CHARACTERIZATION OF BEES ALGORITHM INTO THE MAHALANOBIS-TAGUCHI SYSTEM FOR CLASSIFICATION

FAIZIR BIN RAMLIE

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

UTM Razak School of Engineering and Advanced Technology
Universiti Teknologi Malaysia

JANUARY 2017

DECLARATION

I declare that this thesis entitled "*Characterization of Bees Algorithm into the Mahalanobis-Taguchi System for Classification*" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Faizir bin Ramlie

Date : 31 January 2017

ACKNOWLEDGEMENT

In the name of Allah, the Most Beneficent, the Most Merciful

Alhamdulillah to Allah the Almighty because of His will, this thesis has been successfully completed. I would like to express my highest gratitude to those who were involved in the completion of this thesis. Especially to my very supportive supervisors, Assoc. Prof Dr. Khairur Rijal and Dr. Rozzeta for their excellent supervisory roles in guiding and exposing me to the true meaning of **P**reseverance, **h**ardship and **D**edication. May Allah bless you here and in the hereafter, Allahu Akbar.

Thank you so much to my beloved wife and beautiful daughters, Dr. Nurhayati Hamid, Nurul Fatihah, Nurul Fatin Izzati and Nurul Farahin Solehah who are always there for me. No words could well express my gratefulness of your patience, financial and emotional supports, motivations and do'a you have been providing me since the first day of my research journey at UTM.

I am also in debted to the Ministry of Education under the myPhD of the myBrain15 scholarship, the Fundamental Research Grant Scheme for Research Student Grant (RSG -VOT R.K130000.7840.4F535), the Research Management Centre (RMC) and the UTM KL Campus Librarians for the oppurtunities and the supports in many forms given to me throughout my journey as a PhD's scholar.

Special thanks to the '*brainy*' people within the MTS community, Dr. Rajesh Jugulum, Dr. Shoichi Teshima and Dr. Shin Taguchi, for their invaluable thougths and encouragements, and giving me the permission to analyse their published data and endorsing me to continue with the research work until completion.

Thank you to my mother, Puan Kamsiah Daud and to my grandparents Haji Daud Jamin and Hajjah Kamariah Abbas who are relentlessly praying for me throughout the completion of this research. Not to forget, my research colleagues, Mohamad Yazid (Dr.), Mohd. Badli Shah, Wan Zuki, Norlia, Izzati, Lokman, Ayie, El-Ghazaly, Razaq Olabomi, Kambiz, Razak School non-academic staffs, En. Zul, Kak Aini, Puan Suriyati, En. Baharim, Pn. Yasmin, Pn Noradibah, and Cik Syaza as well as my family members, Palin, Nojie, Alop, Ina, Mija, Paksu and Maksu, Acek and Cek Sudin, Mak Lang and Pak Lang.

To those who have supported me directly or indirectly in completing my research work, whose names are not mentioned here, thank you. Only Allah could repay your kindness. Finally, Al-Fatihah to my late father, Allahyarham En. Ramlie bin Eitham. May Allah bless him.

Wassalam.

ABSTRACT

Mahalanobis-Taguchi System (MTS) is a pattern recognition tool employing Mahalanobis Distance (MD) and Taguchi Robust Engineering philosophy to explore and exploit data in multidimensional systems. In order to improve recognition accuracy of the MTS, features that do not provide useful and beneficial information to the recognition function is removed. A matrix called Orthogonal Array (OA) to search for the useful features is utilized by MTS to accomplished the search. However, the deployment of OA as the feature selection search method is seen as ineffective. The fixed-scheme structure of the OA provides a non-heuristic search nature which leads to suboptimal solution. Therefore, it is the objective of this research to develop an algorithm utilizing Bees Algorithm (BA) to replace the OA. It will act as the alternative feature selection search strategy in order to enhance the search mechanism in a more heuristic manner. To understand the mechanism of the Bees Algorithm, the characteristics of the algorithmic nature of the algorithm is determined. Unlike other research reported in the literature, the proposed characterization framework is similar to Taguchi-sound approach because Larger the Better (LTB) type of signal-to-noise formulation is used as the algorithm's objective function. The Smallest Position Value (SPV) discretization method is adopted by which the combinations of features are indexed in an enumeration list consisting of all possible feature combinations. The list formed a search landscape for the bee agents in exploring the potential solution. The proposed characterization framework is validated by comparing it against three different case studies, all focused on performance in terms of Signal-to-Noise Ratio gain (SNR gain), classification accuracy and computational speed against the OA. The results from the case studies showed that the characterization of the BA into the MTS framework improved the performance of the MTS particularly on the SNR gain. It recorded more than 50% improvement (on average) and nearly 4% improvement on the classification accuracy (on average) in comparison to the OA. However, the OA on average was found to be 30 times faster than the BA in terms of computational speed. Future research on improving the computational speed aspect of the BA is suggested. This study concludes that the characterization of BA into the MTS optimization methodology effectively improved the performances of the MTS, particularly with respect of the SNR gain performance and the classification accuracy when compared to the OA.

ABSTRAK

Mahalanobis-Taguchi System (MTS) ialah satu kaedah dalam pengecaman pola menggunapakai konsep *Mahalanobis Distance* (MD) dan falsafah kejuruteraan *Taguchi Robust* untuk meneroka dan mengeksploitasi data dalam sistem pelbagai dimensi. Dalam usaha untuk meningkatkan ketepatan pengecaman MTS, ciri-ciri yang tidak memberikan maklumat yang berguna dan bermanfaat kepada fungsi pengecaman akan disingkirkan. Untuk mencapai tujuan ini, MTS menggunapakai satu bentuk matriks yang dipanggil Tatasusun Ortogon (OA) untuk mencari ciri-ciri yang berguna. Namun, penggunaan OA sebagai suatu kaedah utama carian ciri-ciri yang berguna dilihat kurang berkesan. Struktur tetap skim OA dilihat memberikan satu sifat carian yang tidak heuristik yang menjurus ke arah penyelesaian yang suboptimum. Lantaran itu, objektif kajian ini memfokuskan pembangunan satu algoritma menggunakan Algoritma Lebah (BA) bagi menggantikan OA. Ia akan berfungsi sebagai strategi alternatif untuk carian pemilihan ciri-ciri yang berguna bagi meningkatkan mekanisme carian dengan lebih heuristik. Untuk memahami mekanisma Algorithma Lebah, ciri-ciri sifat algorithma ini dikenalpasti. Berbeza dengan kajian-kajian lain yang dilaporkan dalam ulasan kajian terdahulu, rangka kerja yang dicadangkan adalah lebih beridentitikan pendekatan Taguchi kerana formulasi jenis *Larger-the-Better* (LTB) telah digunakan sebagai fungsi objektif algoritma ini. Kaedah *Smallest Position Value* (SPV) telah digunapakai yang mana gabungan ciri-ciri diindeks dalam satu senarai hitungan yang terdiri daripada semua kemungkinan kombinasi antara ciri. Senarai ini membentuk satu landskap carian untuk ejen lebah dalam meneroka penyelesaian yang berpotensi. Rangka kerja pencirian yang dicadangkan telah disahkan dengan cara membandingkan ia dengan tiga kajian kes yang berbeza yang mana semuanya memfokuskan kepada prestasi dari segi peningkatan Nisbah Isyarat Hingar (*SNR gain*), ketepatan klasifikasi dan kelajuan pengiraan berbanding dengan OA. Keputusan daripada kajian kes menunjukkan bahawa pencirian BA ke dalam rangka kerja MTS meningkatkan prestasi MTS terutamanya ke atas peningkatan Nisbah Isyarat Hingar (*SNR gain*). Ia merekodkan peningkatan lebih daripada 50% (secara purata) dan hampir 4% (secara purata) peningkatan ketepatan klasifikasi berbanding dengan OA. Namun, OA secara purata didapati adalah 30 kali lebih pantas daripada BA dari segi kelajuan pengiraan pengkomputeran. Kerja-kerja penyelidikan untuk meningkatkan aspek kelajuan pengiraan BA adalah dicadangkan untuk dilaksanakan pada masa hadapan. Kajian ini menyimpulkan pencirian BA ke atas kaedah pengoptimuman MTS adalah berkesan dalam meningkatkan prestasi MTS terutamanya yang berkaitan dengan peningkataan Nisbah Isyarat Hingar (*SNR gain*) dan ketepatan klasifikasi berbanding OA.

