DEVELOPMENT OF SUSTAINABLE MANUFACTURING DECISION MAKING MODELS FOR SMALL AND MEDIUM ENTERPRISES

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FACULTY OF ENGINEERING
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ABSTRACT

Sustainable manufacturing aims to manage the operations in an environmentally and socially responsible manner. Several organizations have already incorporated the concept of sustainable manufacturing. However, many Small and Medium Enterprises (SMEs) that account for approximately 90% of all enterprises are not yet embraced this opportunity. Therefore, it is important to develop the sustainable manufacturing decision making models that suited to the characteristics of manufacturing SMEs. In order to achieve that, this study aims to identify key sustainable manufacturing performance measures & metrics and develop the sustainability evaluation and strategy selection models.

This study includes an empirical study to identify the key performance measures for sustainability assessment of manufacturing SMEs in an effective and comprehensive manner using the Triple Bottom-Line framework. In order to investigate the importance and applicability of the proposed measures and metrics, a survey was conducted among the practitioners. The result of Mann-Whitney U-test confirms that there is no significant difference between the importance and applicability of the proposed measures. Considering the human reasoning based decision-making in manufacturing SMEs,the development of decision-making models are based on the fuzzy set theory. This study also develops two sustainability performance evaluation models and one strategy selection model. For performance evaluation, the list of sustainability performance measures and metrics that is identified during the empirical study is applied. Consequently, a sensitivity analysis of the proposed method reveals the most important basic indicators affecting overall sustainability, identifying areas which decision makers should place special attention. For strategy selection model, the study develops a hierarchal multi-criteria decision making (MCDM) method by combining

Analytical Hierarchal Process (AHP) and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) methods under interval-valued fuzzy environment. The linguistic variables were expressed in the triangular interval-valued fuzzy sets. Using a case study of manufacturing SME, the final ranking of the strategies was elicited in accordance with this procedure. Subsequently, a sensitivity analysis was performed to validate the stability of the proposed final ranking. Apart from above mentioned studies, this study also includes the development of a fuzzy rule based expert system to provide an easy to access, time-saving and cost-effective way for sustainability evaluation and strategy selection. The expert system has two components: (1) sustainability evaluation and (2) strategy selection. The measures that are found important during sustainability evaluation process are considered as selection criteria for strategy selection. The applicability of the models and expert system were validated by implementation in manufacturing SMEs.

This study contributes in several ways to the research field of sustainable manufacturing decision making. It provides a list of key performance measures and metrics for sustainability evaluation of manufacturing SMEs. In conjunction with the sustainability evaluation models and strategy selection model, this study assists the decision maker for improving their sustainability performances. An easy to access expert system provides a time saving, cost effective way for sustainable manufacturing decision making. The list of key performance measures & metrics, various modelling approaches and an expert system should also enrich the literature.

ABSTRAK

Pembuatan mampan bertujuan untuk menguruskan operasi dengan cara yang lebih mesra alam dan sosial. Beberapa organisasi telah menerapkan konsep pembuatan mampan. Walau bagaimanapun, kebanyakan Perusahaan Kecil dan Sederhana (PKS) yang mencakupi kira-kira 90% daripada semua perusahaan masih belum dapat merangkul peluang ini. Oleh itu, adalah penting untuk membangunkan model mampan bagi membantu membuat keputusan pembuatan yang sesuai dengan ciri-ciri PKS pembuatan. Untuk mencapai itu, kajian ini bertujuan untuk mengenal pasti ukurandan metrik prestasiutama bagi pembuatanmampandan membangunkan penilaian kemampanan dan model pemilihan strategi.

Tesis ini merangkumi kajian empirikal untuk mengenal pasti ukuran-ukuran prestasi utama bagi penilaian kemampanan PKS pembuatan dengan cara yang berkesan dan menyeluruh. Konsep kemampanan Triple Bottom-Line telah diadaptasi sebagai rangka kerja bagi mewujudkan satu set ukuran dan metrik dalam penilaian prestasi kemampanan. Dalam usaha untuk menyiasat kepentingan dan kesesuaian ukuran dan metrik yang dicadangkan, tinjauan telah dijalankan di kalangan pengamal PKS pembuatan. Hasil ujian U Mann-Whitney mengesahkan bahawa tidak ada perbezaan yang signifikan di antara kepentingan dan kesesuaian ukuran-ukuran yang dicadangkan.Teori set kabur telah dicadangkan untuk membangunkan model bagi membuat keputusan memandangkan proses membuat keputusan dalam PKS pada kebiasaannya berhadapan dengan masalah ciri-ciri maklumat yang tidak lengkap dan pembuat keputusan lazimnya mengalami perbezaan dan percanggahan pendapat.Disamping itu, kajian ini juga membangunkan dua model penilaian prestasi kemampanan dan satu model pemilihan strategi. Untuk penilaian prestasi, senarai langkah-langkah prestasi kemampanan dan metrik yang dikenal pasti semasa kajian

empirikal digunakan. Oleh itu, analisis kepekaan terhadap kaedah yang dicadangkan mendedahkan petunjuk asas paling penting yang mempengaruhi kemampanan keseluruhan, dimana ia mengenal pasti faktor-faktor yang perlu diletakkan perhatian khusus oleh pembuat keputusan.Di dalam penyediaan model pemilihan strategi, kajian ini membangunkan kaedah membuat keputusan multi-kriteria hirarki dengan menggabungkan kaedah-kaedah Proses Hirarki Analisis (AHP) dan VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR), di bawah persekitaran selang-bernilai kabur. Selain kajian yang dinyatakan di atas, kajian ini juga termasuk pembangunan sistem pakar berdasarkan peraturan kabur bagi membantu penilaian kemampanan dan pemilihan strategi yang mudah untuk diakses, menjimatkan masa dan lebih kos efektif. Sistem pakar ini mempunyai dua komponen: (1) penilaian kemampanan dan (2) pemilihan strategi. Langkah-langkah yang didapati penting semasa proses penilaian kemampanan akan digunapakai sebagai kriteria pemilihan semasa pemilihan strategi. Kesesuaian model dan sistem pakar telah disahkan oleh pelaksanaan di beberapa PKS pembuatan.

Kajian ini menyumbang dalam pelbagai cabang bidang penyelidikan membuat keputusan pembuatan mampan. Ia menyediakan satu senarai langkah-langkah prestasi utama dan metrik untuk penilaian kemampanan PKS pembuatan. Bersempena dengan model penilaian kemampanan dan model pemilihan strategi, kajian ini membantu pembuat keputusan untuk meningkatkan prestasi kemampanan mereka. Sistem pakar yang mudah untuk diakses dapat menjimatkan masa dan menyediakan kaedah yang lebih tinggi keberkesanan kos bagi membuat keputusan pembuatan mampan. Senarai langkah-langkah prestasi utama dan metrik, pelbagai pendekatan pemodelan dan sistem pakar juga telah memperkayakan tesis ini.

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LIST OF SYMBOLS

$\mu_{\tilde{A}}(x)$	Membership of x in fuzzy set $\tilde{A}$
$\tilde{A} = (a, b, c, d)$	Trapezoidal Fuzzy set $\tilde{A}$
$\tilde{A} = (a_l, a_m, a_u)$	Triangular Fuzzy set $\tilde{A}$
$\tilde{x} = [(x_1, x_1^{'}); x_2; (x_3, x_3^{'})]$	Interval-valued triangular fuzzy number 'x'
$\tilde{w}_i$	Fuzzy weight of i^{th} criteria
λ_{max}	Largest Eigen value of pairwise comparison matrix under evaluation
$\tilde{f}_{ij}$	The performance of *jth* indicator /strategy A_j with respect to criterion C_i is indicated by fuzzy number
S_j	Maximum group utility of j^{th} Strategy
R_j	Minimum regret of opponent for j^{th} Strategy
Q_j	VIKOR value of j^{th} Strategy

LIST OF ABBREVIATIONS

SMEs: Small and Medium Enterprises

FIS: Fuzzy inference system

AHP: Analytical Hierarchal Process

VIKOR: VlseKriterijuska Optimizacija I Komoromisno Resenje

FAHP: Fuzzy Analytical Hierarchal Process

BSC: Balanced Scorecard

NGOs: Non-Government Organizations

TBL: Triple Bottom Line

CSR: Corporate Social Reporting

LCA: Life cycle analysis

DEA: Data Envelopment Analysis

MCDM: Multi-Criteria Decision Making

ANP: Analytical Network Process

MILP: Multi Integer Linear Programming

DEMATEL: Decision-Making Trial and Evaluation Laboratory

TOPSIS: Technique for order of preference by similarity to ideal Solution

EOL: End of Life

KPIs: Key performance indicators

EPA: Environmental Protection Agency

ELECTRE: ELimination Et Choix Traduisant la REalite

SAW: Simple Additive Weighting

PROMETHEE: Preference Ranking Organisation METHod for EnrichmentEvaluations

ZOGP: Zero–One Goal Programming

ANN: Artificial NeuralNetwork

GA: Genetic Algorithm

ESI: Environmental Sustainability Indicators

EPfl: Environment Performance Index

EEACSI: European Environmental Agency Core Set of Indicators

EPE: Environment Performance Evaluation

UNCSD: United Nations Indicators of Sustainable Development

DJSI: Dow Jones Sustainability Index

GRI: GlobalReporting Initiative

OECD: Organization for Economic Cooperation and Development

SS: Sustainability Score

OEM: Original Equipment Manufacturer

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CHAPTER 1: INTRODUCTION

1.1 Research Background

Now-a-days, sustainable development has become a major concern in all aspects of our daily activities (Linton et al., 2007). The main objective of sustainable development is to ensure that the needs of the present generation are met without compromising the ability of future generations to meet theirs (Brundtland, 1987). It is a well-established fact that our ecosystem is witnessing a difficult challenge due to limited resources, energy capacity, and waste disposal capability (Solvang et al., 2006). Many studies have attributed that the imbalance in the ecosystem is mainly due to manufacturing operations. In addition, Manufacturing operations are also accompanied by various social concerns at different stages of the production processes (Kemp, 1994; Seuring & Muller, 2008). Various laws and rules have been enforced on manufacturing operations and their resultant products across various countries(Olugu et al., 2011). Therefore, it is important for manufacturing organizations to incorporate the philosophy of sustainability into their manufacturing operations.

The perspectiveof sustainability is often referred as idea of Triple Bottom Line (TBL), which has three dimensions; environmental, social and economic(Seuring & Muller, 2008). Based on TBL approach, sustainable manufacturing strives to minimize negative environmental effects and conserve natural resources. It also focuses on the products and processes which are economically sound and safe for employee and community (ITA, 2007). The implementation of sustainable manufacturing offers a cost effective route in improving the economic, environmental, and social performance (Pusavec et al., 2010). In order to achieve the sustainable manufacturing, organizations are striving to make appropriate changes in their products, processes, and systems (Sutherland et al., 2008).

It has been also reported that those organizations adopting sustainable practices are able to achieve better product quality, higher market share, and increased profits (Nambiar, 2010). Sustainable manufacturing practices have also been seen to be positively associated with competitive outcomes (Rusinko, 2007). In order to achieve sustainable development in the manufacturing sector, it is important that sustainable manufacturing strategies being adopted in both large and small and medium enterprises (SMEs).

Over recent decades, larger organizations are adopting various sustainability strategies in their manufacturing operations due to pressures from consumers, regulators and community (Lee, 2008). In order to achieve better sustainability performance of supply chain, larger enterprises extend these practices to their suppliers. SMEs constitute about 80% of these suppliers (Moore & Manring, 2009). SMEs differ significantly from those for large corporations due to characteristics of SMEs, e.g., personalized management, lack of finances, resource limitations, more flexibility, horizontal structure, small number of customers, access to limited market, and lack of knowledge (Hillary, 2004; Ciliberti et al., 2008; Alshawi et al., 2011). Based on these characteristics; sustainable manufacturing in SMEs cannot be considered as a miniaturized version of the larger organization (Alshawi et al., 2011).

The small and medium enterprises are very instrumental in the growth of any economy (Anuar & Yusuff, 2011). In Malaysia, the contribution of SMEs to gross domestic product (GDP) is 50% and provides employment to 65 % of nation's workforce (The Star online, 2014). SMEs are broadly categories into three sectors of the economy; manufacturing, services and agriculture. Manufacturing SMEs accounted for 96.6 % of the organizations in the manufacturing sector of Malaysia(Aris, 2007). The majority of the manufacturing SMEs are the supplier for multi-national companies in their global supply chain. Therefore, manufacturing SMEs are under the increasing pressure to improve their sustainability performance. For example, larger organizations are adopting sustainable manufacturing practices in their operations as a result of the pressure of directives such as European Union (EU) directives on Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS), and Eco-design for Energy-using products (EuP) (Lee, 2009). The ripple effects of these directives are extended to suppliers in order to enhance the sustainability performance of these larger manufacturing organizations (Moore & Manring, 2009).

Sustainable manufacturing decision making consist of three components: (1) selection of appropriate metrics for assessing the sustainability of manufacturing, (2) the performance assessment tool to identify the weak areas, and (3) selection of suitable strategy to enhance the sustainable manufacturing (Reich-Weiser et al., 2008).To reveal the level of effort that manufacturing organizations require achieving a sustainable manufacturing process, performance assessment of sustainability becomes highly important. Performance assessment is a key component of the sustainable manufacturing strategies. It reflects the need for improvement in areas of poor performance, thus efficiency and quality can be improved (Chan & Qi, 2002). Considering the sustainability to economic, environmental and social dimensions, sustainability assessment methods are still evolving. The sustainable measures and indicators need to be simple and robust, reproducible and consistent, complement regulatory programs, cost effective in data collection and useful for decision-making (Tanzil & Beloff, 2006).The success of the assessment model depends on simplicity, mathematical robustness and selection of performance measures and indicators(Franceschini et al., 2006).

Most of the performance measurement approaches for sustainable manufacturing are based on the set of metrics, methods and models which are designed and tested in large manufacturing companies. Although, there are some studies on indicator development for SMEs such as development of environmental indicators to assess the environmental performances of SMEs (Rao et al., 2006) , but performance assessment perspectives considering all aspects of sustainability about manufacturing SMEs are still missing (Clarke-Sather et al., 2011). Despite the many sets of indices and measures, models and methods has been developed, there is still no focused set of measures and metrics, methods and models available for sustainability performance evaluation and strategy selection for manufacturing SMEs, particularly from developing economy. This study is an attempt to full-fill these research gaps.

1.2 Problem Statement

Manufacturing companies have been facing a lot of challenges in recent years due to various reasons such as globalization, shortening product useful life, increased variety of substitute products, and global economic crisis. In addition, the imbalances in the ecosystem and environmental degradation associated with manufacturing processes have become a major issue in the world. These have resulted in increasing pressure from the government, customers, NGOs and other stakeholders making it indispensable for manufacturers to seek for various sustainable conscious practices. Since recent decades, the larger or bigger organizations are adopting sustainable practices in manufacturing but manufacturing based SMEs are lagging behind. It has been observed in literature that most studies only looked at sustainability in SMEs from a generic point of view (Lepoutre and Heene, 2006; Thompson and Smith, 1991) without having to consider their application to emerging economies. Additionally, manufacturing based SMEs are facing with a myriad of challenges such as poor financing, low productivity, inadequate managerial capabilities and poor access to management and technology

(Wang, 2003). In Malaysia, these challenges also include lack of access to loans, limited adoption of technology, lack of human resources, competition from multinational companies and globalization (Moha, 1999; Saleh and Ndubuisi, 2006). Today, these challenges have been compounded by the emergence of sustainability in manufacturing. Therefore, there is a need to conduct a focused study of the various aspects of sustainable manufacturing decision making that will suit the SMEs especially from an emerging economy's point of view.

1.3 Research Aim and Objectives

This section presents the research aims and objectives of this research study.

1.3.1 Research Aim

This research study is aimed at identifying the performance metrics and measures and developing the decision-making models for sustainable manufacturing in small and medium scale enterprises (SMEs).

1.3.2 Research Objectives

The sustainable manufacturing decision making process is divided into three components based on the different aspects of sustainability initiatives in manufacturing organizations(Reich-Weiser et al., 2008). Based on these components, the following research objectives are developed for this research study.

1. To identify the key sustainability performance measures and metrics for manufacturing SMEs.
2. To develope the decision- making (performance assessment & strategy selection) models for sustainable manufacturing
3. To develope an expert system for sustainable manufacturing decision making in SMEs.

1.4 Scopes of the Research Study

This research study focuses only on the sustainable manufacturing decision making related to performance assessment and strategy selection. The population and sample of the research study are the manufacturing SMEs from Malaysia. The list of sustainable manufacturing performance measures and metrics proposed in this study is based on an empirical study conducted among the manufacturing SMEs from Malaysia only.

The sustainability assessment models were developed using the concepts of fuzzy logic, AHP and BSC. These models were validated by implementation in a manufacturing SME. Using the concepts of interval-valued fuzzy logic, AHP and VIKOR methods the sustainable manufacturing strategy selection model was developed. The usability of this model is validated by implementing in a manufacturing SME.

An easy to access web-based expert system was developed for the practitioners from manufacturing SMEs using the PHP, JavaScript and MySQL programming languages. The manufacturing SMEs are involved in the validation study of this system.

1.5 Significance of the Study

This study focuses on the development of decision making models for sustainable manufacturing in SMEs. A set of sustainable manufacturing performance measures is investigated for the importance and applicability in SMEs. Based on an empirical study, the study proposes the set of measures that is suitable for manufacturing SMEs from emerging economy such as Malaysia. The measures are then used in developing assessment models. Subsequently, an easy to access and user friendly expert system is developed for sustainability assessment in manufacturing SMEs.

Considering the vagueness involved in decision making in manufacturing SMEs. The sustainability assessment models are based on fuzzy logic set theory. In order to cater for the different needs of manufacturing SMEs, the first sustainability assessment is based on the Triple Bottom Line framework of the sustainability whereas second assessment model applied the Balanced Scorecard framework.

To select the best sustainable manufacturing strategy, this study developed a strategy selection model using the concepts of Analytical Hierarchal Process (AHP) and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) methods under interval-valued fuzzy (IVF) environment. The IVF environment provides comparatively more flexibility to decision maker to present their opinions.

The expert system for sustainability assessment and strategy selection enables the practitioners from manufacturing SMEs to make decisions in faster, easier, accurate manner. The web-based expert system can be accessed by the decision maker from any location and any time for self-assessment. It is hoped that expert system would be of benefit to manufacturing SMEs in their efforts to become more effective, competitive and sustainable. Finally, this study is expected to be of beneficial to both researchers and practitioners.

1.6 Organization of the Thesis

The structure of the thesis is based on the article style format. This thesis presents five articles which address various objectives of this research study in chapters 4-7. All these articles are either published or under review in high ranked journals (ISI cited). This thesis is presented in eight chapters. Chapter 1 presents the background to this research, research aim, research objectives and the scope of research study. Chapter 2 presents the review of the literature focuses on the sustainable manufacturing practices in SMEs, sustainability assessment metrics and models, sustainable manufacturing strategies and strategy selection methods and research gaps. The research methods applied in this study are presented in chapter 3. Chapter 4 presents the findings of the empirical study that attempts to identify a set of measures and metrics for evaluating the sustainability manufacturing performance of small and medium enterprises (SMEs). The development of the sustainability assessment models are presented in chapter 5. The strategy selection model for sustainable manufacturing is presented in chapter 6. Chapter 7 presents the development of an expert system for sustainability assessment and strategy selection. Finally, chapter 8 revisits the aims and objectives, provide a summary of the research process and research findings. This chapter also presents the contribution to the body of knowledge, implications for practitioners, research limitations and future research directions.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter aims to review the literature to provide a clear view of sustainable manufacturing practices from SMEs perspectives. As the research aim is to develop the sustainable manufacturing decision making models, the literature review has been focused on sustainability performance metrics and models, sustainable manufacturing strategies and strategy selection models. The following paragraph explains the strategy of doing a literature search, followed by the review of the subjects and lastly research propositions were presented.

This study started with a comprehensive literature review to identifying related literature. Using the keywords (such as Sustainable manufacturing, Green Manufacturing, Sustainability assessment, Sustainable manufacturing strategy, Small-and-medium enterprises, manufacturing strategies, cleaner production), various online databases were searched which generated hundreds of papers from journals, conferences, book chapters and other online resources. Based on the title and/or abstract, all papers indicating the topic of sustainable manufacturing, related strategies and performance assessment methods were collected and read through. Further the list of relevant papers was expanded by adding the references of the relevant papers. This process was continued until new searches started to drawn no new results. During the entire study period, regular searches were conducted to update the literature related to this research. The papers, which were not directly related to the study, were discarded.

2.2 Sustainable Manufacturing and SMEs

Although widely accepted, the Brundtland Commission definition of sustainable development is not an operational one for business and engineering decision makers in manufacturing (Haapala et al., 2013). Sustainable manufacturing is defined by U.S.

department of commerce as ‘‘*the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, as well as being safe for employees, communities, and consumers and economically sound*’’(ITA, 2007). National Council for Advanced Manufacturing (NCAM) proposed that *“Sustainable manufacturing includes the manufacturing of sustainable products and the sustainable manufacturing of all products*”. The former includes manufacturing of renewable energy, energy efficiency, green building, and other ‘‘green’’ & social equity-related products, and the latter emphasizes the “sustainable” manufacturing of all products taking into account the full sustainability/total life-cycle issues related to the products manufactured(Jayal et al., 2010).The Lowell Centre for Sustainable Production defines sustainable production as “*the creation of goods and services using processes and systems that are Non-polluting, conserving energy and natural resources, economically viable, safe and healthful for workers, communities, and consumers, socially and creatively rewarding for all working people*”. In simple words, sustainable manufacturing is all about minimizing various business risks associated with manufacturing operations while maximizing the new opportunities arises from improving manufacturing processes and products (OECD). The sustainable manufacturing concept built upon the TBL concept of sustainability attempts to incorporate economic, environmental and social aspects of manufacturing that can help companies to assess current operations for further improvement, innovate and identify new source of revenue and cost reduction.

Global or bigger companies have been developing the capability required to achieve the sustainable manufacturing over the recent decade. In 2005, General Electric announced Ecoimagination to dramatically increase the company business keeping in mind the environmental aspect. Returning from the verge of bankruptcy in 2008, General Motors adopted sustainability as an important principle in its business practices. The success in sustainability initiative stories of larger companies such as BMW, Dalmer, Coca-Cola and many more are well reported and recognized. But focusing on sustainability reporting it is found that percentage of larger companies publishing CSR is around 95%, whereas only around 48% small and medium scale enterprises (SMEs) publish their CSR (KPMG CRR, 2011).

In Malaysia, manufacturing sector SMEs are defined as firms with sales turnover not exceeding RM50 million or employment not exceeding 200 workers(SMECORP, 2014). The manufacturing SMEs constitute approximately 98.5% of the total number of manufacturing organization (The Star online, 2014). The Malaysian SMEs are very important for the economy as they provide employment to 65% of the employment and 50% of Gross Domestic Product (GDP) of Malaysia(SMECORP, 2014). However, it is seen that manufacturing SMEs are lagging behind in terms of their sustainable manufacturing efforts.

The lack of sustainability efforts in SMEs is attributed due to characteristics of SMEs. SMEs often lack the awareness, expertise, skills, finance, and human resources to build the required changes for sustainability within the organization (Lee, 2009; Fatimah et al., 2013). Further, these limitations are also supported by Thiede et al. (2013).Hillary (2004) identified barriers and drivers for the environmental management system for SMEs. These barriers are lack of knowledge, training, implementation cost, transient cost and so on. The drivers for sustainability in SMEs, as identified by Hillary (2004), are customers, government, local community, employees, insurers, banks and larger companies. This study concluded that despite these barriers, SMEs do achieve benefits from Environmental Management System (EMS). Lepoutre and Heene (2006) reported that firm size and characteristics of SMEs are also recognized as barriers for sustainable practices. An analysis of barriers and drivers for green manufacturing is performed using DELPHI survey method among the Malaysian SMEs by Ghazilla et al. (2015). In this study 39 drivers and 64 barriers have been identified. The weak organizational structure is found to be top barrier for green manufacturing in Malaysian SMEs. However, the effect of these barriers can be nullified by critical analysis and strategy to overcome the constraining barriers.

Now-a-days, SMEs are adopting the green initiatives to enhance their competitiveness to survive in the market (Lee, 2009). For instance, European Union (EU) directives on Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS), and Eco-design for energy-using products (EuP) have forced bigger organizations to adopt the sustainable practices in their operations (Lee, 2009). The ripple effects of these directives are extended to suppliers in order to enhance the sustainability performance of these larger manufacturing organizations. Many of these suppliers are SMEs that represent approximately 80% of global enterprises (Moore & Manring, 2009). Further, SMEs are also under pressure to improve their sustainability performance due to government regulations, local community groups, environmental groups, and investors from financial institutions (Biondi et al., 2000; Hillary, 2004; Lepoutre & Heene, 2006). Using an empirical study, Williamson et al. (2006) reported that business performance and regulations are drivers for environmental practices of SMEs. They also emphasised that Manufacturing SMEs try to improve business performances because of the pressures placed on them by market-dominated decision-making frames. Using an empirical study in Turkish SMEs, Agan et al. (2013) concluded that most influential driver for sustainability is expected benefits such as cost savings, increased customer satisfaction, new market opportunities, improved corporate image, and higher profits.

2.3 Sustainability Performance Assessment

Performance assessment provides the feedback or information on activities with respect to meeting customer expectations and strategic objectives (Chan & Qi, 2002). The sustainable manufacturing performance measurement involves quantifying the efficiency and effectiveness of all the activities and processes related to manufacturing operations of the organization. It reflects the need for improvement in areas with unsatisfactory performance, thus efficiency and quality can be improved (Chan & Qi, 2002) or to compare competing alternatives (Beamon, 1999b). The purposes of performance assessment are: external reporting (like, CSR), internal control (managing the activities and processes) and, internal analysis (understanding the activities and process better and continuous improvement) (Hervani et al., 2005). The performance measurement metrics of traditional manufacturing has been expanded to incorporate sustainability (Carter & Rogers, 2008). The following sub-sections present the review of literature on sustainability assessment models and sustainability assessment metrics.

