH UNCERTAIN AND VAGUE OBSERVATIONS

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Chairman: Assoc. Prof. Mohd Khairol Anuar Mohd Ariffin, PhD
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Quality characteristics measurement may include uncertainty due to randomness and fuzziness. Conventional control charts only consider the uncertainty due to randomness. Therefore, the application of fuzzy control charts becomes inevitable when quality characteristics are measured with vagueness, or affected by uncertainty, incomplete information or human subjectivity. To date, several researches have been directed to develop various types of fuzzy control charts, but the application of fuzzy $\bar{X}$-S control charts for monitoring mean and variability of the process is restricted to biased estimation of population standard deviation. A review of the literature on fuzzy control charts also shows that the application of fuzzy set theory to develop fuzzy cumulative sum control charts has not been considered.

In this research, unbiased estimation of population standard deviation for a triangular fuzzy random variable was introduced followed by the development of fuzzy $\bar{X}-S$ and FCUSUM control charts. Percentage of area as a methodology to determine the process state directly when the observations are in the form of triangular fuzzy random variable was developed and optimum γ-level when applying percentage of area to determine the process state in fuzzy $\bar{X}-S$ control charts for various sample was find using a simulation study based on average run length. Transformation techniques to determine the process state indirectly were modified and the optimum transformation techniques was introduced using a comparison study based on average run length when applying fuzzy $\bar{X}-S$ and FCUSUM charts. A simulation study was then made to verify the proposed technique by comparing its performance based on average run length with previous techniques in the literature. Finally, the

proposed fuzzy control charts were validated in a case study that monitored the cooking quality characteristic of chicken nuggets in B.A. Food Production Group and texture quality of noodle preparation in a food laboratory. The proposed fuzzy control charts detected the shift in the process immediately after changing the raw material (wheat) in preparing the noodles, while, conventional control could not detect this shift.

From this study, it was observed that the proposed fuzzy $\bar{X} - S$ and FCUSUM charts could improve the quality through reduction of the variability from 0.1% to as much as 68% compare to the conventional Shewhart control charts and previous techniques in the literature. Fuzzy median is the optimum transformation technique when applying fuzzy $\bar{X} - S$ control charts, while fuzzy median and fuzzy average are the optimum transformation techniques when applying FCUSUM control chart.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN CARTA KAWALAN SAMAR UNTUK PEMANTAUAN PROSES PEMBUATAN DENGAN PEMERHATIAN TIDAK PASTI DAN KABUR ROUTING

Oleh

SEYED MOJTABA ZABIHINPOUR JAHROMI

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Kualiti pengukuran ciri-ciri mungkin termasuk ketidakpastian kerana rambang dan kekaburan. Carta kawalan konvensional hanya mempertimbangkan ketidakpastian kerana rambang. Oleh itu, penggunaan carta kawalan kabur menjadi tidak dapat dielakkan apabila ciri-ciri kualiti diukur dengan kesamaran, atau terjejas oleh ketidaktentuan, maklumat yang tidak lengkap atau subjektiviti manusia. Setakat ini, beberapa kajian telah diarahkan untuk membangunkan pelbagai jenis carta kawalan kabur, tetapi pemakaian X kabur¯-S carta kawalan untuk memantau min dan kepelbagaian proses adalah terhad kepada anggaran berat sebelah standard sisihan populasi. Kajian semula kesusasteraan pada carta kawalan kabur juga menunjukkan bahawa penggunaan teori set kabur untuk membangunkan kabur terkumpul carta kawalan jumlah belum dipertimbangkan.

Dalam kajian ini, anggaran berat sebelah standard sisihan populasi bagi pembolehubah rawak kabur segi tiga telah diperkenalkan diikuti oleh pembangunan carta kawalan kabur dan FCUSUM. Peratus kawasan sebagai kaedah bagi menentukan keadaan proses yang secara langsung apabila pemerhatian adalah dalam bentuk segi tiga pembolehubah rawak kabur dibangunkan dan γ-tahap optimum apabila memohon peratusan kawasan bagi menentukan keadaan proses dalam carta kawalan kabur untuk pelbagai sampel telah mendapati menggunakan kajian simulasi berdasarkan purata panjang larian. Teknik transformasi bagi menentukan keadaan proses yang secara tidak langsung telah diubahsuai dan teknik transformasi optimum diperkenalkan menggunakan kajian perbandingan berdasarkan purata panjang larian apabila memohon carta kabur dan FCUSUM. Satu kajian simulasi kemudiannya dibuat untuk mengesahkan teknik yang dicadangkan dengan membandingkan prestasinya berdasarkan purata panjang larian dengan teknik sebelum ini dalam

kesusasteraan. Akhir sekali, carta kawalan kabur dicadangkan telah disahkan dalam satu kajian kes yang dipantau ciri kualiti memasak ketulan ayam dalam BA Makanan Kumpulan Pengeluaran dan kualiti tekstur penyediaan mi di makmal makanan. Carta kawalan kabur yang dicadangkan dikesan peralihan dalam proses dengan segera selepas menukar bahan mentah (gandum) dalam menyediakan mi, manakala, kawalan konvensional tidak dapat mengesan perubahan ini.