DEDICATION

To Allah (swt), The Knowing and The Embracing Wise;

To my beloved wife and to my most beautiful 'sweeties'.

To my late father.

….And your Lord inspired to the bee, *"Take for yourself among the mountains, houses, and among the trees and [in] that which they construct. Then eat from all the fruits and follow the ways of your Lord laid down [for you]."* There emerges from their bellies a drink, varying in colors, in which there is healing for people. Indeed in that is a sign for a people who give ***thought***…..

Surat An-Naĥl , verses 68:69

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

aOFAT	-	Adaptive One Factor at a Time
ACC	-	Classification Accuracy
ACO	-	Ant Colony Optimization
ANN	-	Artificial Neural Network
ARTN	-	Adaptive Resonance Theory Neural Network
BA	-	Bees Algorithm
BACO	-	Binary Ant Colony Optimization
BPSO	-	Binary Particle Swarm Optimization
CCD	-	Charge Couple Device
CPU	-	Central Processing Unit
DMAIC	-	Define, Measure, Analyze, Improve, Control
DOE	-	Design of Experiment
ECU	-	Engine Control Unit
ED	-	Euclidean Distance
FFA	-	FireFly Algorithm
FN	-	False Negative
FP	-	False Positive
FS	-	Forward Selection
GA	-	Genetic Algorithm
GBPSO	-	Gompertz Binary Particle Swarm Optimization
GSA	-	Gravitational Force Algorithm
HHT	-	Hilbert Huang Transform
KEEL	-	Knowledge Extraction based on Evolutionary Learning
LCD	-	Liquid Crystal Display
LTB	-	Larger-the-better
MD	-	Mahalanobis Distance
MD_T	-	Mahalanobis Distance Treshold

MF-DFA	-	Multifractal Detrended Fluctuation Analysis
MMTS	-	Modified Mahalanobis Taguchi System
MRA	-	Multiple Regresion Analysis
MS	-	Mahalanobis Spance
MSLM	-	Mahalanobis Space Learning Machine
MT-BA	-	Mahalanobis Taguchi-Bees Algorithm
MT-mBA	-	Mahalanobis Taguchi-modified Bees Algorithm
MT-OA	-	Mahalanobis-Taguchi Orthogonal Array
MTS	-	Mahalanobis Taguchi System
MTS-ANN	-	Mahalanobis Taguchi System-Artificial Neural Networks
MTS-PSO	-	Mahalanobis Taguchi System-Particle Swarm Optimization
OA	-	Orthogonal Array
PSO	-	Particle Swarm Optimization
RF	-	Radio Frequency
SI	-	Swarm Intelligence
S_n	-	Sensitivity
S_p	-	Specificity
SNR	-	Signal-to-noise ratio
SOM	-	Self Organising Mapping
SPV	-	Smallest Position Value
SVM	-	Support Vector Machine
TN	-	True Negative
TP	-	True Positive
TSO	-	Two Step Optimization
TWM	-	Total Weight Misclassification
UCI	-	University of Carlifornia Irvine Machine Learning Repository
UNMDC	-	Unsupervised Mahalanobis Distance Classifier

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Overview

Mahalanobis-Taguchi System (MTS) is a pattern recognition tool employing Mahalanobis Distance (MD) and Taguchi robust philosophy to explore and exploit data in a multidimensional system (Taguchi and Jugulum, 2002). MTS is originated from the work of the famous Indian statistician, Dr. Prasanta Candra Mahalanobis (1893~1972) in 1936 with his Mahalanobis Distance (MD) scale formulation. The MD formulation gets motivation from his determination to examine if the Indian people who married European people during the time came from specific caste level (Dasgupta, 1993). The formulation of MD was then extended by Dr. Taguchi who integrates this MD formulation with his Robust Engineering concept deploying two exclusive tools introduced by Taguchi namely Orthogonal Array (OA) and Signal-to-noise ratio (SNR) to enhance the methodology to be a popular application tool for diagnosis and forecasting technique in multidimensional system (Cudney *et al.* 2006). One unique feature about MTS lies on its technique in assessing variability among all level of samples and the ability to evaluate significant and insignificant factors (optimization) using the simplistic approach. Figure 1.1 depicts the basic procedure flow in MTS methodology which involves four fundamental stages. Chapter 2 will elaborate the fundamental stages of MTS in greater details.

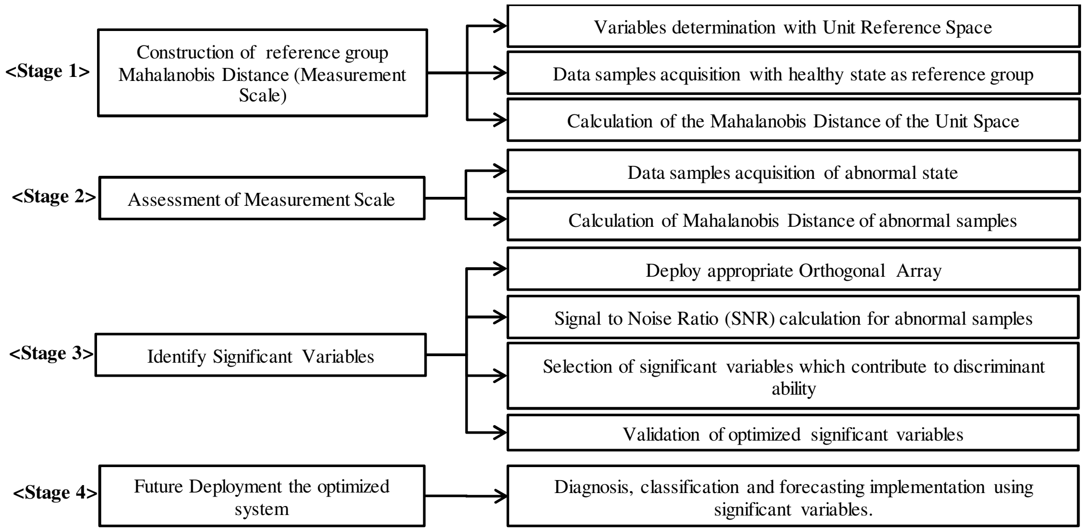

Figure 1.1 Fundamental four stages in MTS (Cudney and Ragsdell 2013)

The optimized pattern recognition model obtained via MTS is considered robust because the SNR identifies the useful variables that are most insensitive to variation (Kestle and Cudney, 2011) and, is of cost efficient as it constitutes smaller number of attributes for better or at least the same system performance as compared to the original system of interest (Taguchi *et al.* 2004). Moreover, MTS is not based on probability model or distributional theory (Taguchi *et al.* 2003). In developing the MD scale, only the measures of descriptive statistics (means and standard deviation) are used.