2.3.1 Sustainability Assessment Methods

There are various studies which tried to measure the sustainability performance of organizations using various modelling techniques. The goal programming approach was used to optimize the performance of a sustainable supply chain (Zhou et al., 2000). In order to address the intangible parameters, fuzzy goal programming is also used for performance optimization of supply chains (Tsai & Hung, 2009).

The balanced scorecard (BSC) is another widely used tool, which is a performance management tool capable of accommodating the financial and nonfinancial measures and facilitates decision-making process. The BSC is used for performance measurement in forward chain of supply network(Tseng et al., 2011) as well as in reverse logistics (Ravi et al., 2005).

Data envelopment analysis (DEA) is a linear programming based analysis of how efficiently an organization operates. The advantage of DEA over other multi-criteria decision-making (MCDM) tools is that it requires fewer inputs and provides ranking of alternatives or measures (Wong & Wong, 2007). This is a very widely used tool for modelling the supply chain performance. Zhou et al., 2008 applied DEA approach to measure the carbon emission performance. Ecological efficiency has also been measured with the help of DEA (Dyckhoff & Allen, 2001).

Analytical hierarchy process (AHP) is a MCDM technique which structures the decision problem in a hierarchy of goals, decision criteria, and alternatives. It is a widely used tool for ranking the alternatives or indicators for performance measurement of manufacturing organizations by performing pair-wise comparisons of components involved(Zhou et al., 2000; Krajnc & Glavič, 2005; Yakovleva et al., 2012).Analytical network process (ANP) is also a MCDM tool like AHP except that hierarchy in AHP is replaced by a network in ANP. This provides a more flexible environment to ANP compared to AHP(Ravi & Shankar, 2005).

Fuzzy set theory is widely used for designing a performance measurement system as there are qualitative metrics involved (Tsai & Hung, 2009; Erol et al., 2011; Lee et al., 2011; Tseng et al., 2011; Olugu & Wong, 2012; Shen et al., 2012). Simulation technique is also used to evaluate the performances (Asif et al., 2012). Multi Integer Linear Programming (MILP) is also used as a modelling technique for performance measurement(Krikke, 2011). Fuzzy AHP method is applied to compute the sustainable manufacturing index at organizational and operational level of manufacturing SMEs (Ocampo et al., 2016).

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique is a comprehensive method for building and analysing a structural model involving causal relationships between complex factors. This technique combined with graph theory and matrix approach is used to assess the sustainable performances of manufacturing organizations (Uysal, 2012). It is also combined with fuzzy set theory for performance measurement model development (Lee et al., 2011).

The Technique for order of preference by similarity to ideal solution (TOPSIS) is a MCDM tool used for performance assessment. This technique has been used for supplier performance assessment in green supply chain environment (Shen et al., 2012) and performance measurement in sustainable manufacturing (Uysal, 2012).Multi-attribute utility technique (MAUT) is another MCDM tool used for performance measurement of manufacturing organizations. Another variant of MAUT, when combined with fuzzy set theory results in fuzzy multi-attribute utility technique (FMAUT)(Shen et al., 2012). As the sustainability performance assessment of manufacturing organizations is very complex, most of the researchers prefer to combine the various techniques to achieve the desired result. These types of approaches are known as hybrid approaches. Other tools used are rough set theory and transport methods for performance measurements. An indicator based holistic (e.g. considering all three dimensions of sustainability) and rapid tool for sustainability assessment is presented by Chen et al. (2014) which is based on combining various assessment methods such as DOW JONES SUSTAINABILITY INDEX, GRI.

2.3.2 Sustainability Performance Metrics

Qualitative and quantitative metrics are necessary for evaluating and improving the sustainability performance of manufacturing processes and systems (Haapala et al., 2013). The ultimate goal of developing metrics for sustainable manufacturing is to improve decision-making criteria when optimizing process and system designs(Jawahir et al., 2006). Singh et al. (2012) presented a review of sustainability assessment methodologies which lists forty-one globally proposed sustainability indices. Numerous guidelines or indicator sets have been developed at organizational, regional, national and international levels to assess the sustainability (Liu et al., 2008; Jawahir et al., 2009; Singh et al., 2012). Many of these are applicable in part to assess the sustainability performance of manufacturing organization. This section presents a review of sustainable manufacturing performance assessment metrics. These metrics are identified from the literature and classified on the basis of the three dimensions of sustainability.

2.3.2.1 Economic performance metrics

The economic dimension of performance measurement recognizes the metrics effectively measuring relations with customers and suppliers that resulted in achieving financial goals (Presley et al., 2007). Better economic performance is always required as it is crucial for the survival of any organization. There is sufficient number of literature available, which dealt with economic performance measurements of manufacturing organizations(Zhu & Sarkis, 2004). The cost related performance measures are found to be most important for manufacturing SMEs (Ghazilla et al., 2015). The manufacturing cost is a metric considered important for manufacturing SMEs (Tan et al., 2015). Net Present Value (NPV) is another metric to measure the performance considering the time series flow of cash(Presley et al., 2007). Investment can also be an economic performance measures for organizations(Azapagic & Perdan, 2000a; Krajnc & Glavič, 2005). Other tactical and operational measures are energy consumption cost(Zhou et al., 2000; Presley et al., 2007; Olugu et al., 2010), materials cost(Zhou et al., 2000; Olugu et al., 2010) and disposal cost(Azapagic & Perdan, 2000a). The recycling cost, disposal cost, recycling efficiency and the cost associated with the collection of EOL products are some of the measures suggested in the literature (Olugu et al., 2010). Table 2.1 provides a comprehensive list of economic performance measures identified during the review process that integrated the economic dimension for sustainable manufacturing.

Table 2.1: Economic Performance metrics for sustainable manufacturing

Literature	Economic performance metrics
Zhou et al. (2000)	Profits, product value, raw material uses, inventory and production cost, non-renewable resource consumption energy consumption.
Veleva and Ellenbecker (2001)	Rate of customer complaints and/or returns
(Krajnc & Glavič, 2005)	Sales, operating profit, investments, capital expenditures, net earnings, research and development cost, number of employee.
(Azapagic & Perdan, 2000a)	Value added contribution to GDP, expenditure on environmental protection, environmental liabilities, ethical investment, human-capital indicators, employment contribution, staff turnover, expenditure on health and, safety, investment in staff development.
(Presley et al., 2007)	Net present value, delivery performance, maintain superior financial performance, cost reduction, improve supply chain efficiency and effectiveness, percent proactive and reactive expenditures, disposal cost, cash to cash cycle time, days in transit, customer return in monetary term ,energy consumed in monetary term.
(Olugu et al., 2011)	Cost associated with environment compliance, cost associated with energy consumption, cost associated with environment friendly materials, green cost per revenue, total decrease in supply chain cost, percentage decrease in delivery cost, percentage decrease in inventory cost, percentage decrease in information sharing cost, percentage decrease in ordering cost, percentage decrease in order lead time, percentage decrease in product development cycle time, percentage decrease in manufacturing lead time, percentage decrease in total supply chain cycle time, percentage increase in on time delivery, percentage decrease in customer's dissatisfaction, percentage decrease in delivery unreliability, percentage decrease in scrap and rework, availability of green product warranty, percentage increase in design flexibility, percentage increase in delivery flexibility, percentage increase in production flexibility, percentage increase in fill rate, cost associate with returning of end of life (EOL) products, cost associate with processing of recyclables, cost of sorting and segregation of recyclables, cost of disposal for hazardous and unprocessed waste

2.3.2.2 Environmental performance metrics

Environmental performance is all about how well an organization manages the environmental aspects of its activities, products, and services(ISO 14001, 2004). The primary goal of environmental performance metric is to evaluate environmental impact, environmental problem that is required to be resolved, and effect of environmental efforts in order to promote environmental activities of organizations and obtain information for decision making. The applicability of environment performance metrics vary from one sector to another, but the commonly and widely used metric is efficient uses of energy (Azapagic & Perdan, 2000a; Zhou et al., 2000; Hervani et al., 2005; Krajnc & Glavič, 2005; Tsoulfas & Pappis, 2008; Olugu et al., 2010). The efficient uses of other resources are also considered for environmental performance measurement(Sundin et al., 2015). Others metrics are the use of green materials and material efficiency (Azapagic & Perdan, 2000a; Zhou et al., 2000; Olugu et al., 2010), minimization of waste (Zhou et al., 2000) , utility used (Olugu et al., 2010), emissions of CO_2, CO, SO_2etc.(Krajnc & Glavič, 2005). At the strategic level, environmental certifications or implementation of environmental management system is recognized as a widely used performance metrics(Hervani et al., 2005; Bhagwat & Sharma, 2007; Darnall et al., 2008; González et al., 2008; Azevedo et al., 2011). Reuse or recycling(Hervani et al., 2005; Krajnc & Glavič, 2005; Presley et al., 2007), percent of product with take-back policy (Veleva & Ellenbecker, 2001), percent of product returned back to process ,waste treatment (Hervani et al., 2005), utility uses in recovery process (Tsoulfas & Pappis, 2008), certification for recycling (Olugu et al., 2010) are some of the measures. A Comprehensive list of the environmental performance metrics are identified from the literature are listed in Table 2.2.

Table 2.2: Environmental performance metrics for sustainable manufacturing

Literature	Environmental performance measures
(Zhou et al., 2000)	Efficient use of resources to minimize waste generation and permanent environment damage should not be allowed.
(Veleva & Ellenbecker, 2001)	Freshwater consumption, materials used, energy use, percent energy from renewable sources (e.g. solar, wind, hydro, biomass), kilograms of waste generated before recycling, global warming Potential, acidification potential, kilograms of persistent, bio accumulative and toxic(PBT) chemicals used, costs associated with EHS compliance, percent of products designed for disassembly, percent of biodegradable packaging, reuse or recycling, percent of products with take back policies in place
(Krajnc & Glavič, 2005)	Total energy consumption, water consumption, air emissions, CO_2 emissions, SO_2 emissions, emission of heavy metals on surface water, waste generation, waste for recycling and disposal
(Azapagic & Perdan, 2000a)	Resource use, global warming, ozone depletion, acidification, eutrophication, photochemical smog, human toxicity, eco toxicity, Solid waste, material and energy intensity, material recyclability, product durability, service intensity), environmental management systems , environmental improvements, above the compliance levels, assessment of suppliers.
(Hervani et al., 2005)	Discharges to receiving streams and water bodies, underground injection on-site, releases to land on-site, discharges to publicly owned treatment works, other off-site transfers, non-production releases, source reduction activities, spill and leak prevention, inventory control, raw material modification, process modifications, cleaning and decreasing, surface preparation and finishing, product modifications, pollution prevention opportunity audits, and materials balances, Costs associated with environmental compliance, environmental liabilities under applicable laws and regulations, site remediation costs under applicable laws and regulations, major awards received, total energy use, total electricity use, total fuel use, other energy use, Total materials use other than fuel; total water use, major environmental, social, and economic impacts associated with the life cycle of products and services, formal, written commitments requiring an evaluation of life cycle impacts, on-site and off-site energy recovery, on-site and off-site recycling, on-site or off-site treatment, quantity of non-product output returned to process or market by recycling or reuse.
(Presley et al., 2007)	Waste reduction, improved compliance, proportion of renewable resources used, engage in sustainable operations practice, direct intervention on nature and landscape, number of green products, hazardous material output, quantity of packing, residual generated per unit of product, number of accidents and spills, violations reported by employees, percent of product reclaimed, percent of recycle or reused

	materials,
(Tsoulfas & Pappis, 2008)	Material recyclability, reusability, energy consumption, energy sources, fresh water use, water reuse, use of recycled material, standardization, disassembality, by-products, defects, production waste, biodegradable products, fuel consumption, motivation to suppliers, motivations to customers, motivations to personnel, personnel's attitude, labelling, sorting, worthy used products, fuel consumption(reverse), use of existing forward chain facility, recyclables, non-hazardous disposed materials, hazardous disposed materials, recyclables / reused locations (own and third party), energy consumption (recovery), water consumption (recovery), by-products reuse, defects reuse
(Olugu et al., 2011)	Suppliers' commitment, level of suppliers' environment certification, level of suppliers' performance on sustainability, numbers of suppliers' initiatives on environment management, level of disclosure of initiative to the public, level of suppliers' processing of raw material, level of process management, available of process optimization for waste reduction, level of spillage, leakage and pollution control, level of waste generated during production, quantity of utility used, number of violations of environmental regulations, product characteristics: level of recycled materials in product, level of products should be disposed to landfills or incinerated, availability of eco-labelling, availability of biodegradable materials in product, level of usage of design-for-assembly in product, level of market share controlled by green product, availability of environmental auditing system, availability of mission statement on sustainability, number of management's environment initiatives, availability of environment reward program, level of management to motivate the suppliers, level of waste generated, ratio of materials recycled to recyclable materials, material recovery time, level of motivation to customers on EOL products, availability of standard procedure for collecting the EOL products, availability of collection centre, availability of waste management schemes, recycling efficiency, percentage decrease in recycling time, availability of recycling standards, availability of standard operation procedures, percentage decrease in utility usage in recycling, efficiency of shredders and dismantlers, percentage reduction in emissions and waste, suppliers commitment, extent of delivery from suppliers back to manufacturer, certification system for supplier in recycling process, number of supplier's initiative in recycling process.

2.3.2.3 Social performance metrics

Social performance measures how well an organization has translated its social goals into practice. Social performance can be evaluated in terms of the impact of organization’s decisions and activities on society that contribute towards sustainable development including health and welfare of society, stakeholder’s expectations, compliance with applicable law and integration throughout the organization (ISO 2600).The Stakeholder’s involvement in decision making is widely used social performance measure(Veleva & Ellenbecker, 2001; Hervani et al., 2005; Krajnc & Glavič, 2005; Presley et al., 2007). Other measures are community spending (Azapagic & Perdan, 2000a; Veleva & Ellenbecker, 2001; Krajnc & Glavič, 2005), number of accidents(Azapagic & Perdan, 2000a; Krajnc & Glavič, 2005), number of employee (Veleva & Ellenbecker, 2001), social and EHS performances (Veleva & Ellenbecker, 2001; Hervani et al., 2005), number of hours for employee training (Veleva & Ellenbecker, 2001), percentage of workers reported job satisfaction (Azapagic & Perdan, 2000a; Veleva & Ellenbecker, 2001; Presley et al., 2007), number of complaints from neighbour(Azapagic & Perdan, 2000a) A comprehensive list of social performance measures has been identified during reviewing the literatures and is listed in Table 2.3.

Table 2.3: Social performance metrics for sustainable manufacturing

Literature	Social performance metrics
(Veleva & Ellenbecker, 2001)	Organization's openness to stakeholder's involvement in decision-making process, community spending and charitable contributions as percent of revenues number of employees per unit of product/dollar sale, number of community company partnerships, lost workday injuries and illness case rate, rate of employees' suggested improvements in quality, social and EHS performance turnover rate (or average length of service of employees), average number of hours of employee training, percent of workers who report complete job satisfaction, organization's openness to stakeholder's involvement in decision-making process.
(Krajnc & Glavič, 2005)	Number of occupational accidents per 200000 hr worked, number of non-profit projects, no. of complains from neighbour.
(Azapagic & Perdan, 2000a)	Preservation of cultural values,-stakeholder inclusion, involvement in community, projects, international standards of conduct, business dealings, child labour, fair prices, collaboration with corrupt regimes, intergenerational equity, income distribution, work satisfaction, Satisfaction of social needs.
(Hervani et al., 2005)	Employee and participative management; publicly available missions and values statement(s), management systems pertaining to social and environmental performance, magnitude and nature of penalties for non-compliance, number, volume, and nature of accidental or non-routine releases to land, air, and water, habitat improvements and damages due to enterprise operations, programs or procedures to prevent or minimize potentially adverse impacts of products and services, procedures to assist product and service designers to create products or services with reduced adverse life cycle impact.
(Presley et al., 2007)	Internal human resources, external pollution, stakeholder's participation, perceived aesthetics, employee satisfaction, maintained skill force, cooperative ventures with government, maintain long-term relationship and alliances, stakeholder's influence, training hours utilized per employee, unfavourable press coverage.
(Olugu et al., 2011)	Level of management to motivate the employee, availability of environment evaluation schemes, level of management's effort to enlighten the consumers on sustainability, level of customer's interest in green product, level of customer's satisfaction from green product, level of customer's dissemination of green information, level of customer's returning of end of life products, level of customer-to-customer dissemination of information, level of understanding of green process by customer

The review of literatures focusing on performance measurement for sustainable manufacturing resulted in more than 200 metrics. To extract the results in the designed framework, these metrics are listed in one of the following categories: 1. Economic performance measures 2. Environmental performance measures and 3. Social performance measures. An alphabetical listing of measures has been done to identify the duplicity or redundancy of measures. The key performance indicators (KPIs) are identified after removing the redundancy due to the same measures, overlapping measures and measures with a different title but practically same meaning. These KPIs are also classified as strategic, tactical and operational as presented in Table 2.4.

Table 2.4: Key Performance metrics for sustainable manufacturing based on literature review

Decision making Level	Performance Metrics
Economic Performance metrics	
Strategic	Net present value, financial performances, cost reduction, investments, research and development cost, investment for recycling facility, Savings due to recycling/ remanufacturing / reuse
Tactical	Efficiency and effectiveness of supply chain, value added, order lead time, product development cycle time, supply chain cycle time, customers complain, flexibility, scrap and rework, recycling efficiency.
Operational	Energy consumption cost, material consumption cost, inventory and production cost, delivery cost, recycling cost per unit, disposal cost per unit.
Environmental performance metrics	
Strategic	Waste generation in production, global warming potential, environmental compliance, percentage of renewable resource use, mission statement on sustainability, environmental initiatives, disclosure of initiatives to public, management initiatives for recycling, minimization of waste generation.
Tactical	Supplier's assessment, motivation to suppliers, percent of recyclable material in product, eco labelling, environmental auditing system, design-for-assembly in product, material recyclability, disassembility, recycling standards, standard operation procedures, certification system for recycling, number of collection centre , recycling audit.
Operational	Violations of environmental regulations, energy consumption, fuel consumption, utility consumption, GHG emissions, hazardous waste, leakage, spillage and pollution control, recycling time, utility uses in recycling, energy consumption, utility consumption, material recovery time,
Social performance metrics	
Strategic	Human resource, stakeholder's participation, management system pertaining to social policy, community spending as percentage of revenue, international standards of conduct, business dealing and fair policies, stakeholder's involvement.
Tactical	Employee satisfaction, employee turnover, number of non-profit projects, social performance, and community projects to promote return of EOL product.
Operational	Training, number of accidents, complaints from neighbour, lost working days, employee suggested plans execution, number of accidents, training for recycling

The following observations were based on statistical analysis of data presented in Table 2.4 with key performance measures for sustainable manufacturing. Environmental consideration is dominant for performance measurement of sustainable manufacturing as almost 50% metrics are environmental performance measures. There is lack of measures for social performance in sustainable manufacturing as only 22 % metrics were identified as KPIs for social performance measures. It was also seen that there is a lack of metrics for the social performance measurement of organizations may be due to various factors like lack of understanding of social responsibility, difficulty in integrating the stakeholder's requirements with social requirements (Baumann & Cowell, 1999; Veleva & Ellenbecker, 2001).

The performance metrics at operational (35%) and tactical level (37%) have received significant attention from researchers and practitioner. However, strategic measures (28%) need to have further attentions as this is very significant for sustainable manufacturing. Quantitative measures are almost 85% of total measures, whereas non-quantitative constitutes only 15%. Non-financial measures (72%) have also received wide attention for sustainable manufacturing performance measurement.

2.4 Sustainable Manufacturing Strategies

The dictionary meaning of strategy is a plan of action or policy designed to achieve a major or overall goal (Dictionary, 2004). Strategies for sustainable manufacturing drive long-term organizational growth and profitability by mandating the inclusion of environmental and social concerns along with economic concerns in manufacturing operations. Sustainable manufacturing strategies strive to enhance the performance in all three dimensions of sustainability. There are many strategies to enhance the sustainability of manufacturing organizations (Maxwell et al., 2006), but researchers are more focused on the strategies related to resource usage and waste minimization (Abdul

Rashid et al., 2008). Some of the often cited label for manufacturing strategies and related literature are discussed in following paragraphs.

Waste minimization is one of the most common strategies mentioned in the literature. According to the United States Environmental Protection Agency, the waste minimization is the use of source reduction and/or environmentally-sound recycling methods prior to energy recovery, treatment, or disposal of wastes. Source reduction is also known as pollution prevention. Over a long period of time, researchers have been focussing on waste minimization as a strategy to deal with problems of waste management, new landfill locations and depletion of raw materials. Reducing the raw material at source conserve the raw materials for other uses, thus enhancing the sustainability performances of organizations.Epstein (2008) considered misappropriate waste generation as a clear sign of inefficiency and poor performances of manufacturing practices. El-Haggar (2010) considered the waste minimization as a component of waste management practices and an important strategy for sustainable manufacturing.

Some companies have adopted product stewardship as a sustainability strategy aimed at waste-free products and processes. Product stewardship can be defined as understanding, controlling, and communicating products 'environmental, health, and safety-related effects throughout its life cycle, from production (or extraction) to final disposal or reuse.Maslennikova and Foley (2000) reported the successful implementation of this strategy at Xerox Corporation and improvement in environmental performance, customers' satisfaction, and overall manufacturing performance. In another study, Preston (2001) reported the success of this strategy at Hewlett-Packard. Schroeder (2012) discussed the growth of this strategy as a dominant business model for recycling of products. In this study, the author suggested that an enterprises information system can be a great help for supporting this strategy. Wagner (2013) adopted product stewardship based framework as a preferred policy for cost-effective recovery of waste.

Lean manufacturing is another strategy that can be applied to sustainable manufacturing which focuses on ‘doing more by employing less’ thinking. This is a management philosophy derived from TOYOTA production system and popularized by Womack and Jones (2010). Lean manufacturing consist of some key tools and techniques such as Kanban, 5S, Visual control, Poke-Yoke and Single minute exchange of dies (Melton, 2005). Based on an empirical study of manufacturing industries, Shah and Ward (2003) presented that effects of all lean practices are associated with better manufacturing performance. Although, lean manufacturing and environmental management practices are distinct and different impact on business performance, lean manufacturing and environmental management practices are synergistic in terms of their focus on reducing waste and inefficiency(Yang et al., 2011).Jabbour et al. (2013) provided the empirical evidence of positive effects of lean manufacturing practices in the environmental management of the Brazilian automotive sector. Using a case study, Aguado et al. (2013) demonstrated that sustainability performance can be enhanced by employing lean manufacturing system. Vinodh et al. (2011) presented some of the tools and techniques that enable the achievement of sustainability objectives using lean manufacturing practices.

3R (reduce, reuse, recycle) concept focuses on promoting technologies and tools associated with reduction, reuse and recycling of materials to enhance the green performance of manufacturing organizations.Memon (2010) proposed integrated solid waste management system based on the 3R concept. The 3R concept has been extended to 6R (reduce, reuse, recover, redesign, remanufacture, and recycle) forming a basis for sustainable manufacturing. The 6R concept transforms the product model from open-loop single-life to closed-loop multi-life (Jawahir et al., 2006). Remanufacturing is proposed as a means for achieving low-carbon SMEs in Indonesia by Fatimah and Biswas (2016)

Increasing the material efficiency of the manufacturing operations is also regarded as an important sustainable manufacturing strategy. Material efficiency is the proportion of material used against the raw material necessary for manufacturing of a product(Abdul Rashid et al., 2008; Epstein, 2008). Allwood et al. (2011) presented four strategies to reduce the material demand through material efficiency: longer-lasting products; modularisation and remanufacturing; component re-use; designing products with less material.Halme et al. (2007) proposed that 'material efficiency as additional service' is the most promising business model for manufacturing organizations. In this study, authors discussed that material efficiency services can be outsourced to specialized companies.Worrell et al. (1997) summarized the various material efficiency improvement options such as good housekeeping; material-efficient product design; material substitution; product reuse and material recycling. It is also observed that improvement in material utilization contributed towards energy efficiency and minimization of waste(Worrell et al., 2009). Söderholm and Tilton (2012) presented an economic perspective of material efficiency arguing with the engineering approach to material efficiency presented by Allwood et al. (2011). They argued that policy measures that address particular environmental problems and information externalities will enhance material efficiency in a more effective manner.

Resource efficiency is a sustainable manufacturing strategy that seeks the productive utilization, decrease of movement and less consumption of resources extracted from nature. The efficiency of the resources can be measured and expressed as the amount of goods or outcomes that come as a consequence of the spending of item resources(Abdul Rashid et al., 2008). It is a well-established strategy to enhance the sustainability performances of manufacturing organizations (Dyllick & Hockerts, 2002; Schaltegger et al., 2006; Houy et al., 2011). Materials and energy are two major resources used by manufacturing organizations that affect their sustainability. Smith and Ball (2012) provided guidelines for material, energy and waste flow to enhance the sustainability. Rosen et al. (2008) argued that use of exergy is described as a measure to identify and explain the benefits of sustainable energy and technologies, so the benefits be clearly understood and appreciated by experts and non-experts alike, and the utilization of sustainable energy and technologies can be increased. Further, they developed a new sustainability index as a measure of how exergy efficiency affects sustainable development.

Eco-efficiency is another sustainable manufacturing strategy that focuses on the development of the economy with a minimum effect on the environment. With the utilization of this strategy, sustainable manufacturing is able to adopt and achieve competitive prices of goods and fulfilling the community necessities with the enhancement of their living standard (Verfaillie et al., 2000). Kerr and Ryan (2001) illustrated the gain obtained by the implementation of this strategy at photocopier remanufacturing at Fuji Xerox Australia. Eco-efficiency is improved by reducing the environmental impact while maintaining or increasing the monetary value added. World Business Council for Sustainable Development (WBCSD) outlined two types of indicators that are suited to measure eco-efficiency at a business level, being generally applicable indicators which can be used by virtually all businesses and business specific indicators which are likely to be individually defined from one to another business or sector (Schmidheiny & Stigson, 2000). Eco-efficiency at the product level is defined as product value per unit of environmental impact (Kobayashi et al., 2005). Other than product level, eco-efficiency is also adopted to measure services, strategies, tactics and policies. For examples, eco-efficiency analysis used to evaluate operation (Guenster et al., 2011), to evaluate economic value, (Li et al., 2012b), to evaluate manufacturing process, and to evaluate value and waste in manufacturing see (Simboli et al., 2014).