Dari kajian ini, ia telah diperhatikan bahawa carta kabur dan FCUSUM dicadangkan itu boleh meningkatkan kualiti melalui pengurangan kepelbagaian dari 0.1% kepada sebanyak 68% berbanding dengan konvensional carta kawalan Shewhart dan teknik sebelum ini dalam kesusasteraan. Median kabur adalah teknik transformasi yang optimum apabila memohon carta kawalan kabur, manakala median kabur dan purata kabur adalah teknik transformasi optimum apabila memohon carta kawalan FCUSUM.

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I certify that a Thesis Examination Committee has met on 16 February 2015 to conduct the final examination of Seyed Mojtaba Zabihinpour Jahromi on his thesis entitled "Development of Fuzzy Control Charts for Monitoring Manufacturing Process With Uncertain and Vague Observations" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U. (A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory committee were as follows:

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This is to confirm that:

- The research conducted and the writing of this thesis was under our supervision;
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

SPC	Statistical process control
DOE	Design of experiments
FRV	Fuzzy random variable
ARL	Average run length
CUSUM	Cumulative sum
PA	Percentage of area
OC	Operation characteristic

CHAPTER 1

INTRODUCTION

1.1. Background

A control chart is a graphical display of a quality characteristics measurement obtained from a random sample versus time or sample number. However, quality characteristics are sometimes measured with a combination of two kinds of uncertainty; randomness and fuzziness (Faraz and Shapiro, 2010). In practice, uncertainty due to randomness comes from random sampling and uncertainty due to fuzziness arises in many situations such as measurement error, costly skilled inspectors, sophisticated measurement instruments, environmental conditions and imprecise specification limits. Conventional control charts can properly handle the uncertainty due to randomness. Developing fuzzy control charts, which have the ability to handle both kinds of uncertainty in quality characteristics measurements have been considered by several researchers since 1990 (Wang & Raz, 1990; Raz & Wang, 1990; Kanagawa *et al.*, 1993; Cheng, 2005; Gulbay & Kahraman, 2004, 2006, 2007; Senturk & Erginel, 2009; Faraz & Shapiro, 2010; Alizadeh & Ghomi, 2011). Reviewing the literature on fuzzy control charts revealed the following problems.

1.2. Problem statement

When dealing with a fuzzy quality characteristic, it is necessary to monitor both the fuzzy mean and fuzzy variability. Faraz and Shapiro (2010) and Senturk and Erginel (2009) introduced a framework of fuzzy variable control charts, but their models were based on a biased estimation of population standard deviation. Biased estimation of population standard deviation has a negative impact on the control charts performance which is unable to detect shift immediately (Cryer and Ryan, 1990; Derman and Ross, 1995; Jensen *et al.*, 2006). For instance, if the sample size is 5, after 50 sample it could detect the shift (Faraz and Shapiro, 2010). This shift detection in certain condition is not acceptable. This is especially true for the food industry due to vagueness in quality characteristic. In order to avoid this, the author proposed to develop unbiased estimation of population standard deviation that would improve the quality detection process by integrating fuzzy in $\bar{X} - S$ control charts.

If small variations in quality control become an issue and sample size only consists of one unit, it is recommended to utilize a cumulative sum control chart (Hawkins and Olwell, 1998; Oakland, 2008). A cumulative sum control chart could incorporate information from several samples in order to detect small shifts in the process (Montgomery, 2009). Hence, for small variation control charts measured with the combination of randomness and fuzziness, it is necessary to apply a fuzzy cumulative sum (FCUSUM) control chart. FCUSUM can provide more information from the process by considering uncertainty due to fuzziness in addition to the uncertainty due to randomness. Up to date, the application of fuzzy set theory to construct fuzzy cumulative sum control charts has not been considered in quality control.

Determining the process state indirectly through transformation techniques and directly through percentage of area are two existed methodology to determine the process state when applying fuzzy control charts (Wang and Raz, 1990; Taleb and Limam, 2002; Gulbay and Kahraman, 2004, 2006, 2007; Erginel, 2008, Faraz and Shapiro, 2010; Senturk and Erginel, 2009, Alizadeh and Ghomi, 2011). The disadvantage of determination process using transformation techniques is that it is difficult for the users to select the best transformation technique that can detect shifts more quickly (Taleb and Limam, 2002; Alizadeh and Ghomi, 2011). In this research, the authors present the parametric equation of transformation techniques and find optimum transformation technique for determining the process state which resulted in minimum ARL by introducing the fuzzy control chart.

Selecting the optimum value for γ to determine the process state directly through percentage of area is very important (Gulbay and Kahraman, 2007). Increasing the value of γ will result in decreasing the risk of type I error but at the same time will increase the risk of type II error. Therefore, it is crucial to develop a theoretical or numerical method for γ-level determination so that the risk will be minimized. However, based on the literature there is little evidence of a logical procedure being used to decide the optimum value for γ. In this research, the authors develop percentage of area for proposed fuzzy control charts and find the optimum value for γ to determine the process state.