These characteristics have drawn great interests from various scholars in using MTS to conduct studies and solve various pattern recognition problems (Ghasemi *et al.* 2015). Figure 1.2 shows an increasing trend of a number of studies conducted since 2001 based on the number of paper published in the literature. The statistics were based only on papers published in various sources and publishers outside Japan. Figure 1.3 illustrates the breakdown of case studies conducted in terms of application/industrial sectors based on the data in Figure 1.2 where we can see that manufacturing sector (i.e. automotive, electronics, electrical appliances, software, manufacturing processes) dominates the figure while service industry (i.e. medical and healthcare, finance, corporate management, ICT) as well as machinery and equipment health surveillance sector are gaining more interest in deploying MTS for improvement on respective system performances.

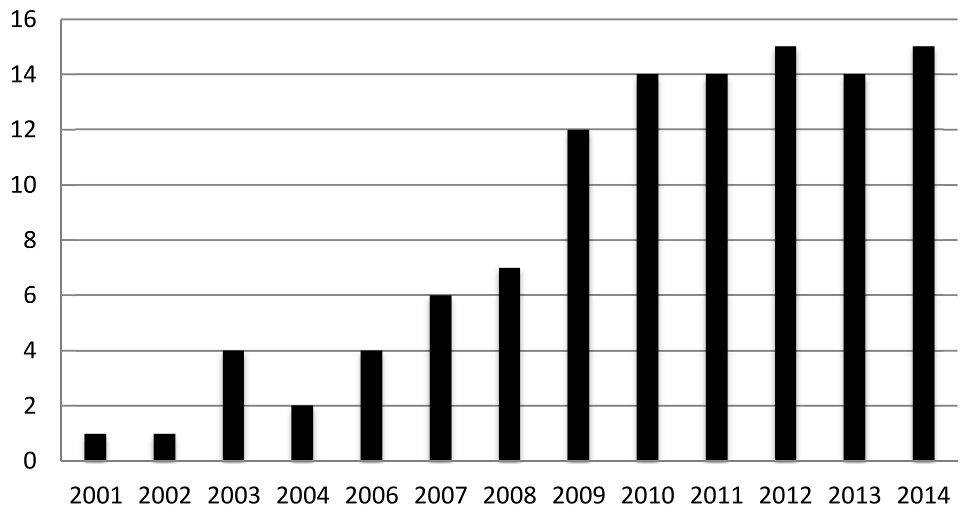

Figure 1.2 Trend of studies conducted in MTS since 2001

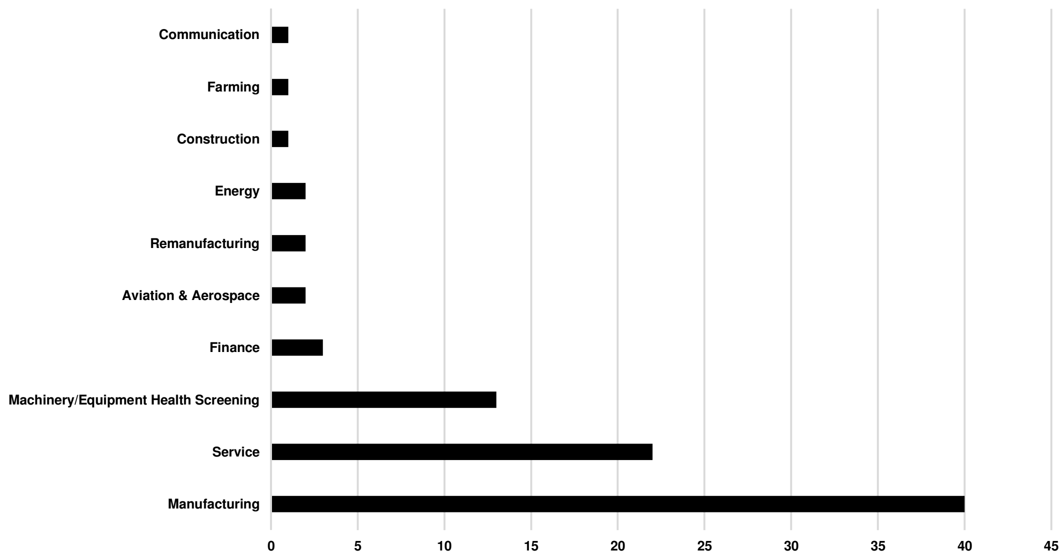

Figure 1.3 Reviewed papers published based on the sector in deploying MTS from 2001 until 2014

1.2 Research/Problem Background

In any pattern recognition system including the MTS, an efficient system would require less system features (system variables) from the original feature sets without the loss of recognition quality or better. Therefore, optimum feature selection is a prime motive since not only it increases recognition accuracy, it also provides computational cost benefits since the resulting recognition will be faster and use less memory (Thangavel and Pethalakshmi 2009). In the literature, this process is also known as variable selection, attribute selection, variable subset selection (Kumar and Minz 2014), or dimensionality reduction (Maaten *et al.* 2009) in which irrelevant, redundant or noisy features are discarded through effective means of useful feature selection procedures with an appropriate decision functions (objective function or evaluation criterions) (Jain *et al.* 2000). The reduced feature set constitutes the minimum number of features that is relevant enough to account for the observed property of the sample data for future predictions.

In the context of MTS, significant feature selection process is conducted in stage 3 (optimization stage) of the methodology using a designed matrix called orthogonal array (OA) while the signal-to-noise ratio (SNR) is used as the evaluation function for the decision criterion. However, the feature selection search mechanism using orthogonal array (OA) for dimensionality reduction purpose is claimed inadequate and produced an inaccurate and sub-optimal solution (Hawkins, 2003; Woodall *et al.* 2003; Abraham and Variyath, 2003; Bach and Schroeder, 2004; Pal and Maiti, 2010).

Hawkins (2003) argues that the deployment of OA produced sup-optimal results as it is a type of fractional factorial designed matrix and not a full factorial type; thus it is not guaranteed to obtain optimal solutions due to the simplicity of the OA matrix structure. The argument is supported by the work of Woodall *et al*. (2003) where they attempted to optimize features in a medical diagnosis of liver disease using OA and benchmarked the results based on full factorial combination tests. In the design of experiment literature, a full factorial search is similar to exhaustive search algorithm where it will search and evaluate each and every possible solution within the search domain. Via this strategy, the ‘true’ optima of any given optimization problem is guaranteed to be found (Jain *et al.* 2000) however, it requires large computational efforts (i.e. long computing time). In the clinical study conducted by Woodall *et al*. (2003), they found that the optimized features obtained via full factorial vary significantly with the optimized variables obtained via OA. They pointed out that OA fails to explore other potential optimum combinations of features since the exploitation on higher order interaction among features under OA search structure was seen insufficient.

In dealing with the lack of higher order combinations of the OA scheme, Abraham and Variyath (2003) attempted to optimize the significant features of the same medical diagnosis case study (the liver disease) using forward selection procedure by adding the features value one by one. In their study, the first feature selected for entry has the maximum SNR value. The second feature to enter the model is the one that has maximum SNR value together with the feature already selected. The result showed that via this method, much better optimal combination was found in comparison to the optimal combination obtained via OA based on the improvement in SNR value. However, forward selection method may suffer from 'nesting-effect' that is, once the feature of interest is chosen, there is no way for it to be omitted (Theodoridis and Koutroumbas 2009). Thus searching flexibility using forward selection method is seen vulnerable.