2.4.1 Strategy Selection Methods

Selection of the best strategy for sustainable manufacturing strives for desired level of economic and social growth without compromising the ecological balance (Vinodh et al., 2011). Sustainable strategy selection models rely heavily on the central decision making in the order to select a best strategy with multiple criteria, thus making this a MCDM problem. The theories and methods of MCDM problems have been applied in various areas such as personnel selection (Güngör et al., 2009), project selection (Huang et al., 2008), mining equipment selection (Aghajani Bazzazi et al., 2011), supplier selection (Chamodrakas et al., 2010; Shemshadi et al., 2011) and many more. The goal of decision-making process is to select the feasible number of strategies characterized by multiple conflicting criteria (Li et al., 2012a).

Several MCDM methods have been developed by researchers to suit the varying needs of decision-making problems. The MCDM is divided into two different branches. The first one is multi-attribute decision making (MADM) that focuses on selection activities and other branch is multi-objective programming alternatives are not predetermined but a set of objective functions is optimized to a set of constraints (San Cristóbal, 2011).

MADM method selects the best solution among several strategies considering the same attributes. Some of the popular approaches in MADM are Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Analytical Hierarchal Process (AHP), ELimination Et Choix Traduisant la REalité (ELECTRE), Simple Additive

Weighting (SAW), Preference Ranking Organisation METHod for Enrichment Evaluations (PROMETHEE) and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR). This subsection presents an overview of literature on some of the strategy/ alternative selection methodologies.

Analytic Hierarchy Process (AHP) is an extensively used MCDM approach to rank the alternative by obtaining the relative weights of the criterion (Saaty, 1980; Saaty & Vargas, 2001). Bevilacqua and Braglia (2000) applied this method to select the best maintenance strategy in an Italian oil refinery. Wei et al. (2005) presented an AHP based approach to select an ERP system. Muerza et al. (2014) used AHP method to select products in technological diversification strategies in Spanish automotive sector. There is a limitation of AHP method that criteria considered should be independent for evaluation of alternatives. In order to overcome this limitation, another method was proposed in the literature known as Analytic Network Process (ANP).

ANP method is used to obtain the criteria weights for decision making with dependence and feedback (Saaty, 1996). Considering the interdependence of criteria, Shyur and Shih (2006) applied ANP method to develop an approach to the vendor selection problem. Cheng et al. (2005) used ANP method to select the location of a shopping mall.Ocampo and Promentilla (2016) applied ANP method for sustainable manufacturing strategy development by integrating manufacturing strategy and sustainable manufacturing.

TOPSIS method was originally proposed by Hwang and Yoon (1981) to help select the best alternative with a finite number of criteria. This method has been applied in various areas for alternative or strategy selection such as candidate selection problem in human resource management to select middle-level managers in an Information Technology company by Kelemenis and Askounis (2010). The wide application of this method is reported by Behzadian et al. (2012) in a state-of-the-art survey of TOPSIS applications.

ELECTRE is a family of MCDM methods that originated in Europe in the mid-1960s. It evolved into ELECTRE I (*electre one*) and the evolutions have continued with ELECTRE II, ELECTRE III, ELECTRE IV, ELECTRE IS and ELECTRE TRI (*electre tree*), to mention a few(Figueira et al., 2005).Jun et al. (2014) applied ELECTRE II for micro-site selection of solar/ wind hybrid power station among seven alternatives. Liu and Zhang (2011) presented a supplier selection methodology based on ELECTRE III.

Simple additive weighting (SAW) is a simplest multi-criteria decision analysis (MCDA) / MCDM method for evaluating a number of alternatives in terms of a number of decision criteria (Triantaphyllou, 2000).Şener et al. (2006) applied SAW methodology for selection of landfill site. Afshari et al. (2010) applied this method to personnel selection with using the opinion of the experts.

The PROMETHEE family of outranking methods, including the PROMETHEE I for partial ranking of the alternatives and the PROMETHEE II for complete ranking of the alternatives, were developed by Brans et al. (1986). It has unique advantages when important elements of the decision are difficult to quantify or compare, or where collaboration among departments or team members are constrained by their different specializations or perspectives. PROMETHEE methods have been applied in various area such as for business decisions see Albadvi et al. (2007), for manufacturing related decision making see Anand and Kodali (2008) and for sustainability concept selection see Vinodh and Jeya Girubha (2012). A comprehensive literature review on methodologies and applications of PROMETHEE was presented by Behzadian et al. (2010).

Another technique known as VIKOR which is a compromise ranking method was developed by Opricovic (1998). It is used to rank the alternatives and obtain compromise solution as a feasible solution closest to ideal solution (Opricovic & Tzeng, 2004). The VIKOR method is a helpful tool in a situation where decision makers are not sure about their preferences at the beginning of system design (Opricovic & Tzeng, 2004).

In order to utilize the advantages of various methods, researchers either integrate two or more methods together or extend the applicability of these methods to a new environment to develop a hybrid or innovative method. Vahdani and Hadipour (2011) extended the applicability of ELECTRE method to an interval-valued fuzzy environment. Liu et al. (2014) presented a hybrid TOPSIS method for failure mode and effect analysis under intuitionistic fuzzy environment. Vinodh et al. (2014) applied fuzzy VIKOR method for fit concept selection in a manufacturing organization. Thakker et al. (2008) combined the three well-known methods; the Cambridge Material Selector based method, the adapted value engineering techniques, and the TOPSIS to propose a new way for material selection strategy. Zaerpour et al. (2009) presented an integrated AHP and TOPSIS method for partitioning of products under fuzzy environment. Kaya and Kahraman (2010) applied integrated fuzzy VIKOR & AHP method for selection of the best renewable energy alternative. Zamani et al. (2014) proposed a hybrid method by combining AHP and VIKOR under fuzzy environment for contractor selection.Fouladgar et al. (2012) proposed a fuzzy AHP-VIKOR method for project portfolio selection. Tsai and Chou (2009) selected a management system among four management systems (International Standards Organization) ISO 9001, ISO 14001, Occupational Health and Safety Management Systems (OHSAS 18001), and Social Accountability (SA 8000) on the basis of integrated Multi-Criteria Decision-Making (MCDM) model that combines the method of Decision Making Trial and Evaluation

Laboratory (DEMATEL), Analytic Network Process (ANP), Zero–One Goal Programming (ZOGP) for sustainable development in Small and Medium Enterprises (SME). Zhou et al. (2009) proposed a method that integrates the Artificial Neural Network (ANN) with Genetic Algorithm (GA) to optimise the objectives of material selection based on both the material characteristics and sustainability strategies and included the environmental factors along with the cost, product and process factors. The author proposed the model for a case example (Drinks Container), the material selection methodology involved in this case study is an MCDM method. The method proposed by the authors proved that it can complement unlike factors and selects the best material.

2.4.2 Strategy Selection Criteria

Strategy selection for sustainable manufacturing is an MCDM problem. (Xu & Yang, 2001) described the common characteristics of selection criteria in MCDM which are often conflicting, a mix of qualitative and quantitative criteria, deterministic and probabilistic with different units of measurements. The criteria for strategy selection needed to be consistent with the overall objective, relevant, practical and effective. Thus, selection criteria for sustainable manufacturing strategy should be able to reflect the performance ratings of strategies with respect to three aspects of sustainability (i.e. economic, environmental and social).

Table 2.5: Strategy selection criteria for sustainable manufacturing

Literature	Sustainable strategy selection criteria
(Vinodh & Jeya Girubha, 2012)	Adaptability, simplification, environmental degradation, implementation cost, consumptions of resources, survival, workforce engagement, maintenance, wastage, facility requirements, non-value adding costs, profits, social problems, safety, community development and technological feasibility
(Robèrt et al., 2002)	Dematerialization and substitution, backcasting, implementation cost, return on investment, dialogue and encouragement, transparency, norms & regulations, total material flow, waste, resource productivity, emissions.
(Howarth & Hadfield, 2006)	Wealth creation, cost, waste, competitiveness, emissions, community liaison, employment affects, health and safety, staff training & development, public reporting, reuse, recycling,
(Hu & Bidanda, 2009)	Implementation cost, return on investment, competitiveness, Regulation completeness, health and safety
(Achanga et al., 2006)	Implementation cost, profit, technical capability, resource requirement, adaptability, employee acceptance, employment opportunity, skills enhancement
(Nezami & Yildirim, 2011)	Competitiveness, market share, technical capability, resource requirement, waste, emission, material usage, energy usage, water usage, health &safety, regulation completeness,

2.5 Summarized Research Directions

The literature on sustainable manufacturing focuses primarily on larger enterprises rather than SMEs. Even those studies that have discussed sustainable manufacturing from SMEs perspective are still limited and focused on economic and/or environmental aspects. The SMEs are very instrumental in the growth of any economy (Anuar & Yusuff, 2011). The majority of the manufacturing SMEs are the supplier for multi-national companies in their global supply chain. Therefore, manufacturing SMEs are under the increasing pressure to improve their sustainability performance.

On the basis of the literature reviewed, following research gaps have been identified.

1. There is a lack of focus on identification of measures and metrics for performance assessment of sustainable manufacturing from SMEs perspective.
2. There is lack of decision making models for sustainability assessment and sustainable manufacturing strategy selection for SMEs. This gap can be further elucidated as :
    - Sustainability assessment of manufacturing SMEs was not yet considered in monotonic fuzzy inference system (FIS) framework, which can mimic the human reasoning.
    - There is no published literature that combines AHP and VIKOR methods under interval-valued fuzzy (IVF) environment to select the sustainable manufacturing strategy.
3. There is a lack of an easy to acess and user-friendly expert system for sustainability performance assessment and strategy selection for manufacturing SMEs. This research gap is also highlighted in a study on the development of sustainable manufacturing assessment tool for manufacturing SMEs (Chen et al., 2014).

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This research study is an applied research to investigate and develop the models for sustainable manufacturing decision making in SMEs. This research started with a comprehensive review of literature that is presented in Chapter 2. On the basis of the literature review, best strategies and performance metrics and methods for sustainable manufacturing are identified. In order to suit the need of manufacturing SMEs, an empirical study was proposed to investigate the importance and applicability of sustainability performance measures for manufacturing SMEs. The performance assessment models and strategy selection method have been developed for sustainable manufacturing decision making. These models are based on the fuzzy logic theory to suit the requirement of manufacturing SMEs as most of the decisions are fuzzy in nature. Furthermore, indicators identified from the empirical study on importance and applicability are used in these models to make it suitable for performance assessment of SMEs. Finally, based on these findings and models, a web-based expert system was proposed for sustainability assessment and strategy selection. The research methods and approches applied in this research study are shown in Figure 3.1. The inter-relationship between various components of the research study is presented as research flow diagram and shown in Figure 3.2.

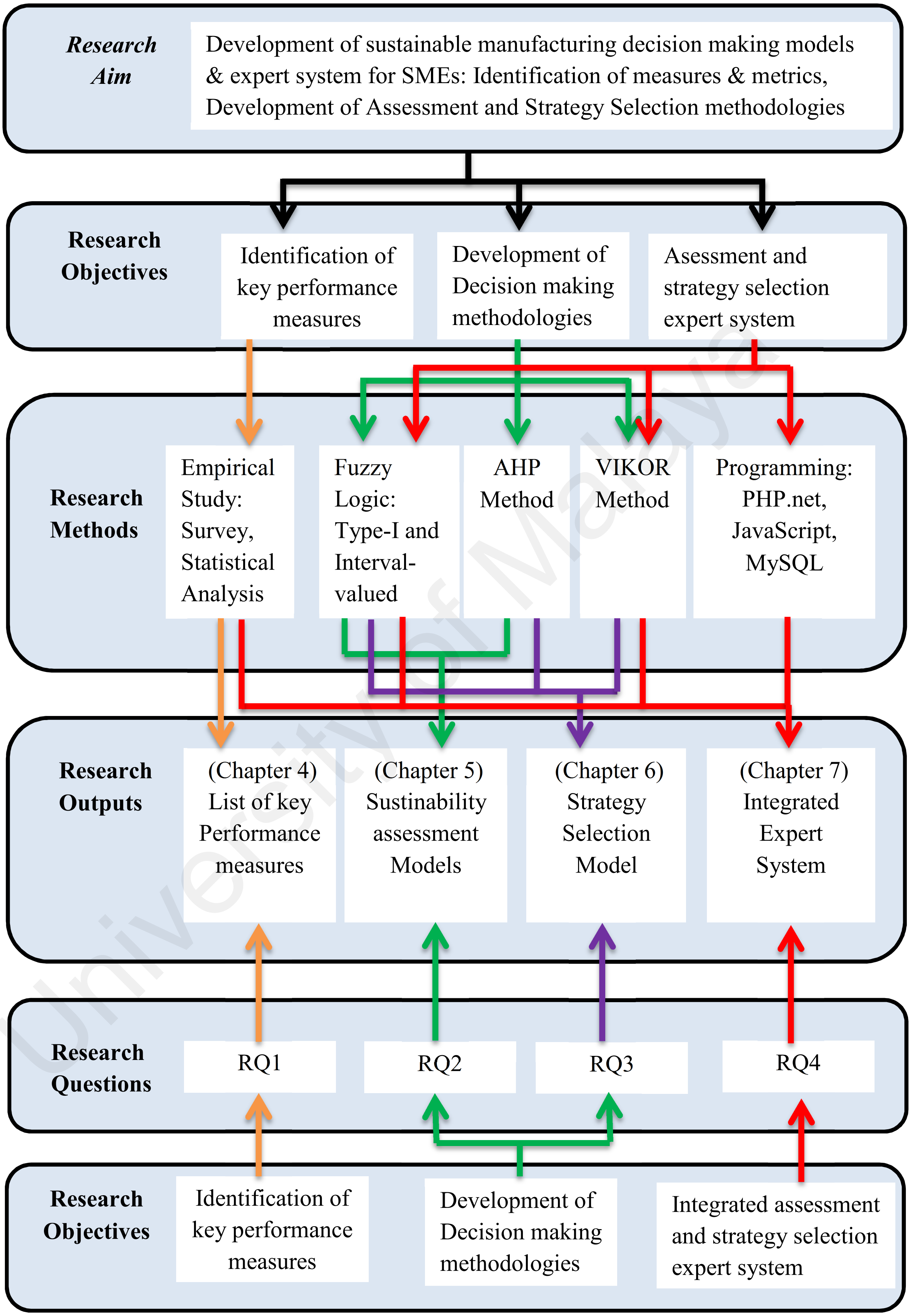


Figure 3.1: Approaches and methods applied in the study

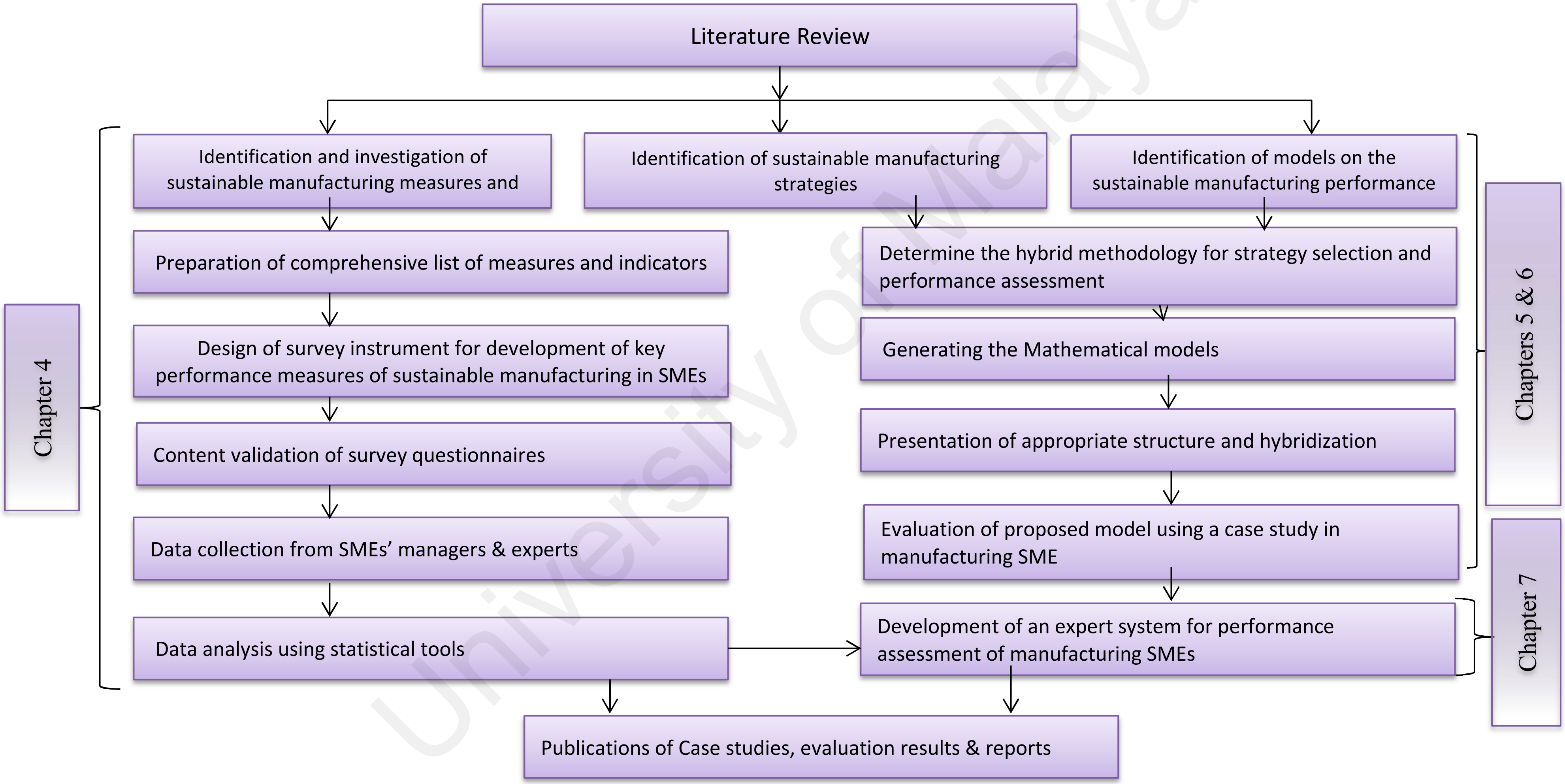


Figure 3.2: Flow diagrams for research study

3.2 Investigations of Importance and Applicability of Performance Measures for Sustainability Assessment in Manufacturing SMEs

To achieve the success in the sustainability initiatives in manufacturing SMEs, it is highly important to identify the suitable set of performance indicators. To investigate the suitability of the sustainable manufacturing performance measures and metrics for manufacturing SMEs, an empirical study is proposed. The empirical study is intended to investigate the importance and applicability of performance metrics in manufacturing SMEs. This process includes the following activities.

a. Review of literature related to sustainable/ green manufacturing performance indicators. A comprehensive review of literature is required for identifying the indicators related to sustainable manufacturing. At this stage, all indicators are collected irrespective of their area of application.
b. Preparation of a comprehensive list of sustainable manufacturing indicators. All the indicators collected during the literature review phase have been checked for redundancy. After removing redundancy or merging the similar type of indicators, a comprehensive list of indicators was prepared.
c. The design of a survey instrument to identify the important indicators. A survey questionnaire is proposed to collect the desired information. This questionnaire intended to obtain the scores of the level of importance and applicability of proposed measures and metrics.
d. Content validation of the survey. The content validation is required to know and improve the questionnaire so that it should address the desired purpose. The content of questionnaire is validated by conducting an initial survey among the domain experts from academics and industry.
e. Data collection from Manufacturing SMEs. The target respondent list is prepared by obtaining the information from various sources. Some intermediate agencies

such as SMEBank were involved in this activity to achieve the high rate of responses.

f. Data analysis using Mann-Whitney U-test. The reliability and significance of data are analyzed by performing the statistical analysis. In this study, considering the normality of data, Mann-Whitney U-test is applied to analyze the significance difference between applicability and importance of measures in manufacturing SMEs.
g. Based upon the result obtained during data analysis, the list is refined to prepare a list of key performance measures for sustainable manufacturing in SMEs.

3.3 Sustainability Performance Assessment Models for Manufacturing SMEs

Novel models for sustainability performance assessment have been proposed. The development process of these models includes following activities:

a. **Determining the methodology.** Based on the literature review and characteristics of decision making in manufacturing SMEs, the fuzzy logic based sustainability assessment models are proposed. The sustainability assessment methods require the performance ratings of the organization with respect to pertinent indicators and importance weights of indicators. The set of indicators identified importantly as well as applicable can be used as sustainability performance indicators. In real life decision-making, either the absolute weights of relative weights are considered. Considering these facts, two fuzzy based models are proposed.
b. **Presenting the appropriate structures.** The first model considers the absolute weights of indicators to evaluate the overall sustainability of manufacturing organization. The 2- stage hierarchical FIS structure is designed to obtain the overall sustainability performance. The other model considers relative weights of indicators. Considering the fuzziness in decision-making, fuzzy AHP is applied as

a tool to obtain the relative fuzzy weights of indicators. The fuzzy weights are then multiplied by fuzzy performance of the organization with respect to corresponding indicator to obtain weighted performance rating. Finally, a 3-stage hierarchal FIS structure is applied to obtain the final sustainability score of the organization. In order to identify the most important measures/ indicators, the study proposes a sensitivity analysis.

c. **Evaluation of proposed models using a case company**. To check the suitability of the proposed methods, real case studies have been performed in manufacturing SMEs. The results obtained from case study established the suitability of the proposed sustainability assessment models for manufacturing SMEs. Based upon the result obtained during the evaluation, models are refined to suit the stated objectives.

3.4 Strategy Selection Model

A Novel method for strategy selection for sustainable manufacturing has been proposed. This development process of this method includes following activities:

a. **Determining the methodology.** Selection of sustainable manufacturing strategy is very critical for the success of any sustainability initiatives. In manufacturing SMEs, decision makers are usually not sure of their preference at the start of the initiatives, thus VIKOR method is considered to deal with this problem. Furthermore, decision making in SMEs consist of uncertainty, vagueness and interval data. Considering these facts, an integrated AHP-VIKOR method under interval-valued fuzzy environment is developed. The AHP method is applied to obtain the relative importance weights of selection criteria.

b. **Presenting an appropriate structure.** It is proposed to obtain the inputs from decision makers in terms of linguistic variables. These linguistic variables are replaced by corresponding IVF triangular fuzzy numbers. The AHP method under IVF environment is applied to obtain the triangular IVF relative weights of criteria. The performance ratings of the strategies are also obtained in terms of triangular IVF numbers. Using Karnik-Mendel algorithm, IVF weights and performance ratings are used to obtain the crisp value. This algorithm applies Center of Area (COA) method to defuzzify the IVF numbers. The crisp values of importance weights of criteria and performance ratings of strategies are used as input to VIKOR method to obtain the ranking of the strategies. Finally, a sensitivity analysis is proposed to check the stability of ranking results.

c. **Evaluation of proposed models using a case company.** The proposed model has evaluated for suitability by implementing in a manufacturing SME for sustainability ranking. The results obtained from the case study prove the suitability of the proposed method for strategy or alternative selection where uncertainty is inherent.

3.5 Development of an Expert System

An expert system is developed for sustainability performance assessment and strategy selection of manufacturing SMEs. This development process includes the following activities:

a. **Determination of programming language and platform.** The first determination being made during the design of an expert system is programming language and platform. The .PHP based Joomla platform is chosen for its robustness, scalability and interfacing with various programming languages such as JavaScript, MYSQL.

b. **Determination of the methodology.** This study proposes a fuzzy rule-based expert system for sustainable manufacturing decision making in SMEs. The proposed system has two components: (1) sustainability evaluation and (2) strategy selection. It is proposed to gather the performance ratings of the organization with respect to metrics and importance weights of metrics in terms of linguistic variables. The fuzzy rule-based expert system is proposed to elicit the performances of all the aspects and overall sustainability of the organization. Using a sensitivity analysis during performance assessment, the system is able to identify the important measures to improve the sustainability performance. The second component of this expert system is based on the VIKOR method to select the best strategy. The important measures obtained during sustainability evaluation process are considered as selection criteria for strategy selection. The perceived improvement in performance ratings of these measures due to respective strategies is considered as performance ratings of strategies. The expert system also examines the stability of the ranking results using a sensitivity analysis.

c. **Codifying the mathematical model using identified programming language.**PHP.net based Joomla was utilized to build the fuzzy-based system because it is widely used for managing web content and its proper presentation. Various tasks like user management, content management, etc. can be done easily using this platform. JavaScript is used to design the front-end dynamic feature for a web-based system. For backend data processing and management MYSQL has been used. PHP.net is a truly revolutionary and gives programmers a much more capable, efficient and flexible way to design the web based systems. In addition, it also supports the integration of various tools such as JavaScript and MYSQL.

d. **Testing of the expert system using a case study.** The proposed expert system has been designed for performance assessment and strategy selection for sustainable manufacturing in SMEs from a holistic and comprehensive approach.

An electrical and electronic part manufacturing SME in India has been selected for testing and evaluation of the expert system. The chosen company was established in 1970. Its staff strength is 341. The system was demonstrated to the unit head of the company to establish its applicability. A team of three managers was formed who belongs to quality control, accounts and production departments. The system was presented to the managers of the company to evaluate the sustainability performance and then select the best strategy from manufacturer perspective. For the sustainability performance evaluation, they scored all the importance and performance of all indicators for each aspect in terms of linguistic values and their mutually agreed scores were input into the system. The performance assessment system came up with the final performance values and list of important measures for sustainability improvement.

For the strategy selection system, all decision makers were agreed to consider all the measures as selection criteria. Based on the results of sensitivity analysis during the evaluation process, four sustainable strategies are considered for evaluation as waste minimization, material efficiency, resource efficiency, and eco-efficiency. The perceived improvement in the performance ratings of measures with respect to each strategy are discussed among the decision makers and their mutually agreed scores were input in the system. The strategy selection system came up with the ranking of these strategies and also shows the stability of ranking using the concept of sensitivity analysis.