1.3. Research objective

The aim of this research is to develop fuzzy control charts for monitoring manufacturing processes with uncertain and vague observations.

The objectives of this research focus on four aspects:

I. To develop fuzzy $\bar{X} - S$ control charts based on the proposed unbiased estimation of standard deviation of a fuzzy random variable.
II. To develop fuzzy cumulative sum (*FCUSUM*) control charts.
III. To determine the process state for the developed fuzzy $\bar{X} - S$ and FCUSUM control charts.
IV. To verify and validate the proposed fuzzy $\bar{X} - S$ and FCUSUM control charts.

The major body of this research consists of work to address these four aspects.

1.4. Scope of the research

This research is focused on construction, validation and implementing fuzzy $\bar{X} - S$ and FCUSUM control charts for monitoring product quality when uncertainties caused by fuzziness, imprecision, ambiguity and/or incomplete information in addition to the inherent uncertainties due to randomness emerge in quality characteristics measurements.

For this purpose, the principle of Shewhart control charts, CUSUM control chart and fuzzy random variable are applied to introduce an unbiased estimation of fuzzy population standard deviation and develop a mathematical model for the fuzzy $\bar{X}-S$ and FCUSUM control charts.

A simulation study was performed to compare and validate the proposed fuzzy control charts based on the average run length (ARL) as an important performance measurement of control charts. All of the simulation studies were developed through MATLAB release 2012a. The simulation model proposed by Semnani and Moghadam (2013) was used for generating the fuzzy random variable. Repeated measures ANOVA, independent-sample t-test and paired-sample t-test were utilized to compare the proposed approach to other similar approaches.

Finally, a case study on the food industry was applied to validate the model. Process parameters in food processing are mostly physical, physico-chemical and bio-chemical, whereby the uncertainty, ambiguity and fuzziness are obviously associated with such measurements. For example, texture, porosity or color, are the most important quality parameters in food industries, which always are measured with fuzziness. In this research, the texture of noodles has been selected and measured through the texture analysis to validate the model. The texture quality of partially cooked noodles was determined by compression test (Lim, 2006) with some modifications using a texture profile analyzer (TA-TX2, Stable Micro Systems, Ltd., Surrey, UK). Proposed fuzzy control charts could also be applied in other industries, where the quality characteristics are measured with the combination of randomness and fuzziness.

1.5. Research contributions

This research provided a mathematical equation for calculating the unbiased estimation of population standard deviation when the observations are in the form of triangular fuzzy numbers, and then applied it to develop fuzzy $\bar{X}-S$ control charts and successfully evaluated. From this research, a new technique using fuzzy random variable for monitoring individual fuzzy observations when detecting small shifts has been developed and verified successfully. A logical procedure to decide on the γ-level and also to select the best transformation technique when determining the process state directly or indirectly was introduced.

1.6. Organization of the thesis

The thesis is organized in six chapters.

Chapter 2 reviews the literature related to Shewhart control charts, CUSUM control charts, performance measurement of control charts, fuzzy set theory, fuzzy random variable, and simulation of the fuzzy random variable. Furthermore, the works published in the area of fuzzy control charts are discussed.

Chapter 3 presents the methodology applied in this study to develop fuzzy $\bar{X}-S$ control charts. The development of unbiased estimation of population standard deviation and fuzzy $\bar{X}-S$ control charts are explained. The parametric equations of fuzzy transformation techniques for a triangular fuzzy random variable are modified. The procedure of specifying the process state through percentage of area is illustrated. Four different transformation techniques were modified and applied in fuzzy $\bar{X}-S$ control charts, and their performance was studied in a comparison study based on ARL by means of repeated measure ANOVA. A detailed study was performed to determine the optimum *accepted out-of-control level* (γ) for various sample sizes when applying percentage of area in fuzzy $\bar{X}-S$ control charts. A comparison study was done to validate the proposed mathematical model by comparing the proposed fuzzy control charts to other similar approaches based on ARL and by means of paired-sample t-test.

In chapter 4, FCUSUM control charts were developed based on the principle of fuzzy random variable and cumulative sum value. Four different transformation techniques were modified and applied in FCUSUM control charts, and their performance was studied in a comparison study based on ARL by means of repeated measure ANOVA. A comparison study was done to validate the proposed mathematical model by comparing the proposed fuzzy control charts to other similar approaches based on ARL and by means of independent-sample t-test.

In chapter 5, the proposed fuzzy control charts were validated in two case studies of the food industry. The first case study is about monitoring the cooking quality of chicken nugget producing in B.A. production group, located in Iran. The second case study considered monitoring the texture quality of noodle preparing in food laboratory.

Chapter 6 concludes this thesis with a discussion of the results of this research study. Suggestions on the scope of future research in this area are also outlined.

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