On similar attempt by Foster *et al.* (2009), to address the searching flexibility issue, they proposed another alternative search procedure based on the DOE concept in the MTS framework. An adaptive One Factor at A Time (OFAT) search scheme was employed where the features are individually removed or added during the feature selection process. Features are retained only if they contribute positively to the improvement in SNR value. A comparison works against traditional OA approach were also studied. The validation was conducted on two case studies namely on medical diagnosis of liver heart disease and image classification case of four well-known portrait paints. It was found that in both cases, OFAT performance outperformed OA approach in terms of larger SNR value. Even though OFAT approach seems a promising strategy; it still suffers the lack of exploitation on higher order interaction of variables since it is another form of the fractional factorial design matrix. In the study, only the order of the 3rd order of interaction was being studied from 17 and 64 total number of features of the case studies respectively.

Orthogonal array concept is also known as *pairwise (2-way)* testing in computer software combinatoric evaluation system. The word *pairwise (2-way)* denotes that the Orthogonal Array exploits a set of any *two combinations* or two columns which contains all possible pairs of elements exactly the same number of times.

An investigation was conducted by Kacker *et al.* (2013) onto the works of a group of reseachers from the National Institute of Standards and Technology (NIST) of the United States on software failures embedded on medical devices, failures reported for a browser, a server and a database systems to get into insights of the kinds of software testing that could have detected the failures and their prevention measures. The result from the investigation suggested an empirical *interaction rule* which rules out most of the failures are induced by either single or joint combinatorial effects (interaction) of two factors. In other words, fewer failure contributions come from the combination (interaction) of more than 3 factors. This finding makes Kacker *et. al.* (2013) to conclude that eventhough pairwise testing such as the orthogonal array scheme seems useful, it may not be sufficient to cater for the remaining 'inherent but useful' higher order combination that may exist and thus, a combinatorial testing technique for greater than 2 and higher combination of factors was recommended.

Therefore, under fractional factorial optimization schemes such as the OA, potential optimal features of the system were not being able to be evaluated thoroughly making the classification accuracy attained to be apprehensive. Therefore, a heuristic search technique that can explore and exploit the higher order interaction among feature subsets such as heuristic search algorithm is sought.

The state-of-the-art meta-heuristic search algorithm is a set of a heuristic search strategy that can be used to define heuristic search methods applicable to a wide range of optimization problems including the MTS. A meta-heuristic search can be seen as a general purpose tailored to guide a specific optimization problem heuristically toward promising areas in the solution search space that contain good quality solutions (Thangavel and Pethalakshmi 2009). Further, the combination of exploration (diversification) and exploitation (intensification) search characteristics in meta-heuristic search strategy increase the ability to find optimal solutions in a reasonable time (Blum and Roli 2003; Yang 2010). Hence, the strategies offered by these algorithmic concepts are worth to be explored.

The recent Swarm Intelligence (SI) is a collection of a meta-heuristic search strategy that mimics the collective social behavior of animals or insects. Particle swarm optimization (PSO), Firefly algorithm (FA), Cuckoo search algorithm (CSA), Gravitational search algorithm (GSA), Artificial fish school algorithm, Bacterial evolutionary algorithm (BEA) to name a few are among the state-of-the-art heuristic search algorithms that fall under the umbrella of SI field (Krause *et al.* 2013). Recent studies have shown that SI search strategies have gained huge appreciations in literature for solving complex and discrete optimization problems with greater success (Blum and Merkle, 2008; Yang 2010) due to the advantageous of exploration and exploitation search characteristics offered by this technique.

In the context of MTS, Pal and Maiti (2010) proposed binary PSO algorithm to solve MTS optimization problem replacing the OA in MTS. In spite of using SNR as the objective function, they formulated a mathematical model decision criteria based on minimization of total weighted misclassification (TWM). Similar optimization approach deploying SI strategy to solve MTS optimization problem were demonstrated by Reséndiz *et al.* (2013) and Reséndiz and Rull-Flores (2013) to replace OA with Binary Ant Colony Optimization (BACO) and Gompertz Binary Particle Swarm Optimization (GBPSO) algorithms respectively. However, the works aimed at only comparing the respective converging performances against BPSO proposed by Pal and Maiti (2010) in MTS framework based on the number of computational iterations towards the optimum solutions. The studies made no discussions on comparing the performances against OA.

1.3 Problem Statement

It was evident from the studies mentioned in the previous section that the orthogonal structure of the OA as an effective feature selection for the MTS is pruned to sup-optimality solution. The feature selection under the OA search scheme is found lacking in exploiting higher number of interaction between the features. Figure 1.4 illustrates this problem. Let say for instance, we have seven (7) original variables that need to be reduced in an example of an optimization problem. In MTS, since we have 7 original features, thus an $L_8(2^7)$ orthogonal array is recommended to be used to search for the significant features since it is enough to accommodate the existing original 7 factors into it columns (Taguchi *et al.* 2001, 2004, 2005; Taguchi and Jugulum 2002; Teshima *et al.* 2012). Note that the '1s' (colored in grey) signify the usage of variables while '2s' signify otherwise. From Figure 1.4, it is observed that, (except row 1 (run 1) of the OA), the other runs of the OA (run 2 to run 8) exploit the order of only three (3) combinations among the original variables. Thus, feature selection in the order of 4 or 5 or even higher order of combinations is not present in the OA structure. Thus based on this limitation, a *heuristic* feature selection strategy which could overcome this limitation of the OA is required.

	A	**B**	**C**	**D**	**E**	**F**	**G**
	1	2	3	4	5	6	7
1	*1*	*1*	*1*	*1*	*1*	*1*	*1*
2	*1*	*1*	*1*	*2*	*2*	*2*	*2*
3	*1*	*2*	*2*	*1*	*1*	*2*	*2*
4	*1*	*2*	*2*	*2*	*2*	*1*	*1*
5	*2*	*1*	*2*	*1*	*2*	*1*	*2*
6	*2*	*1*	*2*	*2*	*1*	*2*	*1*
7	*2*	*2*	*1*	*1*	*2*	*2*	*1*
8	*2*	*2*	*1*	*2*	*1*	*1*	*2*

Figure 1.4 An example of allocation of variables in the OA

Therefore in this research, the significant feature selection (optimization) approach using *heuristic* algorithm such as the Bees Algorithm (BA) replacing the conventional OA technique is proposed. BA is a heuristic search technique in finding optimization result that falls under Swarm Intelligence (SI) field of which the solution search strategy mimics the social behavior of animals or insects. By taking the advantageous of collective population strategy offered by this technique, higher order interactions could be exploited and eventually more optimum combinations of features could be explored. Thus, a higher accuracy in terms of classification performances of MTS using such method could be hypothesized.