CHAPTER 4: INVESTIGATION OF IMPORTANCE AND APPLICABILITY OF PERFORMANCE MEASURES & METRICS

4.1 Introduction

This chapter presents the findings of the empirical study that attempts to investigate the set of measures and metrics for evaluating the sustainability manufacturing performance of SMEs. The initial set of measures and metrics were identified from the literature with consideration of the characteristics of SMEs. Triple Bottom Line (TBL) framework was adopted in order to establish the relevant measures in an effective and comprehensive manner. The three aspects based on TBL framework are Economic, Environmental and Social. Each aspect of sustainability performance assessment comprised of sixteen metrics which were categorized under four economic measures (i.e. Manufacturing cost, Quality, Responsiveness and Flexibility), five environmental measures (i.e., Material usage, Energy usage, Water usage, Waste and Emissions) and three social measures (i.e. Employee wellbeing, Customer wellbeing and Community wellbeing). In order to establish the importance and applicability of the proposed measures and metrics, a survey was conducted among the practitioners from the manufacturing SMEs.

Performance measurement is a key component of the sustainable manufacturing strategies. It reflects the need for improvement in areas of poor performance, thus efficiency and quality can be improved (Chan & Qi, 2002). Sustainable manufacturing performance measurements consist of three components: (1) selection of appropriate metrics for measuring sustainability of manufacturing, (2) assessment tool to identify the weak areas, and (3) adjustment in the system to enhance the sustainable manufacturing (Reich-Weiser et al., 2008). Sustainable manufacturing metrics to assess the performance and quantify the contribution to the triple bottom-line are well developed for larger organizations (Elkington, 1997; Azapagic & Perdan, 2000b; Veleva & Ellenbecker, 2001; Krajnc & Glavič, 2005; Rachuri et al., 2009; Joung et al., 2013). Most of the performance measurement approaches for sustainable manufacturing are based on the set of metrics, which are designed and tested in large manufacturing companies. Although, there are some studies on indicator development for SMEs such as development of environmental indicators to assess the environmental performances of SMEs (Rao et al., 2006) , but performance assessment perspectives considering all aspects of sustainability about manufacturing SMEs are still missing (Clarke-Sather et al., 2011). Despite the many sets of indices and measures developed, there is still no focused set of measures and metrics available for sustainability performance evaluation of manufacturing SMEs, particularly from developing economy. This study is an attempt to fulfil this research gap. The objective of this study is to investigate the importance and applicability of sustainable manufacturing metrics in manufacturing SMEs in the emerging economy.

The rest of the chapter is organized as follows: The framework for categorization of sustainability performance metrics and measures is discussed in section 4.2. Section 4.3 presents the definitions of proposed measures and metrics. Research methodology for this study is discussed in section 4.4.Section 4.5 presents the results of the survey instrument. Implications of results are discussed in section 4.6. Finally, Section 4.7 presents the summary of this chapter.

4.2 Introducing Sustainability Performance Measures for Manufacturing SME

The success of the performance measurement depends on the selection of an appropriate set of performance measures and corresponding metrics. The measures and metrics need to be simple and robust, reproducible and consistent, complement regulatory programs, cost-effective in data collection and useful for decision-making (Tanzil & Beloff, 2006). Due to sustainability concerns, the performance measurement metrics of traditional manufacturing required to expand to incorporate sustainability in the manufacturing (Carter & Rogers, 2008). Although there have been cases where the three dimensions of sustainability (economic, social and environmental) have been integrated to measure sustainability performance (Sarkis, 2001), the majority of the existing frameworks usually evaluates two dimensions of sustainability (economic and environmental) and very rarely do these frameworks embrace all three dimensions (Veleva & Ellenbecker, 2001; Seuring & Muller, 2008; Bai et al., 2012).

Many sets of indices and indicators are available for assessment of global, regional or country-level sustainability such as Environmental Sustainability Indicators (ESI), Environment Performance Index (EPfl), Environmental Pressure Indicators for European Union (EPrl), European Environmental Agency Core Set of Indicators (EEACSI), Environment Performance Evaluation (EPE) and United Nations Indicators of Sustainable Development (UNCSD) (Joung et al., 2013). Some indicators sets, that address the company-level sustainability assessment, are ISO 14000 (including ISO 14020, ISO 14040 and ISO 14064), Dow Jones Sustainability Index (DJSI), Global Reporting Initiative (GRI) and Organization for Economic Cooperation and Development (OECD) (Rachuri et al., 2009). All company level sets of indicators are general in nature except OECD sustainable manufacturing toolkit, which provides 18 indicators with SMEs in mind. However, the limitation of OECD indicators is that it has been developed considering only the environmental dimension of sustainability. Considering the sustainability to economic, environmental and social dimensions, sustainability assessment methods are still evolving.

SMEs represent the majority of manufacturing entities, thus evaluation of its performance is an important issue for achieving the goal of overall sustainable manufacturing. When compared to larger organizations, SMEs are different with numerous inherent limitations. The limitations of awareness, expertise, skills, finance, and human resources towards the sustainability initiatives are evident in SMEs. Hence, using the general sustainability performance measurement models is not suitable for SMEs. The objectives of sustainable manufacturing involve minimization of negative environmental impact, promoting social welfare and being economically competitive. Based on three aspects (i.e., economic, environmental and social) of sustainability, the triple bottom-line framework is found to be a perfect fit for investigation of the importance and applicability of sustainable manufacturing measures and metrics for SMEs.

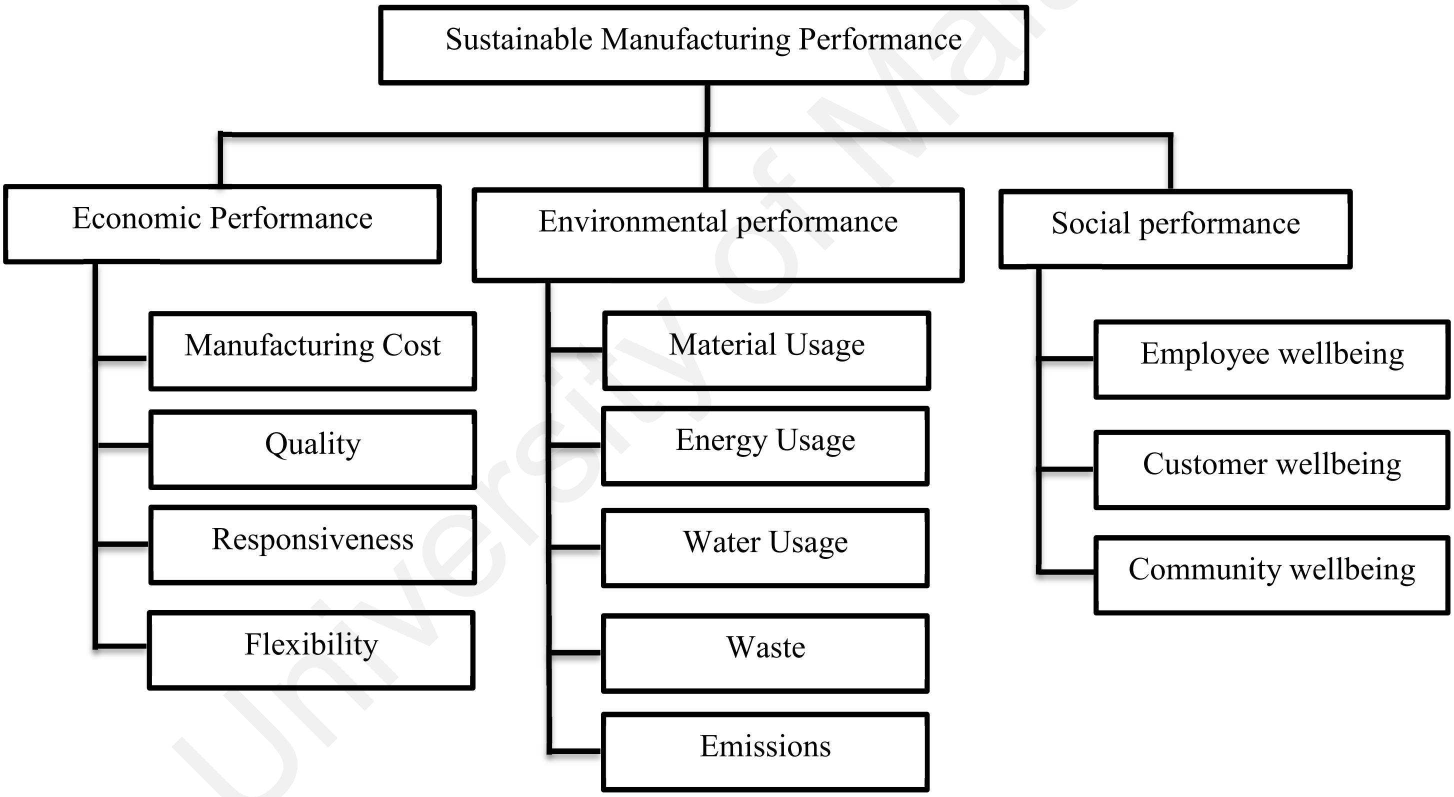


Figure 4.1: Categorization structure based on TBL framework

The review of literatures focusing on performance measurement for sustainable manufacturing resulted in more than 200 metrics as presented in chapter 2. To extract the results in the designed framework (Figure 4.1), these metrics are listed in one of the following categories: 1. Economic performance measures 2. Environmental performance measures and 3. Social performance measures. An alphabetical listing of metrics has been done to identify the duplicity or redundancy of measures. The key performance indicators (KPIs) are identified after removing the redundancy due to the same measures, overlapping measures and measures with a different title but practically same meaning. Furthermore, characteristics of SMEs considered to identify the suitable metrics in designed framework are discussed in the subsequent paragraph.

There are innumerable metrics for sustainable manufacturing, but the suitability of these metrics for manufacturing SMEs depends on how these indicators consider the characteristics of SMEs. The key characteristics which differentiate SMEs from larger organizations are considered in order to identify the suitable measures and metrics. In SMEs, the sustainability issue is exclusively related to cost reduction practices (Williamson et al., 2006). From business perspective, cost is the fundamental principle and driving force for any business activity that can be minimized by reducing the manufacturing cost, waste minimization, decreasing resource usage and increasing productivity of resources and people. Resource limitations in SMEs also indicate that waste level should be kept low and efficiency of resources should be high (Hudson et al., 2001b). Major resources used in manufacturing sectors are material, energy, water, land. Thus, sustainability indicators should be able to assess the productivity of these resources. The small number of customers and limited market accessibility force SMEs to remain competitive and to maintain a good brand image. Hence, customer satisfaction and community involvement should be indispensable indicators for SMEs. SMEs should remain vigilant to maintain a high level of customer satisfaction by providing quality products and services. In addition, SMEs should be flexible enough to accommodate the change in demands. The horizontal organizational structure suggests that SMEs employee have a greater number of jobs and responsibilities. The lack of awareness towards new technology and sustainability has further contributed to the increase in the problem of manpower productivity. Due to these challenges, SMEs employees require more training and high motivation in order to remain productive. Considering characteristics of SMEs, the sustainability indicators should be able to reflect the performance of manufacturing SMEs with regards to cost, quality, flexibility, responsiveness, waste minimization, resource productivity, efforts to enhance human productivity, employee and customers' satisfaction and community involvement.

4.3 Defining Key Performance Measures and Metrics

Based on the TBL framework and evidence consolidated from literature, key performance measures and metrics for sustainable manufacturing in SMEs are then identified and grouped prior to been investigated. This section presents the basic definition of each measure and metric.

4.3.1 Economic Performance

Since the cost associated with sustainability initiatives and corresponding returns are the most important concern of manufacturing SMEs (Williamson et al., 2006), economic measures are aimed at evaluating the economic performance. The effectiveness of this aspect of sustainability will be evaluated by the following measures and metrics.

4.3.1.1 Manufacturing cost

This is overall manufacturing cost incurred by SMEs in making sure that their operations are environment-friendly, safe for employees and society as well as cost competitive. Sustainable manufacturing processes intend to increase the process efficiency while reducing the inputs and waste-related cost. It has been considered important by Jayal et al. (2010), Rachuri et al. (2009), Joung et al. (2013) and many more researchers. Based on its level of consideration and significance, this is one of the important measures for the sustainable manufacturing performance assessment in SMEs. The metrics for this measure are discussed in ensuing paragraphs.

4.3.1.1(a) Reduction in material cost. This involves the totality of capital invested by an organization towards the acquisition of raw, recycled and remanufactured materials. It is a known fact that in order to obtain recycled and remanufactured materials; a company will have to spend less capital compared to the acquisition of virgin material (Zhu & Sarkis, 2004). Usage of the recycled or remanufactured materials also yields saving in energy, hence contributes for overall enhancement in sustainability performances. This metric is considered important byJoung et al. (2013), Amrina and Yusof (2011) and other researchers.

4.3.1.1(b) Cost associated with labour. This implies the capital which organization spends on availing the human resources. It is believed that skilled and well informed-manpower cost is comparatively more to a company than semi-skilled of unskilled Manpower cost. This metric is considered important by Amrina and Yusof (2011), Pusavec et al. (2010) and Gupta et al. (2011).

4.3.1.1(c) Decrease in energy cost. Under this cost, the energy which the company consumes in its manufacturing operations is considered. Specifically, it includes energy cost associated with plant and machineries, and that spent on the other functional aspects of the organization (Olugu et al., 2011). For sustainable manufacturing, the level of consumption of energy should be low. Some of the researchers that considered this cost important areRao et al. (2006), Zhu et al. (2008) and Gupta et al. (2011).

4.3.1.1(d) Decrease in delivery cost. This cost includes capital spend on the transportation and other resources required to deliver the finished goods to customers. Considering the sustainable performance, it is believed that delivery cost will be reduced under the sustainable manufacturing. Gupta et al. (2011), Abdallah et al. (2012), Cheng et al. (2013) and many more researchers have considered it as an important metric for sustainable manufacturing performance assessment.

4.3.1.1(e) Increased in recycling cost. This is the cost associated with the recycling process. It is observed that recycling cost is comparatively lower than cost of logging, mining, and other processes associated with the production of virgin materials. The more an organization is investing in recycling implies a positive shift in sustainability. Olugu et al. (2011) and Inderfurth (2004)considered it as remanufacturing cost that is vital for sustainable manufacturing. This metric is also considered important by Gupta et al. (2011) and Bi (2011).

4.3.1.1(f) Reduction in waste disposal cost. At the end of manufacturing and recycling processes, there is always a waste. Hence, reduction in the cost associated with the disposal of this waste is an evidence of improved sustainability. The cost associated with disposal is considered here by Zhu et al. (2008), Pettigrew and Nghiem (2011) and Singh et al. (2013).

4.3.1.1(g) Increase in environment protection cost. This cost includes capital invested on activities related to minimizing the negative environmental impact of manufacturing such as cost incurred on the implementation and maintenance of the environmental management system and others. This metric is considered important by Joung et al. (2013), Rao et al. (2006) and Rosen and Kishawy (2012).

4.3.1.2 Quality

This is a distinct attribute of the product, which measures its standard. This measure has been considered by many researchers as having very high impact on the economic performance of the organization (Labuschagne et al., 2005; Olugu et al., 2011; Joung et al., 2013). The metrics for this measure are discussed in subsequent paragraphs.

4.3.1.2(a) Increase in delivery reliability. The tardiness in the delivery of finished goods is an important metric to determine the quality. It also affects the level of customers' satisfaction due to satisfactory delivery of products. In order to obtain better performance, delivery reliability should be comparatively higher. This metric is considered important for sustainable manufacturing byOlugu et al. (2011), Zhu et al. (2008)and Habidin et al. (2013).

4.3.1.2 (b) Percentage decrease in level of scrap. The finished products that do not satisfy the quality requirements and cannot be reworked are known as scrap. It is believed that reduced level of scrap represents the high level of quality of manufacturing process. Olugu et al. (2011) and Zhu et al. (2008) identified this metric as an important one.

4.3.1.2(c) Percentage decrease in level of rework. The proportion of wrong products manufactured with respect to specifications and required to rework due to some reasons. It is believed that reduced level of rework represents high level of quality of manufacturing process. This is also an important metric to assess the quality of manufacturing process as suggested by(Gupta et al. (2011); Joung et al. (2013)) and Zhu et al. (2008).

4.3.1.3 Responsiveness

This is a measure of the response of the organization to certain elements such as order lead time, manufacturing lead time and product development time. It is believed that responsiveness of an organization will be affected by sustainability initiatives and thus, a measure of this effect is necessary (Olugu et al., 2011; Joung et al., 2013). The metrics used to evaluate the responsiveness are as follows:

4.3.1.3(a) Decrease in order lead time. This is time elapsed between placing ordering for material acquisition and when the material received. This metric is found to be effective in measuring the responsiveness of organizations (Pawlewski & Greenwood, 2014). This is also considered important by Olugu et al. (2011) and Amrina and Yusof (2011) for assessing the sustainability of manufacturing organizations.

4.3.1.3(b) Decrease in manufacturing lead time. This measures the time elapsed between an order ready for manufacturing and completion of manufacturing of that order. This is very crucial metric for manufacturing organizations as considered by Olugu et al. (2011) and Barreto et al. (2010).

4.3.1.3(c) Decrease in product development time. This is the time taken from conceptualization of an idea until the completion of final design of a product. This metric is considered important for sustainable manufacturing by Olugu et al. (2011) and Amrina and Yusof (2011).

4.3.1.4 Flexibility

This implies the ability of organization to adjust itself to various scenarios which arise due to unforeseen changes in normal processes. This measure is regarded as important by Olugu et al. (2011), Reich-Weiser et al. (2008) and Tanzil and Beloff (2006). The changes that are affected by different metrics due to sustainable manufacturing are considered as follows.

4.3.1.4(a) Increase in demand flexibility. This is the ability of the organization to accommodate the changes in orders due to customers' demand. The organization should be flexible enough to ful-fill the changes in customers' order without much effect on the manufacturing system (Olugu et al., 2011). Amrina and Yusof (2011) have considered it as an important metric.

4.3.1.4(b) Increase in delivery flexibility. This is the ability of the organization to accommodate the changes in methods and delivery time, etc. (Stevenson & Spring, 2007). Bhagwat and Sharma (2007)called it response in urgency while Beamon (1999a) termed it as delivery flexibility. This is an important metric for sustainable manufacturing (Amrina & Yusof, 2011; Olugu et al., 2011).

4.3.1.4(c) Increase in production flexibility. Flexibility is defined as the ability of a production system to meet the varying needs of customers without adding new equipment (Stevenson & Spring, 2007). Calvo et al. (2008) termed production flexibility as the ability of the organization to deal with uncertainties associated with production. This metric is considered important by Olugu et al. (2011).

4.3.2 Environmental Performance

The environmental measures are used to evaluate the impact of manufacturing activities on the environment. It is also seen that most of the sustainable strategies related to environmental impacts focus on the minimization of the resource consumption and waste generations. Thus, under this aspect, material usage, energy usage, water consumption, waste generation and emissions produced are identified as important measures.

4.3.2.1 Material usage

This is an important measure considered by researchers to achieve the sustainability goals of manufacturing organizations. The importance of this measure is evident in the study done by Zhu et al. (2008) and Abdul Rashid et al. (2008). Other researchers that took material usage into consideration are Veleva and Ellenbecker (2001), Krajnc and Glavič (2004) and Van Hoof et al. (2014). Following metrics are considered under this measure.

4.3.2.1(a) Decrease in material intensity. This is a ratio of the amount of materials needed to the amount of materials used in manufacturing of products. This metric is also known as the input-output material ratio that is closely related to the material efficiency of a manufacturing process. For better sustainability performance, the material intensity should be low. This metric is considered important by Veleva and Ellenbecker (2001), Zhu et al. (2008) and Tseng et al. (2009).

4.3.2.1(b) Percentage decrease in virgin material usage. This is a percentage of specific virgin materials used by an organization. Sometimes, it is also represented in terms of the virgin material ratio which is a ratio of the amount of virgin material to the total material used by an organization. This metric is considered important to assess the sustainability performance of manufacturing organization by Veleva and Ellenbecker (2001), Rao et al. (2006),Abdul Rashid et al. (2008) and Jasch (2000). To achieve enhanced sustainability performance, there should be decreased in usage of virgin materials.

4.3.2.1(c) Increase in recycled/ remanufactured/ reused material usage. This is amount and type of recycled/ reused/ remanufactured materials used and the amount of material within a process or product that can be recycled by an organization. This metric is used byRao et al. (2006), Gupta et al. (2011) and Tseng et al. (2009). There should be an increase in usage of recycled materials for manufacturing organizations to be considered sustainable.

4.3.2.1(d) Percentage decrease in hazardous material usage. A material is known as hazardous if it has potential to cause harm to humans, animals or environment, either by itself or through interaction with other factors. This is regarded as a very important metric for sustainability performance of manufacturing organization (Veleva & Ellenbecker, 2001; Rao et al., 2006; Gupta et al., 2011; Olugu et al., 2011).

4.3.2.2 Energy usage

The energy consumption by the organization in its manufacturing operations is considered under this measure. Specifically, it includes both renewable and non-renewable energy as well as saving in energy consumption. This impact of energy usage on the environment is very important during manufacturing, thus it is indispensable from the sustainability perspective. This is also considered important by many researchers such as Joung et al. (2013), Tanzil and Beloff (2006) and Erol et al. (2011).

4.3.2.2(a) Decrease in total energy consumption. This is the amount of energy consumed by an organization to operate the plant and machineries and on the other functional aspects. Considering the sustainability performance, total energy usage should be comparatively less. This metric is considered important by Gupta et al. (2011), Krajnc and Glavič (2004) and Tseng et al. (2009).

4.3.2.2(b) Percentage increase in renewable energy usage. The amount of energy obtained and from a source that is not depleted when used, such as wind or solar power. This metric is considered important by Rao et al. (2006), Amrina and Yusof (2011) and Tseng et al. (2009). To minimize the negative environmental impact, the percentage of energy used from these sources should be comparatively more.

4.3.2.2(c) Percentage increase in energy saving. This is a way of managing and restraining the growth of energy consumption in the organization due to an implemented improvement in efficiency or conservation. The concept of energy saving is very much related to energy efficiency. This metric is considered important by Jasch (2000) and Fan et al. (2010) for the sustainability of manufacturing organizations.

4.3.2.3 Water usage

This takes into account the quantity and quality of fresh and recycled water used in a company over a given period of time. This is considered important by Olugu et al. (2011), Joung et al. (2013), Tanzil and Beloff (2006), and Labuschagne et al. (2005). Following metrics are considered under this measure.

4.3.2.3(a) Decrease in total water consumption. This is the amount of water that is used to satisfy the various needs of manufacturing organization such as steam generation, cooling, washing of products, hydraulic transportation or fire-fighting. This is an important metric that shows how the ecosystem be tapped with cautions(Krajnc & Glavič, 2004; Rao et al., 2006; Olugu et al., 2011; Joung et al., 2013).

4.3.2.3(b) Percentage increase in recycled water usage. This is the amount of wastewater that is treated and reused within an organization or a manufacturing process. This metric is considered important by Amrina and Yusof (2011) and Jasch (2000).

From the sustainability perspective, the usage of recycled water should be comparatively more.

4.3.2.4 Waste

This is known as discarded materials or substances as that are no longer useful after the manufacturing process. This is an important measure to assess the sustainability performance of manufacturing organization (Jasch, 2000; Amrina & Yusof, 2011; Joung et al., 2013). Following metrics are considered for this measure.

4.3.2.4(a) Decrease in total waste generated. The definition of waste proposed by Department of Environment Conservation, US as "*Solid wastes are any discarded or abandoned materials. Wastes can be solid, liquid, semi-solid or containerized gaseous material.*" This metric is considered important for sustainable manufacturing by Olugu et al. (2011), Joung et al. (2013), Rao et al. (2006) and Tseng et al. (2009).

4.3.2.4(b) Increase in level of recyclable/remanufacture/ reused waste. Using waste recovery processes, materials can be recycled, remanufacture or reused to decrease the permanent loss of materials and energy. The amount of waste recovered and used in the manufacturing process by recycling, remanufacturing or reused processes are considered under this metric. This metric is considered important by many researchers such as Joung et al. (2013),Rao et al. (2006), Gupta et al. (2011) andKrajnc and Glavič (2004).

4.3.2.4(c) Percentage decrease in landfill. The waste materials that cannot be recovered by any recovery process are to be disposed in appropriate manner. The landfill is a place to dispose of refuse and other waste material by burying it and covering it over with soil, especially as a method of filling in or extending usable land. This metric is considered important for sustainable manufacturing by Olugu et al. (2011), Rao et al. (2006), Krajnc and Glavič (2004) andJasch (2000). Considering the sustainability of manufacturing process, landfills should be comparatively low.

4.3.2.4(d) Percentage decrease in hazardous material in waste. This is the amount of hazardous wastes generated by an organization according to the definition of hazardous waste as referred to in the Basel that includes regulated materials, hazardous, radioactive, heavy metals, toxic chemicals, etc. The importance of this metrics has been highlighted by Rao et al. (2006), Gupta et al. (2011), Krajnc and Glavič (2004)and Tseng et al. (2009). It is believed that minimization of hazardous material in waste helps to enhance the sustainability performance.

4.3.2.4(e) Percentage decrease in waste water. The percentage of the total water that is adversely affected in quality due to usage in manufacturing process and finally discharged to sewer. This metric is important for sustainable manufacturing as considered by Rao et al. (2006), Gupta et al. (2011), Krajnc and Glavič (2004) and Subic et al. (2012).

4.3.2.5 Emissions

This measure considers the production and discharge of gases that have negative environmental impacts. The following metrics are identified to represent this measure. For better sustainability performance, emissions of these gases should be low.

4.3.2.5(a) Decrease in CO_2 emission. The amount of Green House Gases emitted by an organization's manufacturing process such as emissions of CO_2, CH_4, N_2O, CFCs, NOx, SOx, etc. This metric is considered important by Olugu et al. (2011), Joung et al. (2013) and Subic et al. (2012).