It was also evident that the attempts to characterize Swarm Intelligence (SI) search technique into the MTS framework specifically in solving the MTS feature selection (optimization) problem by replacing the OA are found to be very few. Hence, possible strategies offered by other Swarm Intelligence (SI) search techniques such as the Bees Algorithm is worthy of study to evaluate its heuristic potential in enhancing the MTS recognition accuracy. The above statements have brought the attention to the following research questions:

i. What are the potential characteristics of the Bees Algorithm as the proposed SI candidate that is suitable to replace the OA in MTS?
ii. If it is suitable, then how would the strategy be to characterize it into the MTS framework with a more Taguchi-sound manner?
iii. If it is could be characterized, then how significant is the designed characterization strategy as compared to the OA in improving the feature selection scheme and the overall classification accuracy performance of MTS?
iv. If it is significant, then how much impact would it have in terms of the overall computational cost (i.e. computational speed) in comparison to existing OA approach?

To find the answers to the above questions, the following research objectives were commissioned.

1.4 Research Objectives (RO)

***RO1*:** To determine the characteristics of Bees Algorithm (another recent SI heuristic search optimization strategy) in its ability to handle feature selection (optimization) problem of the MTS.

***RO2*:** To develop the algorithmic characterization architecture based on the characteristics of the Bees Algorithm to replace the Orthogonal Array in the existing MTS framework in a more Taguchi-sound manner.

RO3: To verify the performances of the MTS under the designed algorithms against the existing OA approaches on several benchmarked datasets.

RO4: To validate the effectiveness of the designed characterization algorithms against real industry data.

1.5 Research Scope

To enhance the optimization process of MTS to be able to exploit higher order interaction among subset features, a Bees Algorithm (a recent swarm intelligence search strategy) is proposed. This nature-inspired heuristic search approach mimics social interaction behavior of a social animal or insect particularly in food foraging activity (solution search) (Pham *et al.* 2006). Chapter 2 will elaborate in further details on Bees Algorithm literature. The optimization problem is treated as Combinatorial Optimization for classification problem and the search design architecture will be based on Taguchi's robust engineering concepts. The main outcome of this research is to compare the performances between the proposed approaches against the existing method based on the following indexes:

i) Gain in signal-to-noise ratio (SNR Gain) of both optimized systems as suggested by Taguchi and Jugulum (2002);
ii) Classification accuracy and classification cost (computing speed) as suggested by Jain *et al.* (2000);

1.6 Significance of the Study

This research investigates the possibilities of other swarm intelligence (SI) techniques to be deployed in MTS methodology by replacing the existing OA in improving MTS optimization and eventually enhancing its recognition performance. Bees Algorithm (BA) is introduced to solve the MTS optimization problem using the SNR as the selection decision criterion which proven to be successful in enhancing the accuracy performance of MTS in comparison to the existing OA approach. Consequently, the architecture designed in this work opens the opportunity of studies not only restricted to SI but to other kinds of state-of-the-art meta-heuristic algorithms to be incorporated into MTS in the quest for MTS perfection with a more Taguchi sound approach. Further, the proposed optimization strategy could also be expanded into Taguchi robust parameter design framework in which OA is currently one of the key optimization tools used in this Taguchi's robust design methodology.

Secondly, despite the critics and limitations on the ineffectiveness of using Orthogonal Array (OA) in MTS by literature, this research reveals that OA has one major advantage. OA facilitates the search mechanism for optimization in MTS at a much faster rate. This finding could ease the critics and tensions towards OA deployment in MTS literature. This study could suggest improvement research works on enhancing OA structure be conducted in the future (i.e. hybridization of the OA with State-of-the-Art algorithms, modification on the OA matrix structure with other orthogonal matrix theory such as the Hadamard matrix etc.) to enhance OA's searching capability and consequently improve its optimization accuracy while benefiting from the computing time advantage that it could offer.

1.7 Organisation of the Thesis

This thesis consists of eight (8) chapters. Chapter 1 presents the overview, problem background, research questions and objectives as well as the significance of the study. Chapter 2 explains the fundamental concepts of Mahalanobis Distance (MD) and Mahalanobis-Taguchi System (MTS). A brief review of the utilization of the MTS in various engineering fields as well as on the current research works reported in the literature on improving the MTS particularly with respect to replacing the OA will also be presented to get a sense of appreciation by various scholars towards MTS deployment. An overview of Swarm Intelligence (SI) literature will also be presented in this chapter to get an insight of this recent meta-heuristic search technique and its current contributions with respect to improving the MTS which become the basis of the motivation of this research work. An overview of Bees Algorithm, from nature to algorithm architecture and the significant features of BA as well as its capabilities in solving various complex optimization problems will also be discussed in this chapter.

Chapter 3 presents the overall methodology of this research work which highlights the conceptual idea behind designing the Bees Algorithm into the MTS framework. The details framework and architectural design of the proposed characterization algorithms are also presented in this chapter which become the main contribution of this research work.

Subsequently, the deployment and experimental analysis of the designed algorithms are demonstrated in Chapter 4, 5 and 6 based on the three (3) different case studies respectively to evaluate its effectiveness in improving the MTS performances. The final results and findings from the above case studies are then further discussed in terms of its overall effectiveness, efficiency, consistency and viability of this characterization study in relation to the main issues of the research topic in Chapter 7 before the final conclusion be made in Chapter 8 which relates the research outcomes to its objectives together with several recommendations for future research works.

REFERENCES

Abdullah, S., Alzaqebah, M. (2013) 'A hybrid self-adaptive bees algorithm for examination timetabling problems', *Applied Soft Computing*, 13(8), 3608–3620.

Abraham, B., Variyath, A.M. (2003) 'Discussion', *Technometrics*, 45(1), 22–24.

Alcalá-Fdez, J., Fernández, A., Luengo, J., Derrac, J., García, S., Sánchez, L., Herrera, F. (2011) 'KEEL data-mining software tool: Data set repository, integration of algorithms and experimental analysis framework', *Journal of Multiple-Valued Logic and Soft Computing*, 17(2-3), 255–287.

Bach, J., Schroeder, P.J. (2004) 'Pairwise Testing : A Best Practice That Isn ' t', in *In Proceedings of 22nd Pacific Northwest Software Quality Conference*, 180–196.

Bahamish, H.A.A., Abdullah, R., Salam, R.A. (2006) 'Protein conformational search using honey bee colony optimization', 103–108.

Blum, C., Merkle, D. (2008) *Swarm Intelligence: Introduction and Application*, 1st Ed. ed, Springer-Verlag: Berlin, Heidelberg.

Blum, C., Roli, A. (2003) 'Metaheuristics in Combinatorial Optimization : Overview and Conceptual Comparison', *ACM Computing Surveys*, 35(3), 268–308.

Bonabeau, E., Dorigo, M., Theraulaz, G. (1999) *Swarm Intelligence: From Natural to Artificial Intelligence*, 1st Ed. ed, Oxford University Press: New York.

Chen, Y., Phillips, J. (2013) 'ECU Software Abnormal Behavior Detection Based On Mahalanobis-Taguchi Technique', 1(1).

Cudney, E.A., Paryani, K., Ragsdell, K.M. (2006) 'Applying the Mahalanobis-Taguchi System to Vehicle Handling', *Concurrent Engineering*, 14(4), 343–354.

Cudney, E.A., Sharma, N. (2009) 'Forecasting Warranty Cost for Vehicle Handling Using the Mahalanobis-Taguchi System', *SAE International Journal of*

Material and Manufacturing, 1(1), 741–746.

Cudney, E.A.F., Ragsdell, K.M. (2013) ‘Forecasting Using the Mahalanobis-Taguchi System in the Presence of Collinearity’, 2006(724).