4.3.2.5(b) Decrease in BFCs emission. This is the amount of ozone-depleting substances emitted by an organization's manufacturing process which includes BFCs, HCFCs, CFC-x, CH_3Br, VOCs, chlorinated carbons, SF_6, etc. This metric is considered important by Veleva and Ellenbecker (2001), Labuschagne et al. (2005) and Sikdar (2003).

4.3.3 Social Performance

These are measures which are used to evaluate the impact of manufacturing activities on society. Thus, under this aspect, employee wellbeing, customer wellbeing, and community wellbeing are identified as important measures.

4.3.3.1 Employee wellbeing

This measure considers the various dimensions that include training needs, job satisfaction, working conditions, the participation of employee etc. This measure is very important considering the participation of the employee in manufacturing operations (Despeisse et al., 2012; Joung et al., 2013).

4.3.3.1(a) Average number of training hours. This is average hours of training imparted to the employee for implementation of company's formalized skill mapping and developing process over a given period of time. This metric is considered important by Epstein and Wisner (2001), Hassini et al. (2012),and Chalmeta et al. (2012).

4.3.3.1(b) Decrease in employee turnover ratio. This metric is defined as the average tenure of an employee in the organization. Higher turnover means shorter tenure for an employee. The turnover ratio should be comparatively low for achieving success in sustainability initiatives. This metric is considered important by Veleva and Ellenbecker (2001),Lee (2009), Hubbard (2009), and Singh et al. (2014).

4.3.3.1(c) Decrease in number of accidents. This metric considers the accidents that require first aid. For better performance, number of accidents should be as low as possible. The number of accidents can be minimized by implementing the safety programs at the workplace. This metric is considered important by Veleva and Ellenbecker (2001) ,Krajnc and Glavič (2005), Brouwer and Van Koppen (2008).

4.3.3.1(d) Increase in job satisfaction. This is a way to assess whether employees are happy or engaged with work. Job satisfaction is very critical for retention of the employee. This metric is considered important by Despeisse et al. (2012), Tseng et al. (2009), Hubbard (2009) and Burke and Gaughran (2007).

4.3.3.1(e) Improvement in working conditions. This is the ambiance condition in which employee work such as amenities, physical environment, stress, noise levels, safety procedures, etc. This metric is considered important by Maravelakis et al. (2006), Sousa and Aspinwall (2010) and Garetti and Taisch (2012).

4.3.3.1(f) Level of employee participation in decision making. It is observed that participation in decision-making has a greater effect on the morale and awareness of the employee. Furthermore, this also aids in reducing the infrastructure required for continuous monitoring thus helps in cost reduction. This metric is considered important by Veleva and Ellenbecker (2001), Dangayach and Deshmukh (2001) and Gimenez et al. (2012).

4.3.3.2 Customer wellbeing

Until recent years, customer wellbeing is primarily motivated from economic consideration(Sousa & Aspinwall, 2010), but due to awareness of customers towards environmental, health and safety impact of products, this has become an important measure of sustainability performance (Olugu et al., 2011). This measure considers the following metrics.

4.3.3.2(a) Increase in customers' satisfaction. This is a measure of how services and products offered by the organization meet or surpass the customers' expectation. This metric is considered important by Olugu et al. (2011), Sikdar (2003) and Sousa and Aspinwall (2010).

4.3.3.2(b) Disclosure of product & service information. This metric considers the level of easiness and procedure for obtaining the information regarding the organization's services and products. This metric is considered important by Maxwell et al. (2006), Rachuri et al. (2009) and Rosen and Kishawy (2012).

4.3.3.2(c) Level of health and safety assessment of products. This metric considers the availability of the assessment mechanisms for health and safety impacts of products and services during their life cycle stages for further improvement. This metric is considered important by Despeisse et al. (2012), Burke and Gaughran (2007) and Sousa and Aspinwall (2010).

4.3.3.2(d) Availability of take back / warranty. This metric considers the availability and level of take back / warranty policy against delivery of defective products or services. It's evident that this policy enhances the confidence of customers in products of the organization and help to expand their customer base. This metric is considered important by Olugu et al. (2011), Bi (2011) and Epstein and Wisner (2001).

4.3.3.3 Community wellbeing

This measure of the social aspects of manufacturing considers the effect of organization on the education, health, safety and quality of life of local community. The measure is considered important for sustainability performance by Olugu et al. (2011), and Tseng et al. (2009). This measure includes following metrics for assessing the effect of sustainable manufacturing practices on community are as follows:

4.3.3.3(a) Number of community projects. This metric considers the number of community welfare projects such as school, hospital, local infrastructure development, etc. sponsored or run by the manufacturing organization. This metric is considered important by Despeisse et al. (2012), Veleva and Ellenbecker (2001), Singh et al. (2014) and Gimenez et al. (2012).

4.3.3.3(b) Decrease in number of non-compliance. This is the total number of non-compliance of the norms or rules that is locally enforced by state agencies or community over the given period of time. This metric is considered important for sustainability by Despeisse et al. (2012), Burke and Gaughran (2007) and Jayaraman et al. (2012).

4.3.3.3(c) Availability of child labor policy. This metric includes operations identified as having significant risk for incidents of child labor, and appropriate policy implemented for the elimination of child labor. This metric is considered important by Veleva and Ellenbecker (2001), Labuschagne et al. (2005) and Hubbard (2009).

4.3.3.3(d) Composition of work force. This metric looks at the composition of workforce and breakdown employees per category according to gender, age group, minority group membership, locality, etc. This metric is considered important by Cagno et al. (2012), and Vinodh and Chintha (2011).

4.3.3.3(e) Salary compared to local minimum wages. This metric assesses the range of ratios of standard entry level wage compared to local minimum wage at significant locations of operation and range of basic wage of men to women by employee category. This metric is considered important by Veleva and Ellenbecker (2001), Hubbard (2006), and Tapiero and Kogan (2008).

4.3.3.3(f) Community involvement in decision making. This metric considers the level of community involvement in decision-making. It is observed that community involvement has a positive effect on the sustainability performance of organizations. This metric is considered important by Azapagic and Perdan (2000b), Labuschagne et al. (2005) and Zailani et al. (2012).

4.4 Research Design

During the development of measures and metrics, the validation was carried out by mainly three approaches; design or conceptual validation, output validation and end-use validation (Bockstaller & Girardin, 2003). Design or conceptual validation is carried out by peer review of scientific papers. This type of validation is eclipsed by other validation approaches (Mitchell et al., 1995). Output validation is carried out by expert judgments for the selection of variables which should be measures as metric. The end-use validation approach is based on the empirical analysis of data obtained from practitioners. The definition, purpose and method of various validation approaches are presented in Figure 4.2.

In this study, the selection of the appropriate set of sustainable manufacturing measures is illustrated in section 4.2. The definitions of measures and corresponding metrics are included in the section 4.3. For content validation, a pre-testing was conducted among the experts from academia and industry. Subsequently, to assess the importance and applicability of the measures, a survey was carried out among the practitioner from manufacturing SMEs in Malaysia.

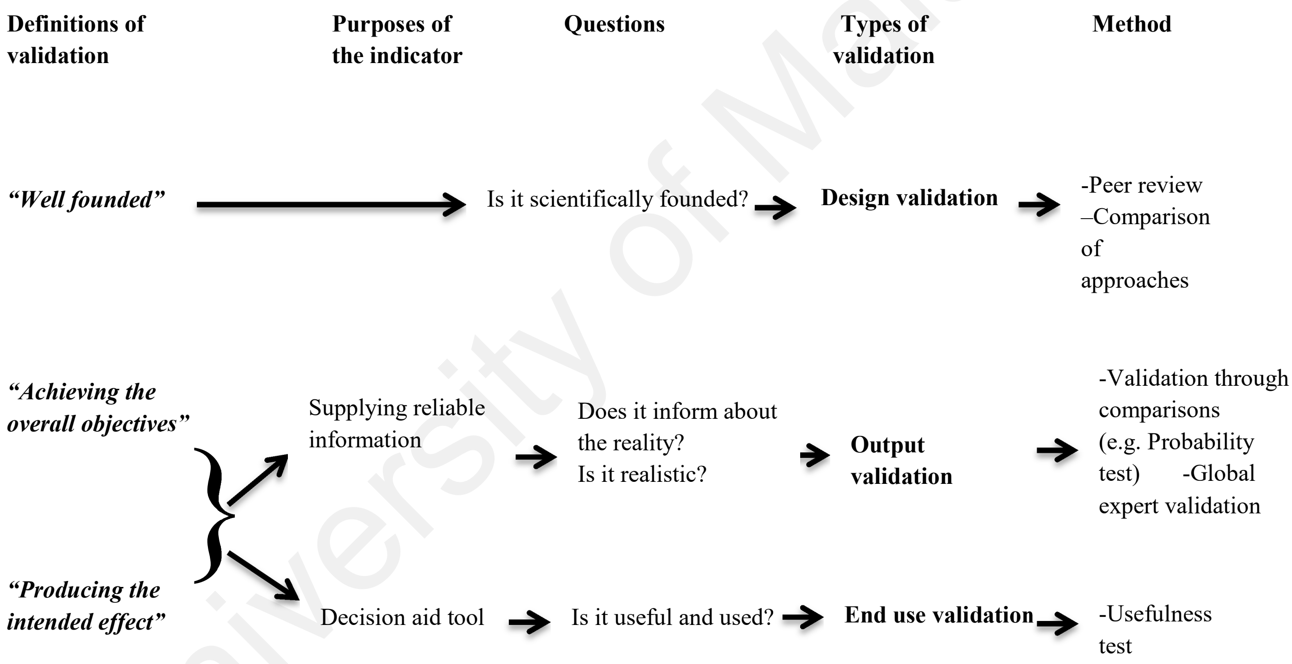


Figure 4.2: A flowchart for framework of indicator validation
(Source: Bockstaller and Girardin (2003))

Based on the TBL framework, a four-page survey questionnaire was developed to investigate the importance and applicability of an initial set of key performance measures and indicators. The questionnaire was divided into three sections: (i) Basic information; (ii) importance of sustainable manufacturing metrics and (iii) applicability of sustainable manufacturing metrics. In the first section, respondents were asked to provide the basic information about their organization such as company size, environmental management certifications, and revenue. In the second section, respondents were asked to rank their perceptions towards the importance of initial sustainable manufacturing indicators. In section three, respondents were asked to provide the level of applicability of these indicators in their organizations. Importance level indicates the amount of perceived importance placed on the metrics while applicability implies the degree to which they can be applied or used in practice. A Likert scale of 0-5 was applied to the importance and applicability score, where 0= no idea, 1= very low, 2=low, 3=moderate, 4=high and 5=very high.

For content validation and improvement in the questionnaire, a pre-testing was conducted. The objective of the pre-testing was to validate and improve in terms of, questions and answers content, wordings, sequences and potential respondents' interest. A group of fifteen persons from industry (practitioners in manufacturing SMEs) and experts (consultants & professionals from academics) were approached for the pre-testing. Ten responses were received, thus giving a response rate of 67%. The comments received from respondents were related to content and construct of the questionnaires. In addition, some comments were received for addition and deletion of some indicators. After incorporating the comments, the questionnaire was improved. The questionnaires were sent back to the experts to confirm that the corresponding changes made were adequate. They confirmed that the contents were clearer and more accurate at eliciting the expected feedback from the respondents. Pre-testing helped for content and face validation of the questionnaire and provided an opportunity for improvement of the survey questionnaire before conducting the full survey. The full survey was conducted in manufacturing SMEs from Malaysia. More than 260 industries were selected as target respondent to evaluate the measures and performance of sustainable manufacturing in Malaysia.

4.5 Results and Discussion

Responses were collected within six months of time from the start using mixed mode of the survey. Online survey form, In-person, and email methods were used to send and collect the survey data. The questionnaires were addressed to the managers of the SMEs. Out of 261 questionnaires, 56 were received back representing a response rate of 21.5 %. The response rate is similar to the study conducted among manufacturing SMEs in Malaysia by Ismail and King (2005) in which the response rate was 25%. In this study, Only 53 complete responses were considered for the purpose of analysis.

The results of the survey were validated for its internal consistency and reliability by using the Cronbach Alpha reliability test. The composite reliability, which is measure of internal consistency reliability, should be higher than 0.70 (Hair et al., 2013). The measures or metrics that obtain Cronbach alpha values less than 0.70 are discarded from further analysis. The results of this reliability test are presented in the Table 4.1 for the measures whose Cronbach alpha values are either equal to or more than 0.70. In this table, Legend 'Imp' refers to Importance of measures and 'App' denotes the Applicability.

Table 4.1 Reliability test using Cronbach Alpha values

Economic Performance measures							
Manf. cost		Quality		Responsiveness		Flexibility	
Imp	App	Imp	App	Imp	App	Imp	App
0.801	0.823	0.79	0.7	0.81	0.846	0.843	0.861

Environmental Performance measures									
Material Usage		Energy Usage		Water Usage		Waste		Emission	
Imp	App	Imp	App	Imp	App	Imp	App	Imp	App
0.907	0.872	0.769	0.856	0.9	0.789	0.823	0.866	0.808	0.844

Social Performance measures					
Employee Wellbeing		Customer Wellbeing		Community Wellbeing	
Imp	App	Imp	App	Imp	App
0.849	0.784	0.833	0.8	0.761	0.781
Legends: Imp-Importance, App-Applicability					

After the reliability test, each measure was evaluated based on the corresponding metrics. Importance and applicability ratings of the measures were computed using mean scores of importance and applicability of corresponding metrics. The summary of the results is presented in Figures 4.3-4.4.

For the economic aspect of sustainability evaluation presented in Figure 4.3, Manufacturing Cost (MC) had the highest score of 4.49, which implies an 89.8% of importance. This was followed Quality (QUAL)-3.97, Flexibility (FLEX)-3.81, Responsiveness (RESP)-3.72, with an importance percentage of 79.4 %, 76.4% and 74.4%, respectively.

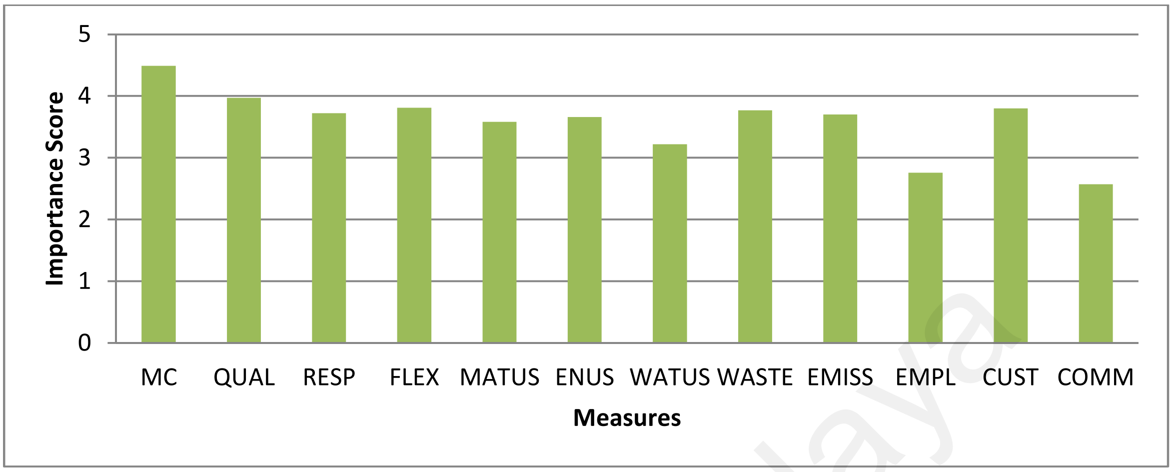


Figure 4.3: The mean importance score for performance measures

For environmental measures presented in Figure 4.3, Waste (WAST) was ranked the highest with an importance score of 3.77, and importance percentage of 75.4%. This was followed by Emissions (EMIS)-3.7, Energy Usage (ENUS)-3.66, Material Usage (MATUS)-3.58 and Water Usage (WTUS) - 3.22, with importance percentage of 74%, 73.2 %, 71.6 % and 64.4% respectively.

Among the measures from social perspectives, customer wellbeing (CUST) was ranked highest with an importance score of 3.80 with importance percentage of 76 %. This was followed by the employee wellbeing (EMPL)-2.76 and community wellbeing (COMM)-2.57 with importance percentage of 55.2 % and 51.4 %, respectively.

In terms of applicability, the results are presented in Figure 4.4 for economic, environmental and social aspects. For economic measures, manufacturing cost was ranked highest in terms of applicability with a score of 4.44. This was followed by applicability score of quality-3.94, flexibility-3.79, and responsiveness-3.54, respectively.

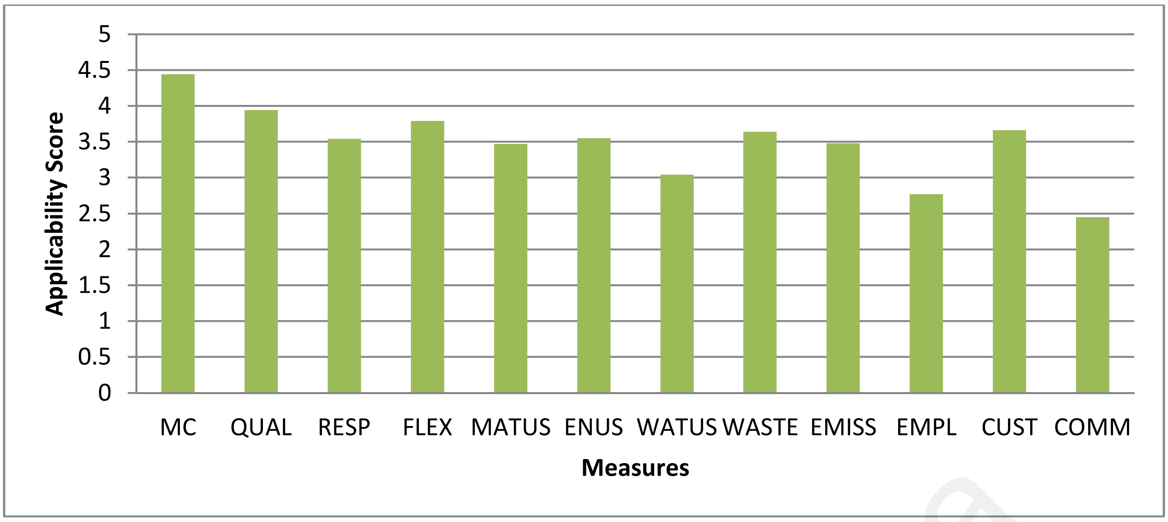


Figure 4.4: The mean applicability score for performance measures

Among environmental measures, as can be seen from Fig.4.4 that waste was ranked highest in terms of applicability with a score of 3.64. This was followed by energy usage, emissions, material usage and water usage with the applicability score of 3.55, 3.48, 3.47 and 3.04, respectively. For social measures, customer well-being was ranked highest with an applicability score of 3.66. This is followed by the employee wellbeing-2.77 and community wellbeing-2.45 as represented in Figure 4.4.

In this study, Mann-Whitney U-test, a non-parametric test, was applied to compare the importance and applicability of proposed measures using SPSS software. Collins et al. (2007) suggested that the minimum sampling size for casual-comparative analysis should be 51. In this study, 53 complete responses are considered. Table 4.1 presents data on the mean ranks; mean score and p-values. The p-values approximately calculate the statistical significance of differences between the importance and applicability of measures. Mean rank shows which variable was higher on average. Mean scores provide information about the relative importance and applicability of proposed measures.

For all the proposed measures, as evident from Table 4.1, the probability (p-value) is not equal to or less than 0.05. The test results, therefore, showed no statistically significant differences between importance and applicability of measures for sustainable manufacturing in Malaysian SMEs. As there were no statistically significant differences between importance and applicability of the measures, there was no need to analyse the mean ranks of these two groups. These results help to reinforce that there is a strong correlation between importance and applicability of the measures (Olugu et al., 2011).

Table 4.2: Mann-Whitney U-test results for sustainable manufacturing measures

Aspects	Measures	P-value	Importance		Applicability	
			Mean ranks	Mean scores	Mean ranks	Mean scores
Economic	Manufacturing Cost	.521	51.31	4.49	47.69	4.44
	Quality	.660	50.76	3.97	48.24	3.94
	Responsiveness	.179	53.35	3.72	46.65	3.54
	Flexibility	.740	50.43	3.81	48.57	3.79
Environmental	Material usage	.173	53.41	3.58	45.59	3.47
	Energy usage	.209	53.08	3.66	45.92	3.55
	Water usage	.092	54.34	3.22	44.66	3.04
	Waste	.127	53.84	3.77	45.16	3.64
	Emission	.231	52.92	3.70	46.08	3.48
Social	Employee wellbeing	.831	48.89	2.76	50.11	2.77
	Customer wellbeing	.165	53.47	3.80	45.53	3.66
	Community wellbeing	.357	52.08	2.57	46.92	2.45

4.6 Implication of Results

From the results obtained, it can be seen that all the economic performance measures obtained a mean importance score above 3.5. The most important measure identified by respondents is manufacturing cost. This implies that manufacturing cost should be considered first in an effort to initiating sustainable manufacturing practices. This is in line with assertions given by Williamson et al. (2006) and Lee (2008) that cost is the highly significant measure for sustainability activities in manufacturing SMEs. Quality and flexibility were also ranked high with a relatively equal importance score. This shows that quality and flexibility have a great influence on the economic performances of manufacturing SMEs. The integration of quality management principles into sustainability management has been highlighted in the literature (Kuei & Lu, 2013), thus supporting its importance in sustainability performance measurement. To mitigate the uncertainty in manufacturing SMEs, flexibility is also considered an important measure of sustainable manufacturing (Nagarajan et al., 2013). In addition, all the literature considered responsiveness as an integral part of the sustainable manufacturing performance measurement framework.

Considering the applicability of economic performances measures, all the measures showed a relatively high applicability score of more than 3.5. This implies that they are all applicable for performance measurement of sustainable manufacturing in SMEs. The most applicable measure is manufacturing cost, followed by quality, flexibility, and responsiveness.

For the environmental performance measures, it can also be observed that all measures scored an average around 3.5 in terms of importance and applicability. This implies that all the measures are essential and can be applied for sustainability assessment of manufacturing SMEs. As evident from Figure 4.3 & 4.4, waste minimization is the most significant measure among environmental measures. The literature on sustainable manufacturing also highlighted the waste minimization as a central focus of all the sustainable strategies (Abdul Rashid et al., 2008; Simboli et al., 2014). High score for the emissions implies its effect on the environmental performance of manufacturing SMEs. Energy usage and material usage are also ranked high considering the importance of resources in manufacturing. Worrell et al. (2009) and

Womack et al. (2007) have also highlighted the importance of energy and material usage for sustainable manufacturing. On the other hand, water usage did not show a considerable high level of importance compared to other measures. This may be due to easily availability of water.

In terms of applicability, all measures showed a considerably high score. Waste minimization and energy usage are the most applicable measures. Other measures which showed comparatively high level of applicability are emissions and material usage. Water usage showed a comparatively low applicability score among environmental performance measures. This might be because; the respondents believed that it is difficult to assess the water treatment & recovery in the performance measurement of sustainable manufacturing.

For the social performance measures, customer wellbeing ranked considerably higher than employee and community well-being. This implies that the customer wellbeing has an enormous impact on the effectiveness of the social performance. This result is as per expectation as the limited number of customers for manufacturing SMEs play very important role for their survival.

In terms of applicability of social performance measures, it is observed that customer wellbeing is the most applicable measure. Other measures which showed considerably low applicability are employee wellbeing and community wellbeing. This is in line with a corporate social responsibility study conducted by Lu (2013) on Malaysian SMEs. He also highlighted that for manufacturing SMEs, the core issue for sustainability is consumers or customers' well-being. The comparative low score of applicability for employee wellbeing and community wellbeing might be due to conflicting interests and concerns of stakeholders.

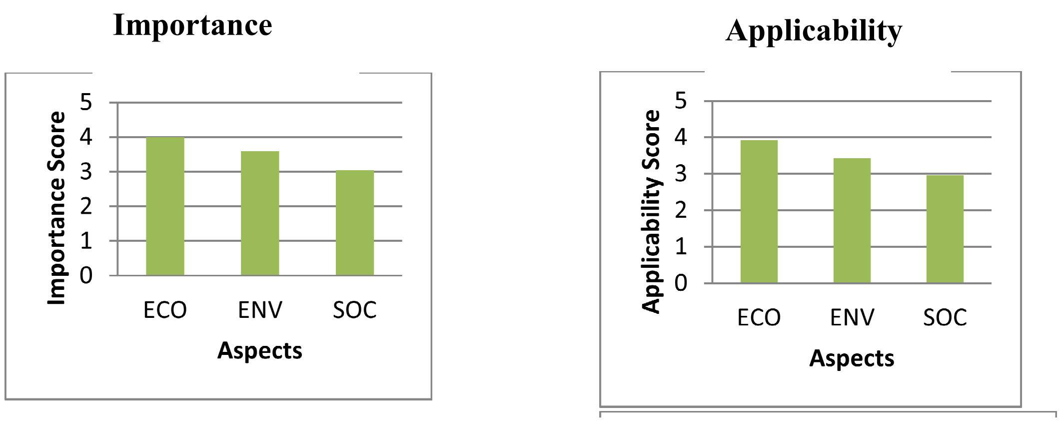


Figure 4.5: Overall means scores for Economic (ECO), Environmental (ENV) and Social (SOC) aspects

Based on Mann-Whitney-U-Test, it is concluded that all the measures are as important as applicable for performance assessment of sustainable manufacturing in SMEs. Further, all the measures are grouped into economic, environmental and social. The overall mean scores for each aspect in terms of importance and applicability is presented in Figure 4.5. In all, it can be seen that economic measures scored highest in terms of importance and applicability. This shows that economic decisions are most important to an organization and are the most significant for the sustainability performance of manufacturing SMEs. It can be also inferred that the social aspect of the sustainability is not regarded as important and applicable as economic or environmental aspects. This might be due to comparatively more subjectivity of social measures and issues related to fair allocation of benefits among the employees and communities.