Das, P., Datta, S. (2007) ‘Exploring the effects of chemical composition in hot rolled steel product using Mahalanobis distance scale under Mahalanobis–Taguchi system’, *Computational Materials Science*, 38(4), 671–677.

Das, P., Datta, S. (2012) ‘Developing an unsupervised classification algorithm for characterization of steel properties’, *International Journal of Quality & Reliability Management*, 29(4), 368–383.

Dasgupta, S. (1993) ‘The evolution of the D-Statistic of Mahalanobis’, *The Indian Journal of Statistics*, 55(3), 442–459.

Engelbrecht, A.P. (2006) *Fundamentals of Computational Swarm Intelligence*, John Wiley and Sons: US.

Farago, A. (2014) ‘Optimizing Massive Distance Computations in Pattern Recognition’, *International Journal of Machine Learning and Computing*, 4(1), 114–119.

Feng, S., Hiroyuki, O., Hidennori, T., Yuichi, K., Hu, S. (2011) ‘Qualitative and quantitative analysis of gmaw welding fault based on mahalanobis distance’, *International Journal of Precision Engineering and Manufacturing*, 12(6), 949–955.

Foster, C.R., Jugulum, R., Frey, D.D. (2009) ‘Evaluating an adaptive One-Factor-At-a-Time search procedure within the Mahalanobis-Taguchi System’, *Internatinal Journal of Industrial and Systems Engineering*, 4(6), 600–614.

Frey, D.D., Sudarsanam, N. (2008) ‘An Adaptive One-Factor-at-a-Time Method for Robust Parameter Design: Comparison With Crossed Arrays via Case Studies’, *Journal of Mechanical Design*, 130(2), 021401.

Ghasemi, E., Aaghaie, A., Cudney, E.A. (2015) ‘Mahalanobis Taguchi system: a review’, *International Journal of Quality & Reliability Management*, 32(3), 291–307.

Gower, J.C. (1982) ‘Euclidean Distance Geometry’, *Mathematical Scientist*, 7, 1–14.

Guo, W., Yin, R., Li, G., Zhao, N. (2013) 'Research on Selection of Enterprise Management-Control Model Based on Mahalanobis Distance', in Qi, E., Shen, J. and Dou, R., eds., *The 19th International Conference on Industrial Engineering and Engineering Management*, Springer Berlin Heidelberg: Berlin, Heidelberg, 555–564.

Häcker, J., Engelhardt, F., Freyw, D.D. (2002) 'Robust manufacturing inspection and classification with machine vision', *International Journal of Production Research*, 40(6), 1319–1334.

Hamming, R.W. (1950) 'Error detecting and error correcting codes', *Bell System Technical Journal*, 29, 147–160.

Hasan, S. (2014) *Multi-Strategy Self-Organising Map Learning*.

Hawkins, D.M. (2003) 'Discussion', *Technometrics*, 45(1), 25–29.

Hedayat, A.S., Sloane, N.J.A., Stufken, J. (1999) *Orthogonal Arrays: Theory and Applications*, 1st Ed. ed, Springer-Verlag New York, Inc.: New York.

Hornby, A.S. (1995) *Oxford Advanced Learner's Dictionary*, 5th Ed. ed, Oxford University Press: Oxford.

Hsu, T., Huang, C. (2010) 'Modeling a Dynamic Design System Using the Mahalanobis Taguchi System — Two-Step Optimal', in *Second International Conference, ICCCI 2010, Kaohsiung, Taiwan, November 10-12, 2010. Proceedings, Part II*, Springer Berlin Heidelberg: Taiwan, 327–332.

Hu, J., Zhang, L., Liang, W. (2012) 'Incipient machine degradation assessment by MF-MTS system', *2012 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering*, 635–640.

Hu, J., Zhang, L., Liang, W. (2013) 'Dynamic degradation observer for bearing fault by MTS–SOM system', *Mechanical Systems and Signal Processing*, 36(2), 385–400.

Huang, C.-L., Chen, Y.H., Wan, T.-L.J. (2012) 'The mahalanobis taguchi system—adaptive resonance theory neural network algorithm for dynamic product designs', *Journal of Information and Optimization Sciences*, 33(6), 623–635.

Huang, C.-L., Hsu, T.-S., Liu, C.-M. (2009) 'The Mahalanobis–Taguchi system –

Neural network algorithm for data-mining in dynamic environments', *Expert Systems with Applications*, 36(3), 5475–5480.

Huang, C.L., Yang, C.L., Hsu, T.S., Liu, C.M. (2008) 'Modeling a combination of projects selection system- using the Mahalanobis Taguchi system', *2008 IEEE International Conference on Industrial Engineering and Engineering Management*, 1539–1541.

Huang, J.C.Y. (2010) 'Reducing Solder Paste Inspection in Surface-Mount Assembly Through Mahalanobis–Taguchi Analysis', *IEEE Transactions on Electronics Packaging Manufacturing*, 33(4), 265–274.

Hwang, I., Park, G. (2011) 'A multi-objective optimization using distribution characteristics of reference data for reverse engineering', *International Journal for Numerical Methods in Engineering*, (85), 1323–1340.

Ionescu, M.M. (2006) *Adaptive Measures of Similarity, Fuzzy Hamming Distance, and Its Applications to Pattern Recognition Problems*, *University of Cincinnati*.

Iquebal, A.S., Pal, A., Ceglarek, D., Tiwari, M.K. (2014) 'Enhancement of Mahalanobis-Taguchi System via Rough Sets based Feature Selection', *Expert Systems with Applications*, 41(17), 8003–8015.

Itagaki, M., Takamiya, E., Watanabe, K., Nukaga, T., Umemura, F. (2007) 'Diagnosis of quality of fresh water for carbon steel corrosion by Mahalanobis distance', *Corrosion Science*, 49(8), 3408–3420.

Jain, A.K., Duin, R.P.W., Mao, J. (2000) 'Statistical Pattern Recognition : A Review', *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 22(1), 4–37.

Jamil, M., Zepernick, H.-J. (2013) 'Levy Flights and Global Optimization', in *Swarm Intelligence and Bio-Inspired Computation*, Elsevier Inc.: London, 49–72.

Jiang, J.C., Lin, T.Y. (2012) 'Improved Atomic Force Microscopic Inspection Process of Liquid Crystal Display', *Applied Mechanics and Materials*, 217-219, 2716–2721.

Jiangtao, R., Yuanwen, C., Xiaochen, X. (2011) 'Application of Hilbert-Huang transform and Mahalanobis-Taguchi System in mechanical fault diagnostics using vibration signals', *IEEE 2011 10th International Conference on*

Electronic Measurement & Instruments, 299–303.

Jin, X., Chow, T.W.S. (2013) ‘Anomaly detection of cooling fan and fault classification of induction motor using Mahalanobis–Taguchi system’, *Expert Systems with Applications*, 40(15), 5787–5795.

Kacker, R.N., Kuhn, D.R., Lei, Y., Lawrence, J.F. (2013) ‘Combinatorial testing for software: An adaptation of design of experiments’, *Measurement: Journal of the International Measurement Confederation*, 46(9), 3745–3752.

Karaboga, D., Akay, B. (2009) ‘A survey: algorithms simulating bee swarm intelligence’, *Artificial Intelligence Review*, 31(1-4), 61–85.

Kestle, R.S., Cudney, E.A. (2011) ‘An Evaluation of Mahalanobis-Taguchi System Experiment Metrics’, in *IIE Annual Conference and Proceedings of the 2011 Industrial Engineering Research Conference*.