4.7 Summary

The manufacturing SMEs are under pressure from consumers, community, regulators and investors to adopt sustainable manufacturing practices in their operations. Although sustainability issue has grown over recent decades, only few studies have been conducted on sustainable manufacturing in SMEs. This chapter proposes key sustainability performance measures and metrics for manufacturing SMEs. Based on TBL framework, four economic performance measures with 16 metrics, five environmental measures with 16 metrics and three social performance measures with 16 metrics are proposed. A survey was conducted among experts from academics and manufacturing SMEs from Malaysia. Subsequently, based on the Maan whitney-U-test result, it is established that there is a high correlation between importance and applicability of the proposed measures. This set of measures can be applied by manufacturing SMEs to assess their sustainability performances. Larger companies can also apply this set of measures and metrics for the performance assessment of their suppliers that are SMEs.

CHAPTER 5: FUZZY-BASED SUSTAINABLE MANUFACTURING ASSESSMENT MODELS

5.1 Introduction

In the case of sustainability performance evaluation of manufacturing organizations, major challenges are to determine the relative importance of each performance indicator and to evaluate the performance of organization with respect to various indicators that are usually incommensurable and fuzzy in nature (Azadegan et al., 2011; Vinodh et al., 2013b). Furthermore, in a group decision-making such as sustainability performance evaluation, each decision maker has different knowledge and opinion regarding the importance of indicators and performance rating of the organization. Therefore, sustainability evaluation for manufacturing SMEs involves uncertainties such as fuzziness and interval data. Due to the nature of such problems, the fuzzy logic based methods have been reasonably derived to suit the specific needs of sustainability evaluation. The Fuzzy inference system (FIS) developed by Mamdani (1978) provides a basis for sustainability evaluation methods that can effectively deal with the nature of this problem.

This chapter presents two FIS-based sustainability evaluation models for sustainability evaluation of manufacturing SMEs. The first model is based on the Triple Bottom Line framework which considered the absolute weights of the performance indicator. The inputs in this model are performance and importance weightage of indicators and measures, which are gathered from the decision makers. The results of sustainability assessment process in a manufacturing SME assists decision-makers to take better decisions (revise, improve or sustain) pertaining to their sustainable manufacturing strategies.

The second model is based on the Balance Scorecard framework in which relative weights of performance indicators are used. The fuzzy analytic hierarch process (FAHP) method provides a basis to obtain the relative weights of performance indicators is proposed. Consequently, an integrated fuzzy AHP-FIS method is proposed to deal with sustainability evaluation of manufacturing SMEs. The Balanced Scorecard (BSC) framework is used to consider the financial and non-financial indicators to reflect operational and strategic performances of SMEs. This model is implemented in a manufacturing SME to evaluate the effectiveness of its sustainability initiative. The sensitivity analysis of this method provides a list of the most important indicators affecting sustainability performance. The results obtained from the case company show the applicability of the proposed method.

The remainder of this chapter is structured as follows: next section presents an overview of fuzzy set theory, AHP, and balanced Scorecard. Section 5.3 presents fuzzy sustainability assessment model based on TBL framework. Section 5.4 presents the FIS method based on the balanced scorecard framework. In the final section, a summary of the chapter is presented.

5.2 Overview of Fuzzy Set Theory, AHP and Balanced Scorecard

This section presents basic concepts and definitions of fuzzy set theory, AHP, and balanced scorecard.

5.2.1 Fuzzy Set Theory

The concept of fuzzy set theory was conceived and proposed by Zadeh (1965), about five decades ago as a method to cope with vagueness in decision-making. Vagueness is usually represented in the terms of fuzzy sets which are defined by their membership functions. The fuzzy sets are functions that map a value as a number of set to a number between zero and one, and representing its degree of membership. The degree of membership as zero means values not belonging to a set, and a degree of one means a complete representation of the set. Assuming X is a set of items, known as the universe, and its elements are denoted by x as shown in equation 5.1.

$$X = x_1, x_2, x_3, x_4, \ldots. x_n \tag{5.1}$$

Therefore, a fuzzy subset '*A*' in '*X*' is characterized by a membership function $\mu_A(x)$ which is associated with each element 'x' in 'A' and a real number in the interval [0, 1]. The membership function $\mu_A(x)$ maps each element x to a membership value between 0 and 1, and this value represents the degree of membership of 'x' in 'A'.

$$A = \mu_1(x_1), \mu_2(x_2), \mu_3(x_3), \ldots\ldots \mu_n(x_n) \tag{5.2}$$

Different membership functions can be associated with each input and output response in fuzzy logic. In essence, they are used as weighting factors to obtain the outcomes of the fuzzy rules. Augmenting Zadeh's initial formulation, a fuzzy rule based system was proposed by Mamdani (1978), which deals with crisp inputs and outputs(Kickert & Mamdani, 1978). Mamdani's FIS has four components as shown in Figure 5.1.

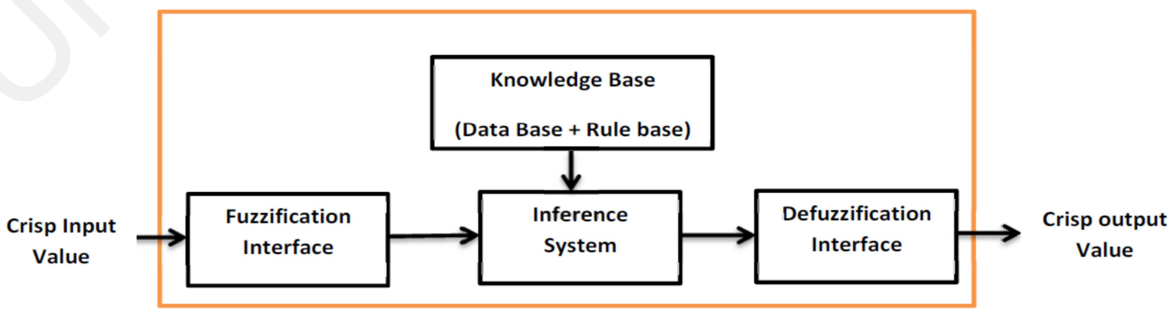


Figure 5.1: The Mamdani's fuzzy inference system

The fuzzification interface implements the mapping of crisp value of inputs to fuzzy inputs, which are represented by membership functions. There are a number of membership forms available to suit the various fuzzy environments. For example, forms can be linear, concave and convex. Linear triangular and linear trapezoidal are commonly used membership function. The knowledge base is a fundamental part of a Mamdani FIS. It is a repository of data and rules specific to the system under consideration, which establishes the relationship between output and input. Data base consists of linguistic variables used for linguistic rules and membership function defining semantics of linguistic variables. Rule base is a collection of linguistic rules as “If-Then". The “If-Then” rules are designed on the basis of experts’ knowledge. Interface system infers fuzzy inputs into resulting fuzzy output considering the information stored in the knowledge base. The defuzzification interface converts the fuzzy output into crisp output. There are various defuzzification approaches available such as centre of area method (COM), mean of maximum method (MOM), smallest of maximum method (SOM), largest of maximum method(LOM), bisector of area method (BOM) (Sivanandam et al., 2007).

5.2.2 AHP Method

Analytic Hierarchy Process (AHP) is an extensively used MCDM approach to compute the relative weights of the criterion (Saaty, 1980; Saaty & Vargas, 2001).In AHP method, problem structure is generally a multilevel hierarchy. The top layer presents the goal of solving the problem. The middle layers, namely tactic layers, are the involved intermediate links. The bottom layer displays the criteria and sub-criteria used to solving the problem. Pairwise comparison is systematically performed to obtain matrixes by including all the combination of criteria and sub-criteria at the given level. Once the pairwise comparison matrix is formed, local importance is computed by solving for the eigenvector of that matrix. Once local weights are calculated, global weights can be calculated by combining local weights with respect to all successive hierarchal levels(Liberatore, 1987).

In AHP method, consistency ratio (*CR*) value is used to check the consistency of opinions of decision makers toward relative importance weights. *CR* is defined as:

$$CR = \frac{CI}{RI} \tag{5.3}$$

Where, *CI* is the consistency index and *RI* is the random index as presented in Table 1.

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{5.4}$$

Where, $\lambda_{\max}$ is the largest Eigen value of pairwise comparison matrix under evaluation and n is number of criteria considered in the matrix. When $CR < 0.1$, opinions are to be considered consistent.

Table 5.1: Random Index (RI) values for matrices

Size of matrix (*n*)	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.94	1.12	1.24	1.32	1.41	1.45	1.49

5.2.3 Balanced Scorecard (BSC)

The Balanced Scorecard conceived by Kaplan and Norton (1992) provides a comprehensive framework for performance assessment by including four different perspectives such as financial, customer, internal business process and learning and growth. These four perspectives focus on the various stakeholders' interests as shown in Table 5.2. BSC aims to maintain balance ''between short-term and long-term objectives, between financial and non-financial measures, between lagging and leading indicators, and between internal and external performance perspectives'' (Bhagwat &

Sharma, 2007). BSC is a performance assessment tool used in various areas like supply chain performance (Bullinger et al., 2002; Bhagwat & Sharma, 2007; Varma et al., 2008), customer relationship management (Kim et al., 2003), textile industry (Cebeci, 2009), higher education (Tseng, 2010), information technology (Asosheh et al., 2010), banking (Wu et al., 2009) and manufacturing (Fernandes et al., 2006). Although BSC has been used widely for performance evaluation but it has some deficiencies in implementation. These deficiencies include methods to combine the indicators or measures scores to obtain overall performance rating; computation of relative importance weightage of indicators and measures(Abran & Buglione, 2003; Leung et al., 2005; Lee et al., 2008).Ravi et al. (2005) applied ANP with BSC to overcome these deficiencies in the reverse logistic problems of computer hardware industry. Leung et al. (2005) suggested the use of AHP to overcome deficiencies of BSC. Lee et al. (2008) presented a combination of FAHP and BSC model as a solution of these problems.

Table 5.2: Four perspectives of BSC

Perspective of BSC	**Focus**
Financial	On being financially successful (shareholders' view)
Customer	On delivering value to customers (customers' view)
Internal Business Process	On promoting efficiency and effectiveness in process (process based view)
Learning & Growth	On acquiring capabilities to face future challenges (future view)

Source: Kaplan and Norton (1992)

Application of BSC as a performance evaluation framework has been increased in recent decades, but literature related to using of BSC in SMEs is limited. Performance evaluation of manufacturing SMEs differ significantly from those for large corporations due to characteristics of SMEs (Ciliberti et al., 2008; Alshawi et al., 2011). SMEs are more focused on the financial and operational performance and there is lack of measures dealing with other aspects of sustainability(Addy et al., 1994). BSC can be used for performance assessment of SMEs considering the characteristics of SMEs (Hudson et al., 2001a).Kaplan and Norton (2001) reported successful application of BSC in SMEs. Manville (2007) developed and implemented the BSC for not to profit SMEs. Bhagwat and Sharma (2007) applied BSC to study the day-to-day performance of a supply chain in an Indian SME. Fernandes et al. (2006) demonstrated that BSC can be successfully implemented in SMEs using systematic and structured methodology. Other studies that reported successful application of BSC in SMEs are (Tenhunen et al., 2003; Garengo et al., 2005).

5.3Fuzzy Assessment Model Based on TBL Framework

Mamdani's FIS is applied in this study to develop the model because it predicts reasonable results with a comparatively simple structure, and also due to the intuitive and interpretable nature of the rule base (Jassbi et al., 2006a). The basic concepts of the fuzzy inference system considered for design of this proposed system have been discussed in the next subsections and description of the proposed system has been explained through two stages in Figure 5.2.

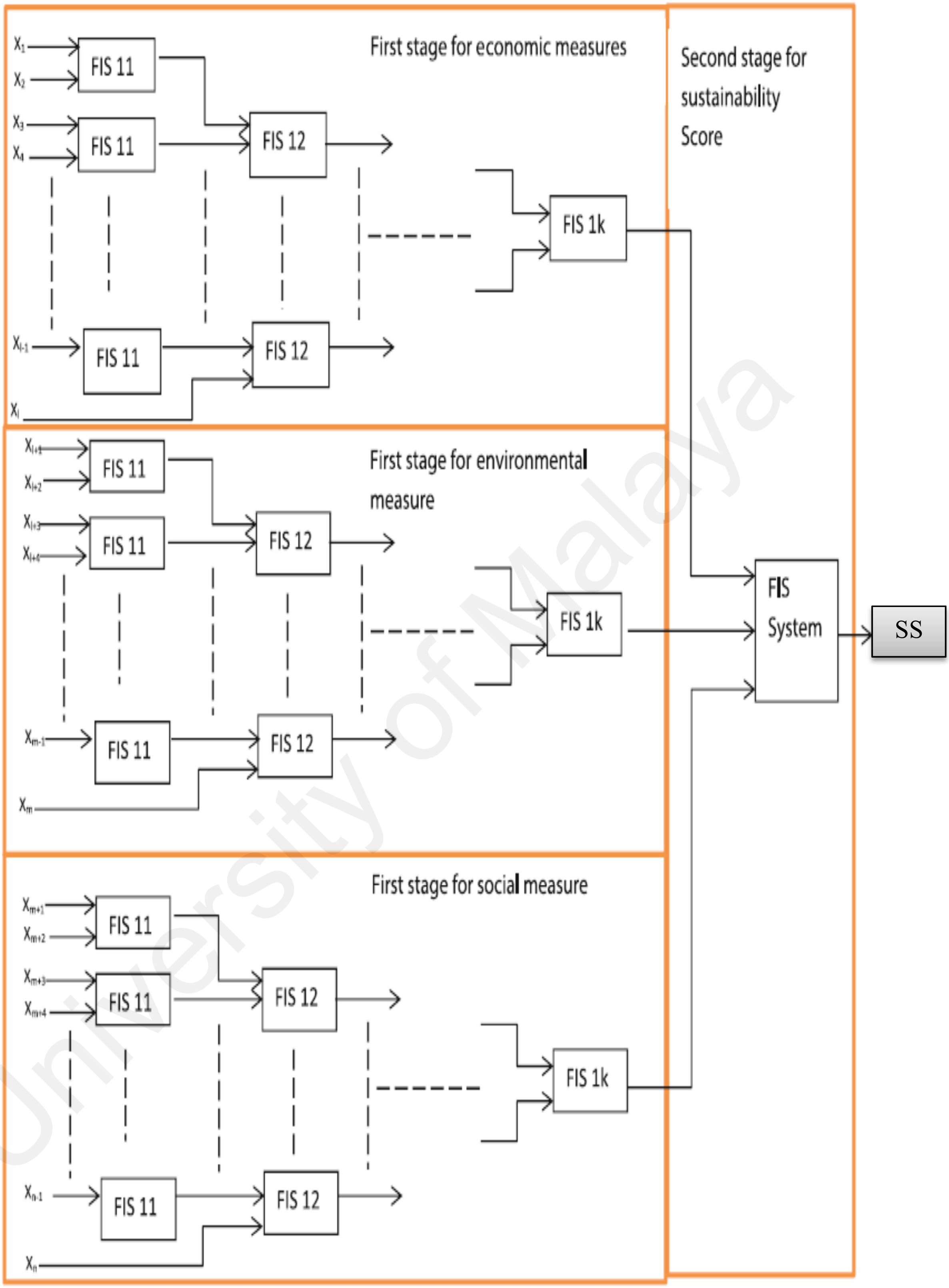


Figure 5.2: Sustainability assessment model (based on TBL framework)

5.3.1 Fuzzy Membership in Proposed Model

In this model, importance of indicators and measures and also sustainable performance of manufacturing SMEs with respect to indicators, are applied based on decision makers' perception of their system. The input variables for assessment of sustainability manufacturing usually have a lot of ambiguity (Vinodh & Balaji, 2011b). Thus, uses of triangular and/ or trapezoidal membership functions are recommended. In this study, trapezoidal fuzzy numbers are used for determining the importance of measures and indicators, and evaluating the sustainable performance of manufacturing SMEs with respect to indicators. A trapezoidal fuzzy number can be represented as $\tilde{A}$= *(a, b, c, d)* as shown in Figure 5.3.

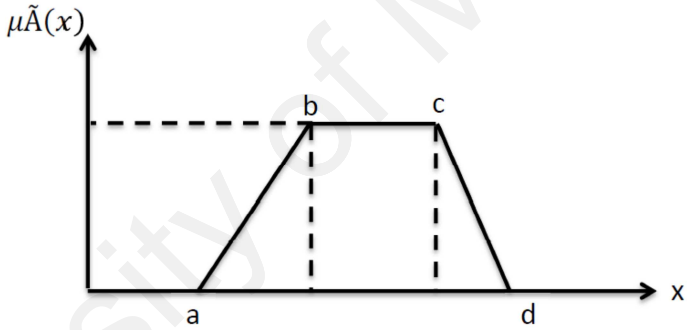


Figure 5.3: Trapezoidal membership function

5.3.2 Membership Function for Inputs and Outputs

Three fuzzy sets of membership functions are applied at first and second stages for both inputs and outputs in the fuzzy inference system. At the first stage, the fuzzy set in terms of linguistic variables includes 'poor', 'fair' and 'good'. These variables are equivalent to fuzzy numbers on a numeric range of 0-10 as shown in Table 5.3.

Table 5.3: Linguistic variables for inputs at both stages and outputs at first stage

Poor	(0, 0, 2, 4)
Fair	(3, 5, 5, 7)
Good	(6, 8, 10, 10)

At the second stage, fuzzy sets in terms of linguistic variables for inputs are same as at first stage. In this stage, linguistic variables for outputs as the sustainability scores of manufacturing SMEs are considered as 'revise', 'improve', and 'sustain'. These variables are equivalent to fuzzy numbers on the numeric range of 0-100 (see Table 5.4).

Table 5.4: Linguistic variables for output at second stage

Revise	(0, 0, 20, 40)
Improve	(30, 50, 50, 70)
Sustain	(60, 80, 100, 100)

5.3.3 Membership Function for Importance Weightage of Indicators and Measures

Three fuzzy numbers in terms of linguistic variables representing 'low importance', 'moderate importance' and 'high importance' are used to evaluate the importance of measures and indicators at both stages. These linguistic variables are equivalent to fuzzy numbers on a scale of 0-1 as shown in Table 5.5.

Table 5.5: Linguistic variables for importance of indicators and measures

Low	(0.0, 0.0, 0.2, 0.4)
Moderate	(0.3, 0.5, 0.5, 0.7)
High	(0.6, 0.8, 1.0, 1.0)

5.3.4 Fuzzy Operations

Two fuzzy operations, addition and multiplication of fuzzy sets have been used in this model. For example, let say A and B are two trapezoidal fuzzy numbers.

$$A= (a_1, a_2, a_3, a_4) \quad (5.5)$$

$$B= (b_1, b_2, b_3, b_4) \quad (5.6)$$

Then,

$$A+B = (a_1+b_1, a_2+b_2, a_3+b_3, a_4+b_4) \quad (5.7)$$

$$A*B = (a_1*b_1, a_2*b_2, a_3*b_3, a_4*b_4) \quad (5.8)$$

5.3.5 Fuzzy Rules in Proposed Model

Based on expert knowledge, fuzzy rule sets are developed for this model. There are two types of indicators for sustainability assessment of manufacturing SMEs. The first types of indicators are preferred to be 'larger is better' like community involvement, employee satisfaction and other type of indicators are preferred to be 'smaller is better' like, material intensity, energy intensity, and so on. On one hand, if an indicator is of 'larger is better' type, then, higher value of an indicator is preferred and this indicator is assigned to the higher fuzzy number for higher value of indicator and vice-versa. On the other hand, if an indicator is of 'smaller is better' type, then, lower value of the indicator is preferred and this indicator is assigned higher values of a fuzzy number for lower value of indicator and vice-versa. Finally, rules are designed on the basis of averaging concept for each FIS as shown in Table 5.6 & 5.7.

Table 5.6: Fuzzy rule base matrix for first stage

First Input / Second Input	Poor	Fair	Good
Poor	Poor	Poor	Fair
Fair	Poor	Fair	Fair
Good	Fair	Fair	Good

Table 5.7: Fuzzy rule base matrix at second stage

First Input	Second Input	Third Input	Output	First Input	Second Input	Third Input	Output
Poor	Poor	Poor	Revise	Fair	Fair	Good	Improve
Poor	Poor	Fair	Revise	Fair	Good	Poor	Improve
Poor	Poor	Good	Revise	Fair	Good	Fair	Improve
Poor	Fair	Poor	Revise	Fair	Good	Good	Improve
Poor	Fair	Fair	Improve	Good	Poor	Poor	Revise
Poor	Fair	Good	Improve	Good	Poor	Fair	Improve
Poor	Good	Poor	Revise	Good	Poor	Good	Improve
Poor	Good	Fair	Improve	Good	Fair	Poor	Improve
Poor	Good	Good	Improve	Good	Fair	Fair	Improve
Fair	Poor	Poor	Revise	Good	Fair	Good	Improve
Fair	Poor	Fair	Improve	Good	Good	Poor	Improve
Fair	Poor	Good	Improve	Good	Good	Fair	Improve
Fair	Fair	Poor	Improve	Good	Good	Good	Sustain
Fair	Fair	Fair	Improve				

5.3.6 Defuzzification

To assess the sustainable performance of manufacturing SMEs, the fuzzy number is to be defuzzified to a real number. In this study, centre of area method (COM) method has been used as shown in Equation (5.9).

$$X_{COM} = \frac{\sum_{i=1}^{n} x_i . \mu_i(x_i)}{\sum_{i=1}^{n} \mu_i(x_i)} \quad (5.9)$$

5.3.7 Monotonic Behaviour of Proposed Model

For applications based on fuzzy inference, a mandatory requirement is that the output of the fuzzy system should be monotonic with respect to its inputs (Kouikoglou & Phillis, 2009). Won et al. (2002) has given the conditions under which defuzzified output of a single-stage fuzzy system is non-decreasing output of its inputs. These conditions are expressed as follows:

Condition 1: The rule bases should be non-decreasing.

Condition 2: The weights used in the defuzzification should be piecewise differentiable and non-decreasing.

Condition 3: The membership functions assigned to the inputs should be piece-wise differentiable, in the sense that they should continuous on the corresponding domains and differentiable at all but a finite number of points. Moreover, for any pair of fuzzy sets A and B, if A < B then $[d\mu_A(x)/dx]/\mu_A(x) \leq [d\,\mu_B(x)/dx]/\mu_B(x)$*, for all x where* $\mu_A(x)$ *and* $\mu_B(x)$ *should be differentiable."*

Kouikoglou and Phillis (2009) have proven that the conditions derived in Won et al. (2002) are also sufficient for the monotonicity of multi-stage, hierarchical fuzzy systems if each inference stage satisfies conditions 1 and 2, and the basic inputs satisfy condition 3.

The rule base developed in proposed model is non-decreasing. The peak value of output fuzzy sets as shown in Figure 5.4 satisfies condition 2. Won et al. (2002) has given condition 3 for a trapezoidal membership function to the basic inputs in FIS is expressed as:

> *"Membership functions* $\tilde{A}= (a, b, c, d)$ *are piece-wise differential, if* $a^p \leq a^q$, $b^p \leq b^q$, $c^p \leq c^q$, *and* $d^p \leq d^q$ *for all membership functions (1... p, q,..m), where* $1 \leq p \leq q \leq m$*."*

In this model, membership functions assigned to each basic input are according to condition 3 for trapezoidal membership.

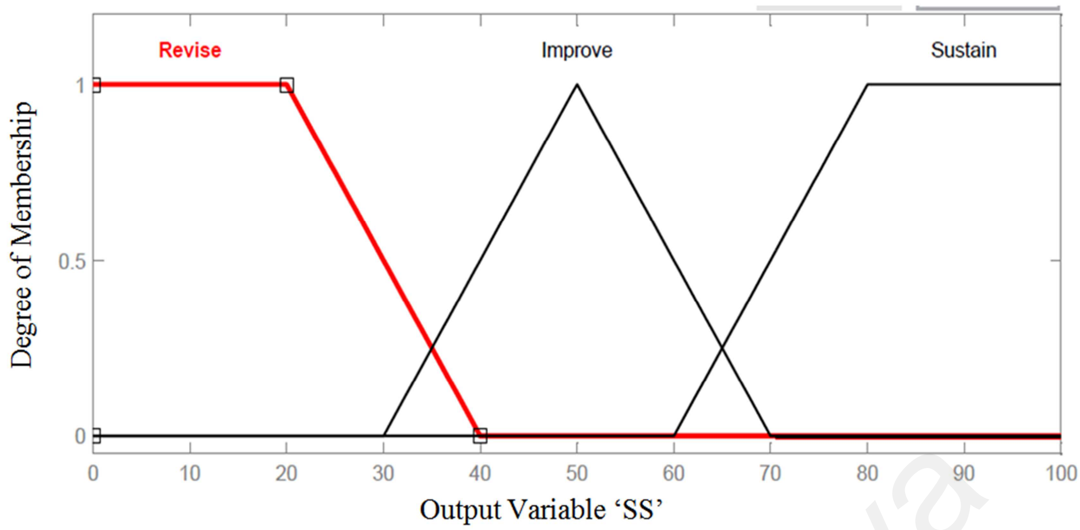


Figure 5.4: Membership functions associated with Output at second stage

5.3.8 Explanation of Proposed Model

In this model, the outcome as the sustainability scores (SS) of manufacturing SMEs depend on various independent indicator's input values. Mathematically, this can be represented as:

$$SS = f(x_1, x_2, x_3 \ldots x_n) \tag{5.10}$$

For the implementation of this model, decision makers will select the indicators pertinent to particular SME from the list of indicators for economic, environmental and social categories (Table 5.8).

Table 5.8: Indicative list of indicators for sustainable manufacturing in SMEs (Model-I)

Measures	Indicator	Relevant?	
Economic			
	Cost	Yes	No
	Quality	Yes	No
	Responsiveness	Yes	No
	Flexibility	Yes	No
Environmental			
	Material Intensity	Yes	No
	Reused material ratio	Yes	No
	Recyclable material ratio	Yes	No
	Hazardous material ratio	Yes	No
	Waste material Ratio	Yes	No
	Renewable Energy Ratio	Yes	No
	Energy Intensity	Yes	No
	Water consumption	Yes	No
	Waste water ratio	Yes	No
	Land usage	Yes	No
	Direct Emissions	Yes	No
	Indirect Emissions	Yes	No
Social			
	Employee turnover ratio	Yes	No
	Labor intensity	Yes	No
	Training hours/ employee	Yes	No
	Customers' satisfaction	Yes	No
	Community Involvement	Yes	No

At first stage, two inputs and one output with three fuzzy membership functions are assigned to each input and output to avoid the rules' explosion and accommodate large number of indicators. Whereas, at second stage, three inputs and one output with three fuzzy membership functions are considered.