Krause, E.F. (1973) ‘Taxicab Geometry’, *National Council of Teachers of Mathematics*, 66(8), 695–706.

Krause, J., Cordeiro, J., Parpinelli, R.S., Lopes, H.S.H. (2013) ‘A Survey of Swarm Algorithms Applied to Discrete Optimization Problems’, *Swarm Intelligence and Bio-Inspired Computation*, 169–191.

Kumar, V., Minz, S. (2014) ‘Feature Selection: A literature Review’, *Smart Computing Review*, 4(3), 211–229.

Lee, Y.-C., Teng, H.-L. (2009) ‘Predicting the financial crisis by Mahalanobis–Taguchi system – Examples of Taiwan’s electronic sector’, *Expert Systems with Applications*, 36(4), 7469–7478.

Liparas, D., Angelis, L., Feldt, R. (2011) ‘Applying the Mahalanobis-Taguchi strategy for software defect diagnosis’, *Automated Software Engineering*, 19(2), 141–165.

Liparas, D., Laskaris, N., Angelis, L. (2013a) ‘Incorporating resting state dynamics in the analysis of encephalographic responses by means of the Mahalanobis-Taguchi strategy’, *Expert Systems with Applications*, 40(7), 2621–2630.

Liparas, D., Laskaris, N., Angelis, L. (2013b) ‘Incorporating resting state dynamics in the analysis of encephalographic responses by means of the Mahalanobis–

Taguchi strategy', *Expert Systems with Applications*, 40(7), 2621–2630.

Lv, Y., Gao, J. (2011) 'Condition Prediction of Chemical Complex Systems Based on Multifractal and Mahalanobis-Taguchi System', 1021022104(2007), 0–3.

Lv, Y., Gao, J., Gao, Z., Jiang, H. (2012) 'Multifractal information fusion based condition diagnosis for process complex systems', *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 227(3), 178–184.

Maaten, L. Van Der, Postma, E., Herik, J. (2009) 'Dimensionality Reduction : A Comparative Review Dimensionality Reduction : A Comparative Review'.

Mahalakshmi, P., Ganesan, K. (2009) 'Mahalanobis Taguchi System based criteria selection for shrimp aquaculture development', *Computers and Electronics in Agriculture*, 65(2), 192–197.

Mahalanobis, P.C. (1936) 'On The Generalised Distance in Statistics', *Proceedings of the National Institute of Science of India*, 2, 49–55.

Marcos, J.V., Hornero, R., Alvarez, D., del Campo, F., Zamarrón, C. (2009) 'Assessment of four statistical pattern recognition techniques to assist in obstructive sleep apnoea diagnosis from nocturnal oximetry.', *Medical Engineering and physics*, 31(8), 971–8.

Mastsuda, R., Ikeda, Y., Kamoshita, T., Touhara, K. (2001) 'Application of Mahalanobis Taguchi System to Fault Diagnosis for Future Spacecraft', in *10th International Space Planes and Hypersonic Systems and Technologies Conference*, 28047.

Miki, S., Hasegawa, T., Umemura, S., Okazawa, H., Otsuka, Y., Matsuki, H., Tsunoda, S., Inujima, H. (2008) 'Remaining Service Life Diagnostic Technology of Phenol Insulators for Circuit Breakers', *IEEE Transactions on Dielectrics and Electrical Insulation*, 15(2), 476–483.

Miki, S., Okazawa, H., Hasegawa, T., Tsunoda, S., Inujima, H. (2009) 'Remaining service life diagnostic technology of insulators for power distribution equipment', *Electrical Engineering in Japan*, 167(2), 1–9.

Miki, S., Okazawa, H., Inujima, H. (2009) 'Evaluation of the degree of deterioration of circuit-breaker insulators using chemical analysis and the Mahalanobis-

Taguchi (MT) method', *Electrical Engineering in Japan*, 168(1), 11–20.

Mitsuyoshi, N., Yamamoto, M., Suzuki, K., Ohuchi, A. (2001) 'A face identi ® cation system based on the Mahalanobis ± Taguchi System', *International Transactions in Operational Research*, 8, 31–45.

Młynarczuk, M., Górszczyk, A., Ślipek, B. (2013) 'The application of pattern recognition in the automatic classification of microscopic rock images', *Computers and Geosciences*, 60, 126–133.

Mohan, D., Saygin, C., Sarangapani, J. (2007) 'Real-time detection of grip length deviation during pull-type fastening: a Mahalanobis–Taguchi System (MTS)-based approach', *The International Journal of Advanced Manufacturing Technology*, 39(9-10), 995–1008.

Nagao, M., Yamamoto, M., Suzuki, K., Ohuchi, A. (1999) 'Facial Image Recognition', *IEEE*, 937–942.

Nechval, N.A., Nechval, K.N., Danovich, V., Berzins, G. (2014) 'Distance-Based Approaches to Pattern Recognition via Embedding', II, 0–5.

Niu, J., Cheng, L. (2012) 'Classification using improved Mahalanobis-Taguchi system based on omni-optimizer', *Systems Engineering - Theory and Practice*, 32(6), 1107–1120.

Okazawa, H., Distribution, P., City, M., Miki, S., City, A. (2012) 'Estimating the remaining service life of switchgear insulators', in *2012 IEEE International Conference on Condition Monitoring and Diagnosis*, 317–319.

Özbakir, L., Baykasoğlu, A., Tapkan, P. (2010) 'Bees algorithm for generalized assignment problem', *Applied Mathematics and Computation*, 215, 3782–3795.

Packianather, M.S., Landy, M., Pham, D.T. (2009) 'Enhancing the speed of the Bees Algorithm using pheromone-based recruitment', *2009 7th IEEE International Conference on Industrial Informatics*, 789–794.

Pal, A., Maiti, J. (2010) 'Development of a hybrid methodology for dimensionality reduction in Mahalanobis–Taguchi system using Mahalanobis distance and binary particle swarm optimization', *Expert Systems with Applications*, 37(2), 1286–1293.

Park, S.H. (1996) *Robust Design and Analysis for Quality Engineering*, 1st Ed. ed, Chapman & Hall: Boundary Row, London.

Phadke, M.S. (1989) *Quality Engineering Using Robust Design*, 1st Ed. ed, Prentice Hall: Englewood Cliffs, New Jersey.

Pham, D.T., A. Ghanbarzadeh, Koc, E., Otri, S., Rahim, S., Zaidi, M. (2006) 'The Bees Algorithm - A novel tool for complex optimization problems', in *2nd I*PROMS Virtual International Conference: Intelligent Production Machines and Systems*, Elsevier Ltd.: Cardiff, UK, 454 – 459.

Pham, D.T., Castellani, M. (2009) 'The Bees Algorithm: modelling foraging behaviour to solve continuous optimization problems', *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 223(12), 2919–2938.

Pham, D.T., Koc, E., Lee, J.Y., Phrueksanant, J. (2007) 'Using the bees algorithm to schedule jobs for a machine', *Proceedings of eighth international conference on laser metrology, CMM and machine tool performance*, 430–439.

Rashedi, E., Nezamabadi-pour, H., Saryazdi, S. (2009) 'GSA: A Gravitational Search Algorithm', *Information Sciences*, 179(13), 2232–2248.

Ren, J., Cai, Y., Xing, X., Chen, J. (2011) 'A method of multi-class faults classification based-on Mahalanobis-Taguchi system using vibration signals', *The Proceedings of 2011 9th International Conference on Reliability, Maintainability and Safety*, 1015–1020.