The model has two stages as shown in Figure 5.2. At first stage, manufacturing SME's sustainable performance with respect to each indicator is multiplied by importance weightage of that indicator. The output is defuzzified to obtain the crisp values as input to FIS systems in first stage. It is noted that after selecting two by two inputs, if one input variable remains, it would be considered as output variable of an FIS system in that category as shown in Figure 5.2. First stage is continued until all input variables are accommodated in various FIS and number of output for each category is reduced to one. There are three output variables at first stage, which are considered as input variables at second stage.

At second stage, these three input variables represent economic, environmental and social measures. The importance weightage of each measure are multiplied by respective input values at second stage. It is seen that multiplying the importance weightages to performance values of input variables results in a reduced range for the sustainability scores. Thus, the output result of this model does not satisfy the aims of rules and delivers incorrect results. To eradicate this problem, FIS inputs at each stage are normalized to remain in designed scale of inputs.

5.3.9 Illustrative Example

The proposed model has been designed for sustainable assessment of manufacturing SMEs from a holistic and comprehensive approach. This model can be used for any number of indicators without any limit. In this section, a case study is used to illustrate the utilization of the proposed model. Case company is a manufacturing company and wants to assess its sustainability practices. As proposed earlier, this model requires input from decision makers towards importance of indicators and measures. It is recommended to involve more than two experts in the decision making process to minimize individual bias. To implement proposed model, data collection has been carried out to get the inputs for FIS system to assess the sustainability of manufacturing SME.

5.3.9.1 Case company

Case company (hereafter will be mentioned as ABC) is located at Manesar, Gurgaon. ABC business portfolio consists of auto electrical for various vehicle segments, Gensets and home appliances. ABC is a tier-2 original equipment manufacturer (OEM) supplier for more than 20 vehicle and Genset manufacturers. ABC has obtained ISO 9001 certification and is striving to get the ISO 14001 certification to enhance its competitiveness. Earlier, the assessment process was not systematic and each department carried out their own assessment against the indicators identified by respective managers. This model has been implemented in ABC to get the overall sustainability score and identify the weak areas for further improvement. A three member assessment team is constituted by involving managers from various departments. Decision makers in this company are either managers or senior managers who are also the head of their departments. The three decision makers contributed to this research are Quality Assurance Manager, who is also responsible for sustainability initiatives in the company, as well as Senior Finance Manager and Production Manager.

5.3.9.2 Data collection

There are three decision makers in ABC from whom input has been collected. The procedure for data collection has been illustrated as:

a. Decision makers have been shown the list of indicators and asked to select the indicators pertinent to ABC Company from economic, environmental and social categories.

b. Decision makers' opinion towards importance weightage of indicators and categories must be recorded in terms of linguistic variables. Decision makers are also asked for their perception towards performance of company against selected indicators as shown in Table 5.9.

The data from decision makers' opinion has been recorded as shown in Table 5.10 & 5.11. The mean fuzzy numbers for categories and indicators has been calculated. These weightage values have been used as importance weightage inputs at first and second stage of the model.

Table 5.9: Data collection process for indicators and categories

Category	Importance			Indicator	Importance		
Economic	Low	Moderate	High	Profit	Low	Moderate	High
				Quality	Low	Moderate	High
Environmental	Low	Moderate	High	Material intensity	Low	Moderate	High
				Pollutants	Low	Moderate	High
				Waste	Low	Moderate	High
Social	Low	Moderate	High	Employee satisfaction	Low	Moderate	High
				Community projects	Low	Moderate	High

Table 5.10: Decision makers' opinion of category importance weight

Category	DM1	DM2	DM3	Mean value
Economic	High (0.6, 0.8, 1, 1)	High (0.6, 0.8, 1, 1)	High (0.6, 0.8, 1, 1)	(0.6, 0.8, 1, 1)
Environmental	Moderate (0.3, 0.5, 0.5, 0.7)	High (0.6, 0.8, 1, 1)	Moderate (0.3, 0.5, 0.5, 0.7)	(0.4, 0.6, 0.6, 0.8)
Social	Moderate (0.3, 0.5, 0.5, 0.7)	Moderate (0.3, 0.5, 0.5, 0.7)	Moderate (0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)

Table 5.11: Decision makers' opinion of indicator importance weightage

Indicator	DM1	DM2	DM3	Mean value
Profit	High (0.6, 0.8, 1.0, 1.0)	High (0.6, 0.8, 1.0, 1.0)	High (0.6, 0.8, 1.0, 1.0)	(0.6, 0.8, 1.0, 1.0)
Quality	High (0.6, 0.8, 1.0, 1.0)	High (0.6, 0.8, 1.0, 1.0)	Moderate (0.3, 0.5, 0.5, 0.7)	(0.5, 0.7, 0.81, 0.9)
Material intensity	Moderate (0.3, 0.5, 0.5, 0.7)	Moderate (0.3, 0.5, 0.5, 0.7)	Low (0.0, 0.0, 0.2, 0.4)	(0.2, 0.33, 0.4, 0.6)
Direct emission	Low (0.0, 0.0, 0.2, 0.4)	Moderate (0.3, 0.5, 0.5, 0.7)	High (0.6, 0.8, 1.0, 1.0)	(0.3, 0.43, 0.56, 0.7)
Material Waste	High (0.6, 0.8, 1.0, 1.0)	Low (0.0, 0.0, 0.2, 0.4)	Low (0.0, 0.0, 0.2, 0.4)	(0.2, 0.26, 0.4, 0.6)
Employee training	Moderate (0.3, 0.5, 0.5, 0.7)	Low (0.0, 0.0, 0.2, 0.4)	Low (0.0, 0.0, 0.2, 0.4)	(0.1, 0.16, 0.3, 0.5)
Community involvement	Low (0.0, 0.0, 0.2, 0.4)	Low (0.0, 0.0, 0.2, 0.4)	Low (0.0, 0.0, 0.2, 0.4)	(0.0, 0.0, 0.2, 0.4)

Decision makers are asked to evaluate the performance of ABC for the selected indicators. It needs to be noted that decision makers' opinion of performance with respect to indicators are same and mutually agreed upon as shown in Table 5.12.

Table 5.12: Sustainability performance of ABC

Indicator	Decision makers' opinion
Profit	Good
Quality	Good
Material intensity	Fair
Direct emission	Poor
Material Waste	Poor
Employee training	Good
Community involvement	Fair

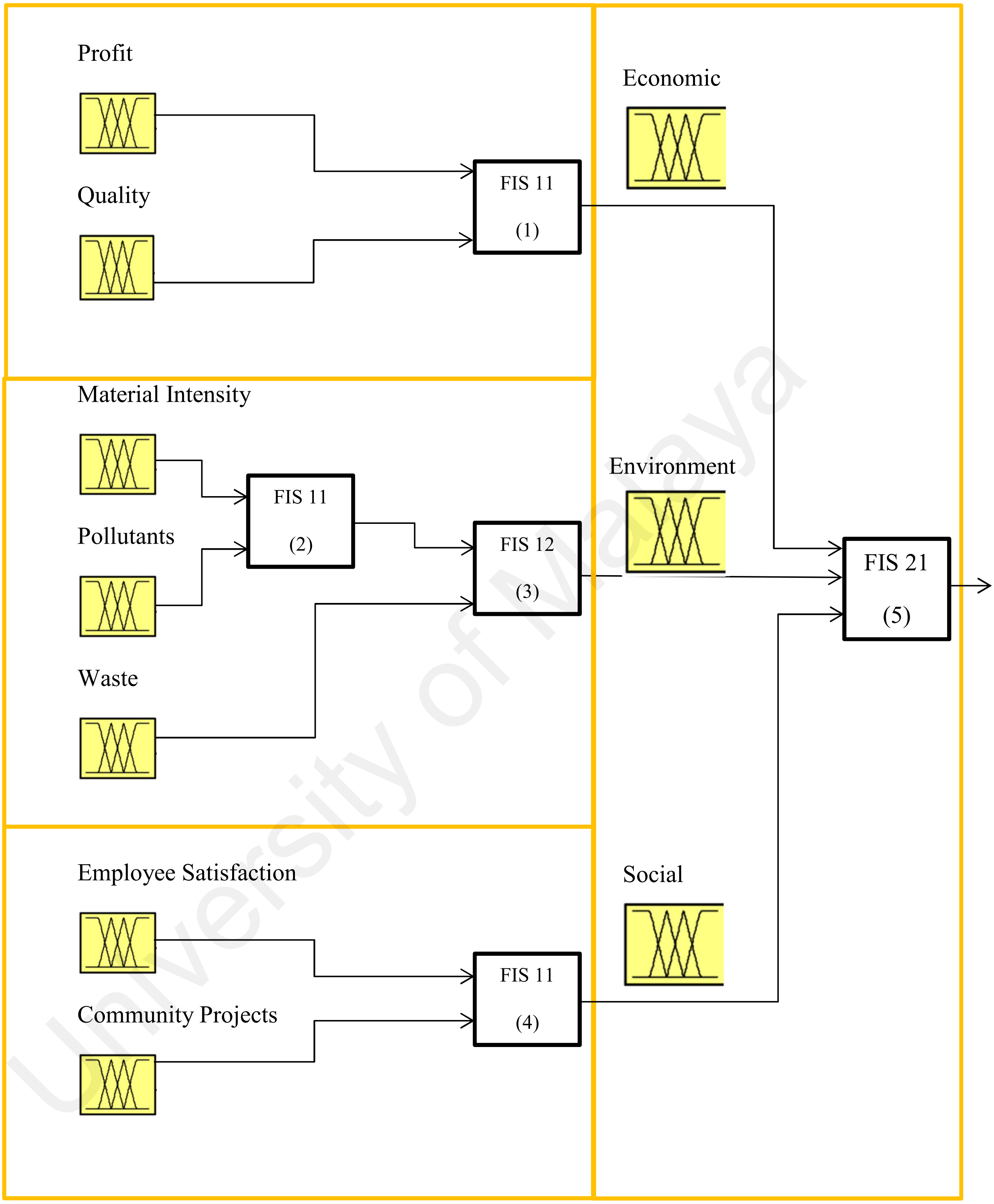


Figure 5.5: The assessment model for illustrative example

5.3.9.3 Implementation and results

During the implementation and result extraction, inputs' values from the data collection process are passed to FIS system to obtain the sustainability score or index.

The implementation model is shown in Figure 5.5. To compare the sustainability performance, two virtual manufacturing SMEs are introduced as the best sustainable company (ideal) and the worst sustainable company (non-ideal). Finally, sustainability score of the targeted company along with virtual companies are calculated as shown in Table 5.13. To exhibit the structure of rule viewer in model, which represents the working of FIS model, one FIS has been chosen. Rule viewer of FIS at second stage of sustainability score is shown in Figure 5.6. In the rule viewer, each rule is plotted along a row and each input variable along a column. Input value of variables can be varied by moving the red line and output can be seen along column representing the output variable. As in this case, there are three input variables and three membership function, the number of rules is 27 (3^3) to obtain the output. To verify these rules, input for variables likes economic, environmental and social has been increased and output was analysed. Three input variables have been varied in the range of [0-10] and output score obtained in the range of [0-100]. The output surface of second stage FIS for sustainability score is shown in Figure 5.7. It is seen that increasing the input values, increases the output value of sustainability score that confirms the monotonic behaviour of the proposed model.

Table 5.13: Validation of proposed model

Enterprises	Assessment result (Sustainability score)				
	COM	MOM	SOM	LOM	BOM
Ideal	84.7	90	80	100	85
ABC	50	50	50	50	50
Non-ideal	15.3	10	0	20	15

The applicability of this model has been proved by obtaining the sustainability score of manufacturing enterprise, which always lies between scores of ideal and non-ideal enterprises. This model has been also tested by applying different defuzzification methods such as centre of area method (COM), bisector of area method (BOM), mean of maximum method (MOM), smallest of maximum method (SOM), and largest of maximum method (LOM).As shown in Table 5.13, assessment results for all three enterprises are same in all defuzzification modes and prove the validity of this model.

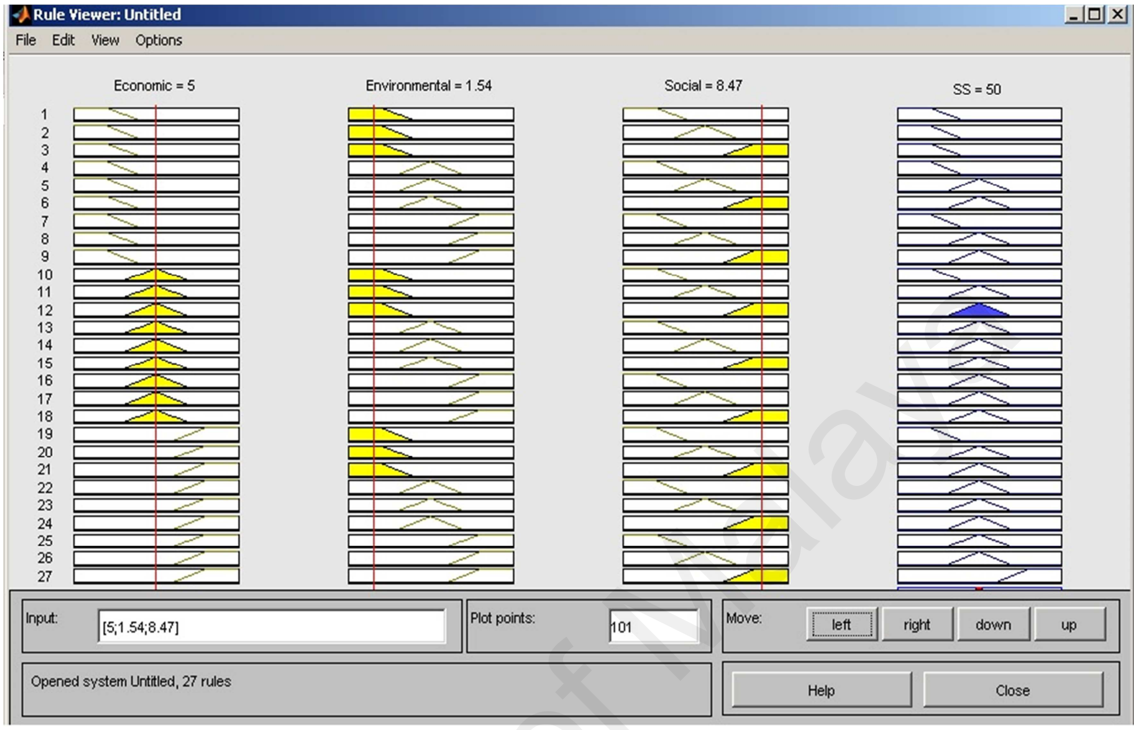


Figure 5.6: Rule viewer for a case in illustrative example

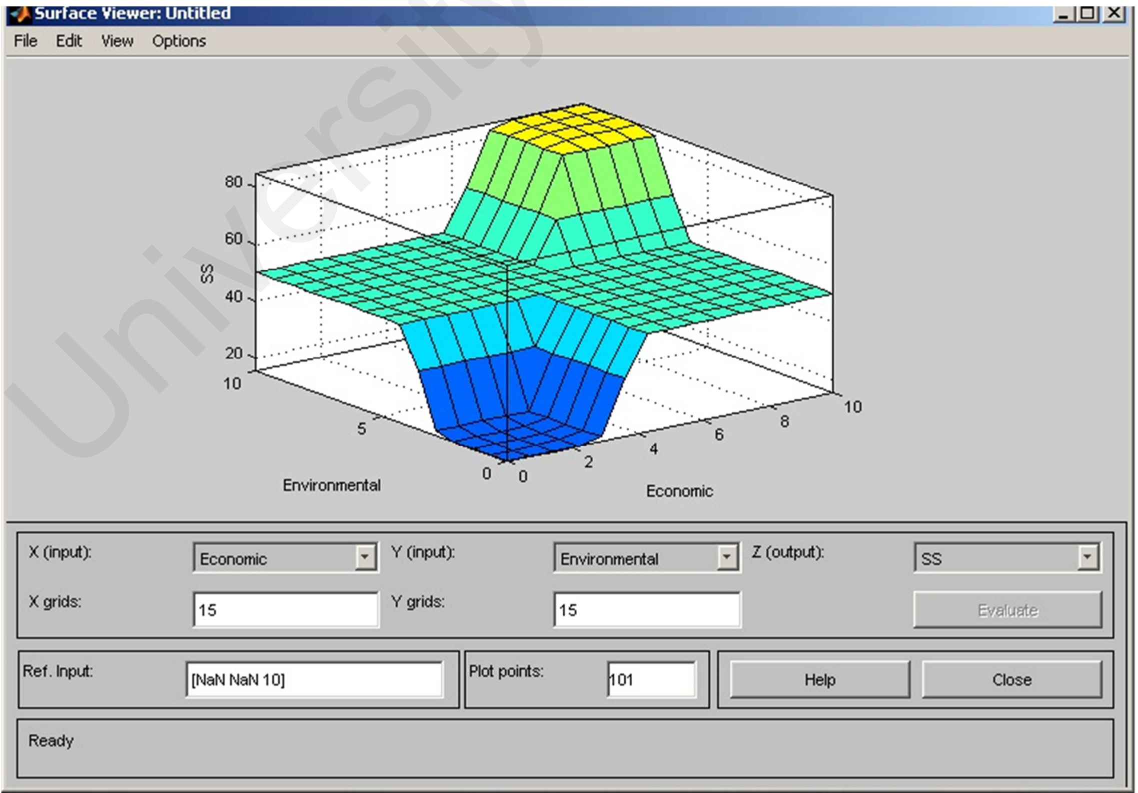


Figure 5.7: Output surfaces of FIS for the case company

During sustainability assessment of ABC, it is found that overall sustainability score is fair and there is room for further improvements to achieve sustainable manufacturing practices. The outputs at first stage for environmental, social and economic measures of ABC are poor, fair and good, respectively. Interpretations of results suggest that environmental aspect of manufacturing sustainability requires more attention than social dimensions. Similarly, social aspect needs more attention than economic aspect to improve the overall sustainability. Based on the output of this study and further deliberations with decision makers, ABC is in process of implementing waste minimization strategy to reduce the environmental impact. During the discussions with decision makers for selection of appropriate manufacturing concept to enhance the performance of weak areas, it is felt that there is need of strategy selection tool based on the characteristics of manufacturing SMEs.

5.4 Sustainability Assessment Model Based on Balanced Scorecard (BSC) Framework

The BSC is applied to classify the selected indicators for sustainable manufacturing among four measures. The hierarchy of the structure of BSC for sustainability evaluation is based on the literature and consultations with the decision makers. The FAHP approach is used to obtain the relative importance weightage of measures and indicators. The performance ratings with respect to indicators and corresponding weightages are used as inputs in hierarchal Mamdani's FIS to obtain the sustainability score of organization as shown in Figure5.8.Mamdani's FIS is a comparatively simpler structure which predicts reasonable results and also includes the intuitive and interpretable nature of the rule base (Jassbi et al., 2006b). The hierarchal structure of the fuzzy inference system is shown in Figure 5.9.

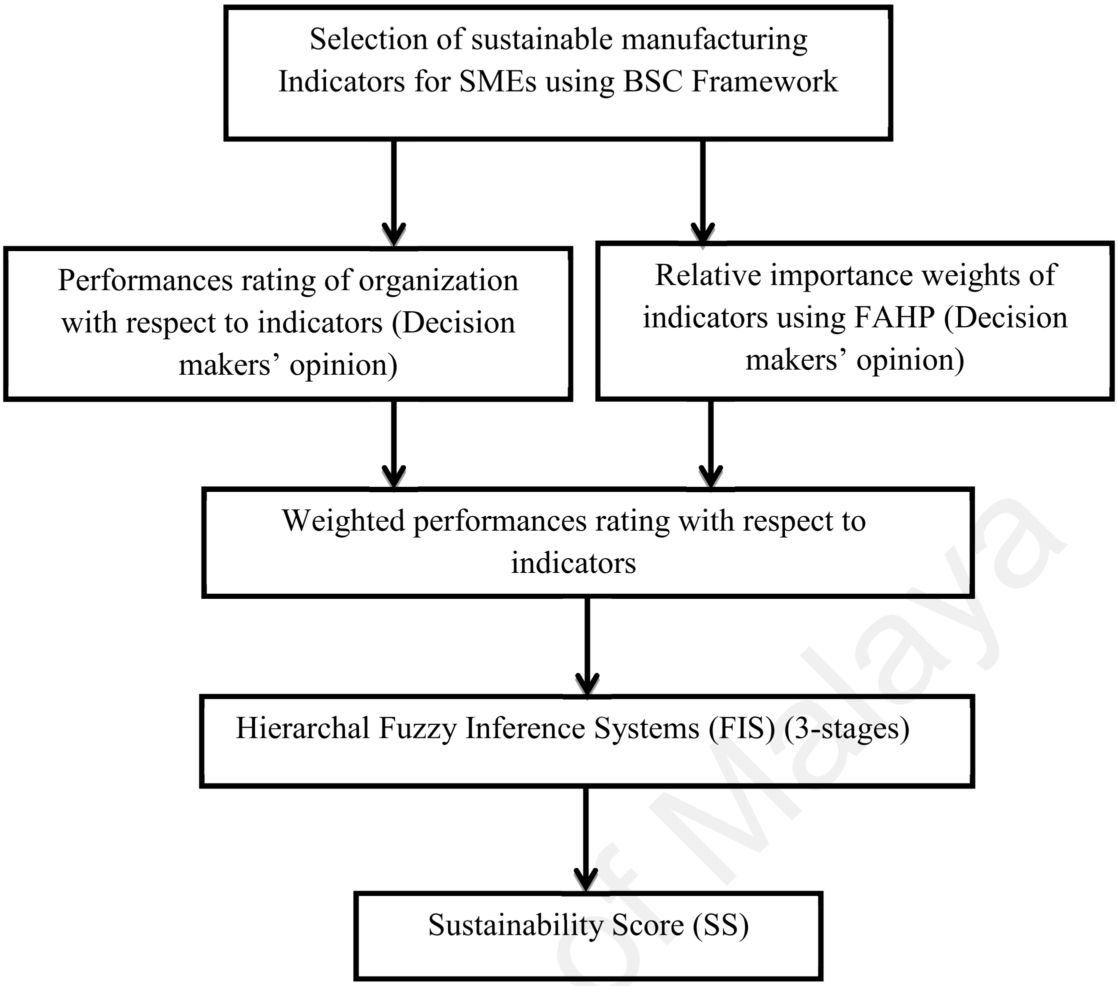


Figure 5.8: BSC based Sustainability evaluation framework

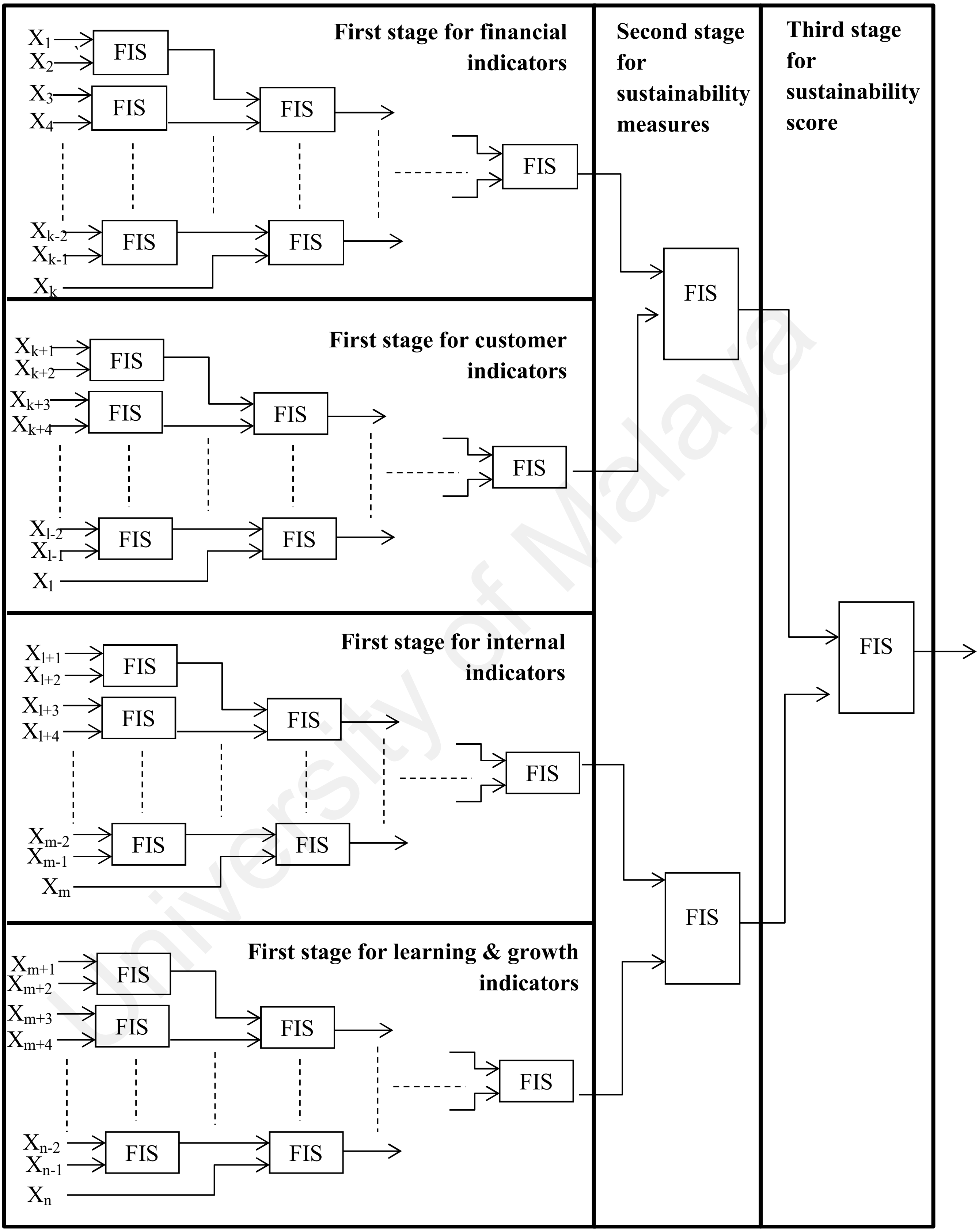


Figure 5.9: Hierarchal structure of fuzzy inference system

5.4.1 Integrated FAHP- FIS Model

The importance of indicators and measures are computed based on FAHP as discussed in subsequent subsection. In addition to that, this model also requires the perception of decision makers about the performance of their system with respect to indicators. Triangular or trapezoidal fuzzy numbers are recommended to overcome the vagueness in manufacturing decision making (Vinodh & Balaji, 2011a). In this study, we have applied triangular fuzzy number (TFN). A triangular fuzzy number can be represented as $\tilde{A} = (a_l, a_m, a_u)$ (shown in Figure 5.10).