Reséndiz, E., Moncayo-Martínez, L. a., Solís, G. (2013) 'Binary ant colony optimization applied to variable screening in the Mahalanobis–Taguchi System', *Expert Systems with Applications*, 40(2), 634–637.

Reséndiz, E., Rull-Flores, C.A. (2013) 'Mahalanobis–Taguchi system applied to variable selection in automotive pedals components using Gompertz binary particle swarm optimization', *Expert Systems with Applications*, 40(7), 2361–2365.

Riho, T., Suzuki, a., Oro, J., Ohmi, K., Tanaka, H. (2005) 'The Yield Enhancement Methodology for Invisible Defects Using the MTS+ Method', *IEEE Transactions on Semiconductor Manufacturing*, 18(4), 561–568.

Sanusi, N.A., Abd Rashid, N.H. (2013) 'An Anlysis of Forecasting Techniques in Detecting The Future Financial Crisis in Malaysia: The Mahalanobis Taguchi System', in *1st International Conference on Robust Quality Engineering*, UTM Razak School of Engineering and Advanced Technology: Kuala Lumpur, Malaysia, 35–38.

Saraiva, P., Fafsca, N., Costa, R., Gonqalves, A. (2004) 'Fault Identification in Chemical Processes Through a Modified Mahalanobis-Taguchi Strategy', in *European Symposium on Computer-Aided Process Engineering*, 799–804.

Schoenberg, I.J. (1938) 'Metric spaces and positive definite functions', *Transactions of the American Mathematical Society*, 44, 522–522.

Shi, J., Cheng, L. (2011) 'Financial Crisis Dynamic Prediction Based on Sliding Window Technology and Mahalanobis-Taguchi System', *2011 International Conference of Information Technology, Computer Engineering and Management Sciences*, 4, 65–68.

Su, C.-T., Hsiao, Y.-H. (2007) 'An Evaluation of the Robustness of MTS for Imbalanced Data', *IEEE Transactions on Knowledge and Data Engineering*, 19(10), 1321–1332.

Su, C.-T., Huie-Chun, W. (2004) 'robust design of credit scoring system by the Mahalanobis-Taguchi System', *The Asian Journal on Quality*, Vol. 5(No.2).

Taguchi, G. (1997) 'Method for pattern recognition'.

Taguchi, G., Chowdhury, S., Wu, Y. (2001) *The Mahalanobis-Taguchi System*, 1st Ed. ed, McGraw-Hill: New York.

Taguchi, G., Chowdhury, S., Wu, Y. (2005) *Taguchi's Quality Engineering Handbook*, 1st Editio. ed, John Wiley & Sons, Inc., John Wiley & Sons, Inc.: New Jersey.

Taguchi, G., Jugulum, R. (2002) *The Mahalanobis-Taguchi Strategy: A Pattern Technology System*, 1st Ed. ed, John Wiley & Sons, Inc.: New York.

Taguchi, G., Rajesh, J., Taguchi, S. (2004) *Computer-Based Robust Engineering: Essentials for DFSS*, 1st Ed. ed, American Society for Quality: Wisconsin, USA.

Taguchi, S., Jugulum, R., Taguchi, G., Wilkins, J.O. (2003) 'Discussion', *Technometrics*, 45(1), 16–21.

Teng, H. (2013) 'Structuring A NRI Simplified Model by MTS: Application of MTS', 2713–2718.

Teshima, S., Hasegawa, Y., Tatebayashi, K. (2012) *Quality Recognition and Prediction: Smarter Pattern Technology with the Mahalanobis-Taguchi System*, 1st Ed. ed, Momentum Press: New York.

Thangavel, K., Pethalakshmi, a. (2009) 'Dimensionality reduction based on rough set theory: A review', *Applied Soft Computing*, 9, 1–12.

Theodoridis, S., Koutroumbas, K. (2009) *Pattern Recogniton*, 4th Editio. ed, Academic Press: London, UK.

Trier, Oivind Due, Jain, A.K., Taxt, T. (1996) 'Feature extraction methods for character recognition - A survey', *Pattern Recognition*, 29(4), 641–662.

Tsai, H.-C. (2014) 'Novel Bees Algorithm: Stochastic self-adaptive neighborhood', *Applied Mathematics and Computation*, 247, 1161–1172.

Wang, J., Duan, C. (2009) 'Structural Health Monitoring Using Mahalanobis-Taguchi System', *2009 International Conference on Information Engineering and Computer Science*, 1–4.

Wang, Z., Lu, C., Liu, H., Fan, H. (2013) 'Fault diagnosis and health assessment for bearings using the Mahalanobis-Taguchi system based on EMD-SVD', *Transactions of the Institute of Measurement and Control*, 35(6), 798–807.

Wang, Z., Wang, Z., Tao, L., Ma, J. (2012) 'Fault diagnosis for bearing based on Mahalanobis-Taguchi system', *Proceedings of the IEEE 2012 Prognostics and System Health Management Conference (PHM-2012 Beijing)*, 1–5.

Woodall, W.H., Koudelik, R., Tsui, K.-L., Kim, S.B., Stoumbos, Z.G., Carvounis, C.P. (2003a) 'A Review and Analysis of the Mahalanobis—Taguchi System', *Technometrics*, 45(1), 1–15.

Woodall, W.H., Koudelik, R., Tsui, K.-L., Kim, S.B., Stoumbos, Z.G., Carvounis, C.P. (2003b) 'Response', *Technometrics*, 45(1), 29–30.

Xu, S., Ji, Z., Pham, D.T., Yu, F. (2010) 'Bio-inspired binary bees algorithm for a two-level distribution optimisation problem', *Journal of Bionic Engineering*, 7(2), 161–167.

Yang, T., Cheng, Y.-T. (2010) 'The use of Mahalanobis–Taguchi System to improve flip-chip bumping height inspection efficiency', *Microelectronics Reliability*, 50(3), 407–414.

Yang, X.-S. (2010) *Nature-Inspired Metaheuristic Algorithms*, 2nd Editio. ed, Luniver Press: United Kingdom.

Yang, X.-S., Cui, Z., Xiao, R., Gandomi, A.H., Karamanogu, M. (2013) *Swarm Intelligence and Bio-Inspired Computation: Theory and Application*, 1st Editio. ed, Elsevier: Manhattan, USA.

Yang, X.-S., Karamanoglu, M. (2013) 'Swarm Intelligence and Bio-Inspired Computation: An Overview', in *Swarm Intelligence and Bio-Inspired Computation: Theory and Application*, Elsevier: London, UK, 2–23.

Zang, H., Zhang, S., Hapeshi, K. (2010) 'A Review of Nature-Inspired Algorithms', *Journal of Bionic Engineering*, 7, S232–S237.

Zeng, J., Wang, B., Hao, J., Fang, F. (2010) 'Mahalanobis Space Learning Machine for Quality Diagnosis', *2010 Second WRI Global Congress on Intelligent Systems*, (1), 106–110.

Zhai, Y., Ong, Y.S., Tsang, I.W. (2014) 'The Emerging "Big Dimensionality'', *IEEE Computational Intelligence Magazine Vol.9 No.3*, 14–26.

Zong, P. (2011) 'MTS Algorithm Based on Vague Set', *2011 International Conference on Intelligence Science and Information Engineering*, 257–260.