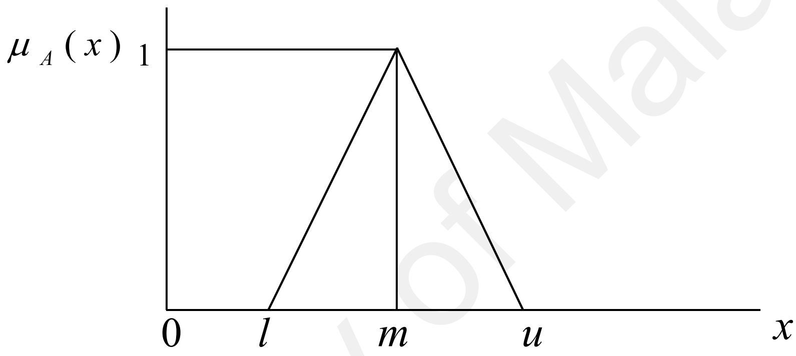


Figure 5.10: Triangular fuzzy number

5.4.2 Membership Functions for Inputs and Outputs

Five fuzzy sets of membership functions are applied for inputs and outputs at all three stages. The fuzzy sets in terms of linguistic variables include 'Very Poor' , 'Poor' , 'Moderate' , 'Good' and 'Very Good'. These variables are equivalent to TFN on a numerical range of 0-100 as shown in Table 5.14 and Figure 5.5.

Table 5.14: Linguistic variables for inputs and outputs at all stages

Linguistic Variables	Triangular Fuzzy number (TFN)
Very Poor (VP)	(0,0,25)
Poor (P)	(0,25,50)
Moderate (M)	(25,50,75)
Good (G)	(50,75,100)
Very Good (VG)	(75,100,100)

5.4.3 Fuzzy Operations

The following fuzzy operations are applied to compute the fuzzy weights of indicators and measures and sustainability score (SS) of manufacturing SME. For example, let say $\tilde{A}$ and $\tilde{B}$ are two TFNs.

$$\tilde{A} = (a_l, a_m, a_u) \tag{5.11}$$

$$\tilde{B} = (b_l, b_m, b_u) \tag{5.12}$$

Then,

$$\tilde{A} \oplus \tilde{B} = (a_l + b_l, a_m + b_m, a_u + b_u) \tag{5.13}$$

$$\tilde{A} \otimes \tilde{B} = (a_l \times b_l, a_m \times b_m, a_u \times b_u) \tag{5.14}$$

$$\frac{\tilde{A}}{\tilde{B}} = (\frac{a_l}{b_u}, \frac{a_m}{b_m}, \frac{a_u}{b_l}) \tag{5.15}$$

5.4.4 Importance Weightage of Indicators and Measures

Analytic Hierarchy Process (AHP) is an extensively used MCDM approach to compute the relative weights of the criterion (Saaty, 1980; Saaty & Vargas, 2001).In AHP method, problem structure is generally a multilevel hierarchy. Each criterion on a given level is of some importance and believed to influence the importance of criterion at next higher levels. This method is focused on obtaining the importance weights of set of criteria at one level of hierarchy to level just above (Liberatore, 1987). This process is repeated from level to level. Weight matrixes are multiplied to obtain the importance weightage of criteria at lowest levels to ascertain their impact on overall goal. Although AHP is a very popular method, it is not able to handle the uncertainties associated with decision making problems (Cheng, 1997). Buckely (1985) proposed FAHP method, a systemic approach based on the AHP which is able to handle imprecise information in form of fuzzy numbers (Ayağ & Özdemir, 2006). FAHP requires decision makers' opinion in the form of a comparison matrix of importance between each criterion to obtain the fuzzy weights.

5.4.4.1 Fuzzy analytical hierarchal process

FAHP is applied to obtain relative importance weights for four measures of BSC and indicators at the respective hierarchy level. The calculation process of FAHP is explained as follows:

a. *Define hierarchal structure of problem.*

   Define the hierarchal structure of sustainability assessment problem based on BSC framework.

b. *Construct the fuzzy positive reciprocal matrix.*

   Decision makers are asked to represent the pairwise comparisons among measures and indicators using linguistic value. The TFN equivalent to linguistic values are shown in Table 5.15. These collected data are used to form pairwise comparison matrix.

c. *Examine consistency of comparison matrixes*

   If $C = [c_{ij}]$ is a positive reciprocal matrix then $\tilde{C} = [\tilde{c}_{ij}]$ is a fuzzy positive reciprocal matrix. Buckley (1985) shown that if the comparison matrix $C = [c_{ij}]$

is consistent, then fuzzy comparison matrix $\tilde{C} = [\tilde{c}_{ij}]$ is also consistent. In this study, we applied this method to validate the responses of decision makers.

Table 5.15: Linguistic scale for importance of indicators and measures for FAHP comparisons

Fuzzy numbers	Linguistic value	Triangular Fuzzy Number (c_{ij})	Reciprocal of TFN (c_{ji})
$\tilde{9}$	Absolutely Important	(7,9,9)	(1/9,1/9,1/7)
$\tilde{7}$	Very strongly Important	(5, 7, 9)	(1/9, 1/7, 1/5)
$\tilde{5}$	Essentially Important	(3, 5, 7)	(1/7, 1/5, 1/3)
$\tilde{3}$	Weakly Important	(1, 3, 5)	(1/5, 1/3, 1)
$\tilde{1}$	Equally Important	(1, 1, 3)	(1/3, 1, 1)
$\tilde{2},\tilde{4},\tilde{6},\tilde{8}$	Intermediate value between two adjacent judgments		

Source: (Mon et al., 1994; Hsieh et al., 2004)

d. *Compute the fuzzy weights of BSC measures and corresponding indicators.*

Lambda-Max method is used to calculate the fuzzy weights of measures and indicators, which was proposed by Csutora and Buckley (2001). A sequence of positive reciprocal matrices is applied to determine the relative weights. The calculation steps are as follows:

A. Let $\alpha = 1$, using α -cut to construct $\tilde{C}_m^1 = [\tilde{C}_{ijm}]_{n \times n}$, This shows that decision makers opinion is the crisp reciprocal matrix $\tilde{C}$, and obtain the fuzzy weight $\tilde{W}_m$ for $\tilde{W}_m = [\tilde{W}_{im}]$ for i= 1, 2, …, n.

B. Let $\alpha = 0$, using α -cut to construct $\tilde{C}_u^0 = [C_{iju}]_{n \times n}$ and, $\tilde{C}_l^0 = [C_{ijl}]_{n \times n}$ in accordance with fuzzy reciprocal numbers. Determine the weights $\tilde{W}_u$, and $\tilde{W}_l$ where $\tilde{W}_u = [\tilde{W}_{iu}]$ and $\tilde{W}_l$ = $[\tilde{W}_{il}]$ for i= 1, 2… n.

C. To normalize the fuzzy weights, the method suggested by Csutora and Buckley (2001) is used. According to this method, lower and upper bounds of the triangular fuzzy weight can be computed as:

$$Q_l = \min\{\frac{W_{im}}{W_{il}} \mid 1 \le i \le n\} \qquad (5.16)$$

$$Q_u = \max\{\frac{W_{im}}{W_{iu}} \mid 1 \le i \le n\} \qquad (5.17)$$

After computing the Q_l and Q_u; the new weights can be calculated as:

$$\tilde{W}_{il}^* = Q_l \times W_{il} \qquad (5.18)$$

$$\tilde{W}_{iu}^* = Q_u \times W_{iu} \qquad (5.19)$$

After obtaining these new fuzzy weights as $\tilde{W}_l^* = [\tilde{W}_{il}^*]$, $\tilde{W}_m^* = [\tilde{W}_{im}^*]$ and $\tilde{W}_u^* = [\tilde{W}_{iu}^*]$, these weights are integrated. The triangular fuzzy weight of ith criteria is obtained as $\tilde{W}_i^* = (W_{il}^*, W_{im}^*, W_{iu}^*)$. For simplicity hereafter $\tilde{W}_i^*$ is represented as $\tilde{w}_i = (\tilde{w}_{il}, \tilde{w}_{im}, \tilde{w}_{iu})$.

5.4.6 Fuzzy Rules in Proposed Model

The fuzzy rule base for this model is based on expert knowledge. Sustainability score depends on performance ratings of organization with respect to indicators. Indicators used in BSC are also identified as 'Smaller is better' and 'Larger is better' types. We applied the method suggested by Singh et al. (2013) to assign the appropriate fuzzy numbers to accommodate both types of indicators. If an indicator is of 'larger is better' type, then, higher value of an indicator is preferred and this indicator is assigned a higher fuzzy number for higher value of indicator and vice versa. For other type of indicator which is 'smaller is better', lower value of indicator is preferred and this indicator is assigned a higher fuzzy number for lower value of indicator and vice versa.

Rules for this FIS model have been developed on the basis of averaging concept as shown in Table 5.16.

Table 5.16: Fuzzy rule base matrix

First Input → Second Input ↓	VP (Very Poor)	P (Poor)	M (Moderate)	G (Good)	VG (Very Good)
VP	VP	VP	P	P	M
P	VP	P	P	M	M
M	P	P	M	M	G
G	P	M	M	G	G
VG	M	M	G	G	VG

5.4.7 Defuzzification Method

It is required to defuzzify the fuzzy number into a real number at each level of hierarchy. We applied centre of area (COA) method for defuzzification as represented by Eqs (5.12).

$$X_{COA} = \frac{\sum_{i=1}^{n} x_i.\mu_i(x_i)}{\sum_{i=1}^{n} \mu_i(x_i)} \qquad (5.20)$$

5.4.8 Monotonic Behaviour of Hierarchal FIS Model

For hierarchal FIS, monotonicity of outputs with respect to its inputs is an indispensable requirement(Kouikoglou & Phillis, 2009). The conditions for non-decreasing output of the single-stage fuzzy system are given by Won et al. (2002) as follows:

Condition 1: The rule bases should be non-decreasing.

Condition 2: The weights used in the defuzzification should be piecewise differentiable and non-decreasing.

Condition 3: The membership functions assigned to the inputs should be piece-wise differentiable, in the sense that they should be continuous on the corresponding domains and differentiable at all but a finite number of points. Moreover, for any pair of fuzzy sets A and B, if A < B then $[d\mu_A(x)/dx]/\ \mu_A(x) \leq [d\ \mu_B(x)/dx]/\ \mu_B(x)$*, for all x where* $\mu_A(x)$ *and* $\mu_B(x)$ *should be differentiable.*

Kouikoglou and Phillis (2009) have expanded the applicability of these conditions by proving that these are also sufficient for the monotonicity of multi-stage, hierarchical fuzzy systems if each inference stage satisfies conditions 1 and 2, and the basic inputs satisfy condition 3.'To satisfy condition 1, non-decreasing rule base is developed. The highest value of fuzzy sets applied in this model as shown in Fig 5.11 satisfies condition 2.

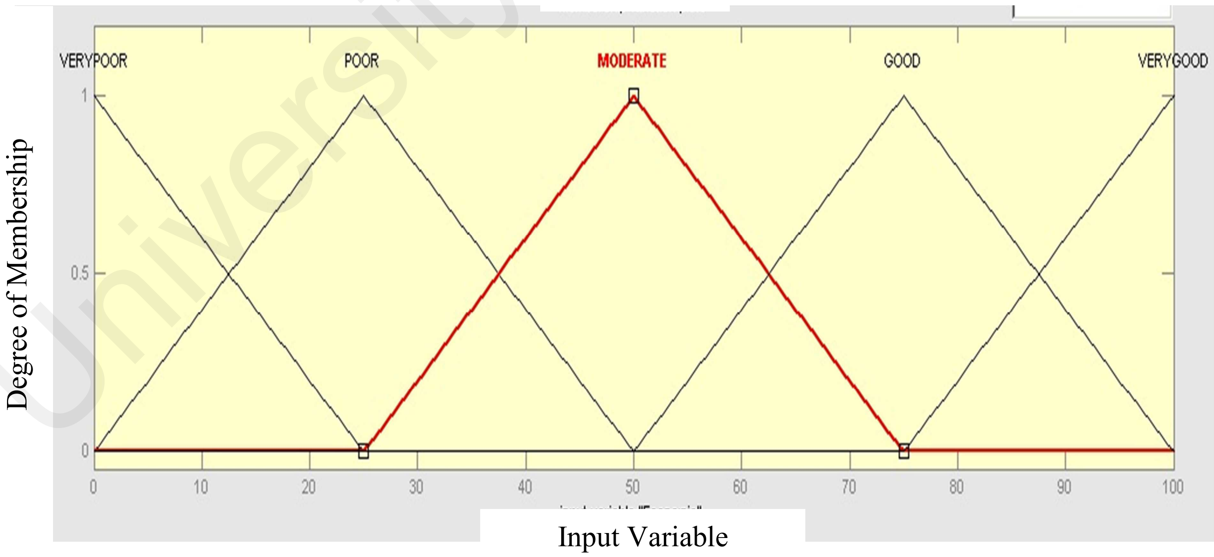


Figure 5.11: Membership functions of output variables

Won et al. (2009) explained the condition 3 for triangular membership function as follows:

Fuzzy systems assigned triangular membership functions $\tilde{A} = (a_l, a_m, a_u)$ *are piece-wise differential, if* $a_l^p \le a_l^q, a_m^p \le a_m^q$ and $a_u^p \le a_u^q$ *for all membership functions (1... p, q,..m), where 1≤ p≤ q≤ m.*

In this study, each input is assigned the membership functions based on condition 3 for triangular membership function.

5.4.9 Explanation of Proposed Model

The output of this model as sustainability score (SS) for manufacturing SME depends on the various indicators' values and their relative importance weights. Decision makers are asked to identify the relevant indicators from each aspect of the BSC.

This hierarchal FIS model has three stages as shown in Fig 5.9. Each FIS is assigned two inputs and one output with five fuzzy membership functions to avoid rule explosion and to accommodate large number of indicators. At each stage, fuzzy performance ratings and fuzzy importance weights of corresponding indicators or measures are defuzzified to obtain the crisp values using Eqs (5.20). At first stage, crisp performance rating is multiplied by a corresponding crisp importance weightage of indicator to obtain the weighted performances rating to be used as input. In the process of selecting two by two inputs, if any remains, it would be treated as output in that particular category. This stage is continued until all selected indicators as inputs are accommodated in hierarchal FIS and output for each category reduced to one. There are four outputs from stage one, which are considered as performance ratings of the organization with respect to four measures of BSC. The performance rating of each measure is multiplied with importance weightage of corresponding measure to obtain four weighted performance ratings as inputs at the second stage. Stage 2 consists of two FIS with four inputs and two outputs. Stage 3 consists of two inputs (outputs from stage

2) and one output. The output of stage three represents the overall sustainable performance of manufacturing SMEs as a sustainability index (SI).

5.4.10 Case Study

In this section, application of this model is illustrated by a case study. The case company (hereafter known as ABC) is located in Manesar, Gurgaon, India. ABC manufactures auto electrical components for various vehicle segments, Gensets and home-appliances. ABC is an original equipment manufacturer (OEM) and supplier to more than 20 vehicles and Genset manufacturers. ABC is an ISO 9001 certified company and striving to obtain ISO 14001 certification due to pressure from customers and also to achieve a competitive edge. ABC was using traditional BSC as a performance evaluation framework for last three years. After deliberations with decision makers, BSC is identified as a holistic and comprehensive approach to be used as a framework for sustainability evaluation. The decision makers also felt that a fuzzy based model, which can accommodate relative importance of indicators and measures, could be used to deal with uncertainties associated with manufacturing decisions. The three decision makers from ABC are Quality Assurance Manager who is also responsible for sustainability initiatives in the company as well as Senior Finance Manager and Production Manager.

5.4.10.1 Data collection

Decision makers were asked to select the indicators pertinent to ABC. Based on decision makers' opinion, the hierarchy of the performance evaluation using BSC has been defined as shown in Fig 5.12. Decision makers' opinion towards importance of measures and indicators at respective levels has been collected in form of pair-wise comparison matrices as shown in Table 5.17. Decision makers were also asked to assess the performances rating of their organization with respect to selected indicators as shown in Table 5.18. It should be noted that decision makers' opinions towards performance of ABC with respect to indicators are mutually agreed.

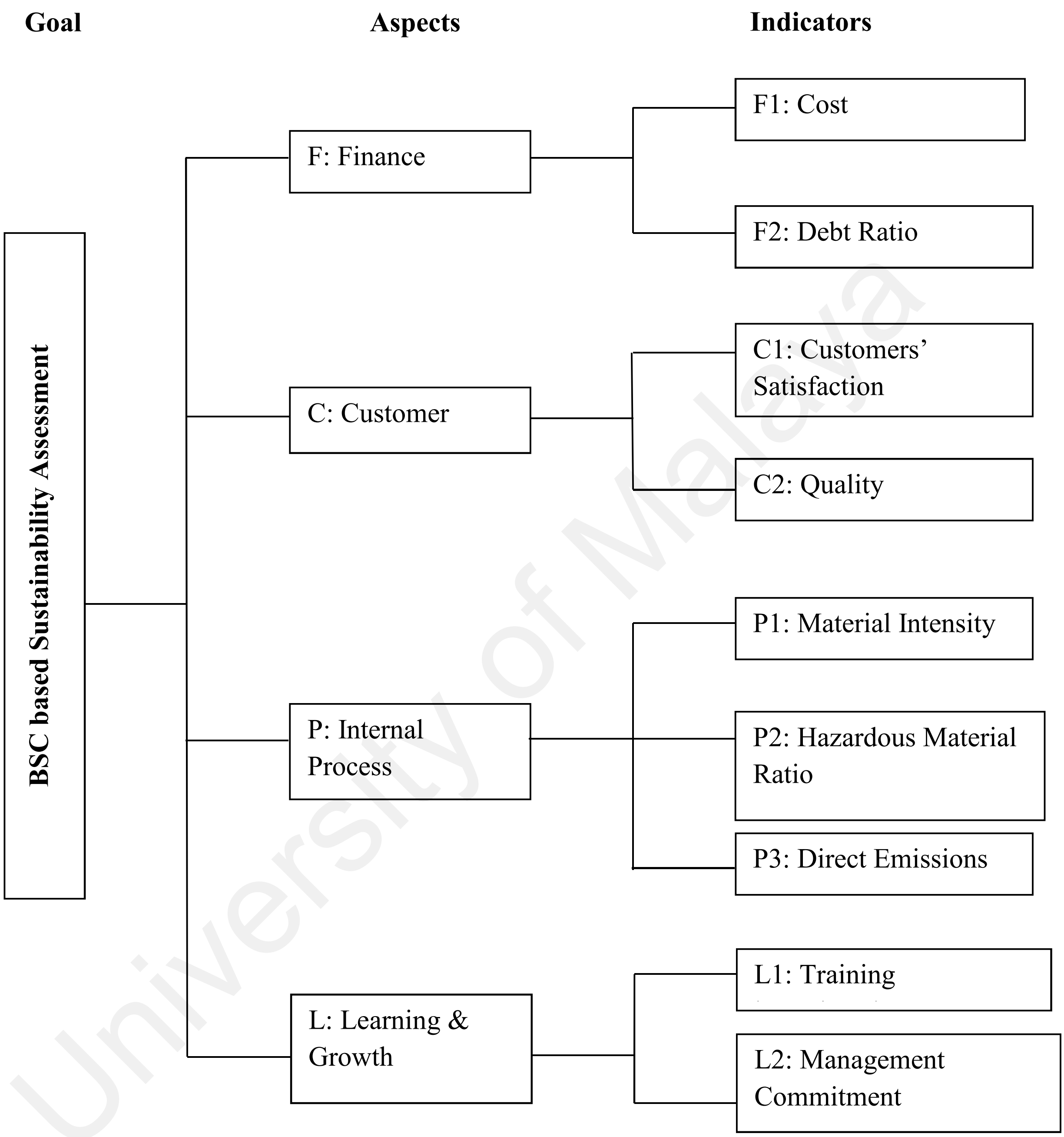


Figure 5.12: Hierarchal structure of BSC for sustainability evaluation in case company

Table 5.17: Pairwise comparison matrix for aspects and indicators

Aspects		F	C	P	L
DM1	F	$\tilde{1}$	$\tilde{9}$	$\tilde{7}$	$\tilde{5}$
	C	$\tilde{9}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{3}$
	P	$\tilde{7}^{-1}$	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$
	L	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$
DM2	F	$\tilde{1}$	$\tilde{7}$	$\tilde{7}$	$\tilde{5}$
	C	$\tilde{7}^{-1}$	$\tilde{1}$	$\tilde{5}^{-1}$	$\tilde{5}$
	P	$\tilde{7}^{-1}$	$\tilde{5}$	$\tilde{1}$	$\tilde{3}$
	L	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$
DM3	F	$\tilde{1}$	$\tilde{9}$	$\tilde{5}$	$\tilde{7}$
	C	1/9	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{5}$
	P	$\tilde{5}^{-1}$	$\tilde{3}$	$\tilde{1}$	$\tilde{5}$
	L	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$

Financial Indicators		F1	F2
DM1	F1	$\tilde{1}$	$\tilde{7}$
	F2	$\tilde{7}^{-1}$	$\tilde{1}$
DM2	F1	$\tilde{1}$	$\tilde{5}$
	F2	$\tilde{5}^{-1}$	$\tilde{1}$
DM3	F1	$\tilde{1}$	$\tilde{9}$
	F2	$\tilde{9}^{-1}$	$\tilde{1}$

Customer Indicators		C1	C2
DM1	C1	$\tilde{1}$	$\tilde{3}$
	C2	$\tilde{3}^{-1}$	$\tilde{1}$
DM2	C1	$\tilde{1}$	$\tilde{5}$
	C2	$\tilde{5}^{-1}$	$\tilde{1}$
DM3	C1	$\tilde{1}$	$\tilde{3}$
	C2	$\tilde{3}^{-1}$	$\tilde{1}$

Internal Process indicators		P1	P2	P3
DM1	P1	$\tilde{1}$	$\tilde{5}^{-1}$	$\tilde{3}$
	P2	$\tilde{5}$	$\tilde{1}$	$\tilde{5}$
	P3	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$
DM2	P1	$\tilde{1}$	$\tilde{7}^{-1}$	$\tilde{5}$
	P2	$\tilde{7}$	$\tilde{1}$	$\tilde{5}$
	P3	$\tilde{5}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}$
DM3	P1	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{5}$
	P2	$\tilde{3}$	$\tilde{1}$	$\tilde{7}$
	P3	$\tilde{5}^{-1}$	$\tilde{7}^{-1}$	$\tilde{1}$

Learning & Growth Indicators		L1	L2
DM1	L1	$\tilde{1}$	$\tilde{7}$
	L2	$\tilde{7}^{-1}$	$\tilde{1}$
DM2	L1	$\tilde{1}$	$\tilde{5}$
	L2	$\tilde{5}^{-1}$	$\tilde{1}$
DM3	L1	$\tilde{1}$	$\tilde{3}$
	L2	$\tilde{3}^{-1}$	$\tilde{1}$

Table 5.18: Sustainability performance of case company

Indicator	Decision makers' opinion
F1: Cost	Very Good
F2: Debt Ratio	Good
C1: Customers' satisfaction	Average
C2: Quality	Good
P1: Material intensity	Good
P2: Hazardous Material Ratio	Very Good
P3: Direct Emission	Average
L1: Training hours/ Employee	Poor
L2: Management's Commitment	Good

5.4.10.2 Implementation and results

During Implementation and result extraction process, importance weightage of measures and indicators were computed using FAHP (Eqs. (5.16) - (5.19)). All fuzzy positive reciprocal matrixes were examined for consistency by obtaining the consistency index of corresponding positive reciprocal matrices. In the case of inconsistency, decision makers were asked to re-evaluate their opinions. This process was continued until the consistency ratio for all comparison matrices became less than or equal to 0.10. These fuzzy weights were converted to crisp values using centre of area (COA) defuzzification method using Eq. (5.20) as shown in Table 5.19. Similarly performances rating of ABC with respect to indicators were also defuzzified to obtain real numbers (Table 5.20). Crisp values of importance weight and performance rating for corresponding indicator were multiplied to obtain weighted performance ratings as input values for stage 1. At stage 2, crisp values of importance weightage of measures are multiplied by crisp values of performance ratings of organization with respect to respective measures. The weighted performances ratings with respect to measures were used as input at this stage. There are four inputs and two outputs at stage 2. At stage 3, two outputs obtained from stage 2 were used as inputs. Finally, the output of stage 3 is an overall sustainability index or score of the organization. It is seen that values obtained after the multiplication process have been reduced in proposed scale. To eradicate this problem, these values were normalized at each input stage.

Table 5.19: Aggregated importance weightage of measures and indicators

Measures	TFN Weights	Crisp Values	Indicators	TFN Weights	Crisp values
Financial	(0.57, 0.62, 0.64)	0.61	F1:Manufacturing Cost	(0.72, 0.87, 0.90)	0.84
			F2: Debt Ratio	(0.10, 0.13, 0.21)	0.15
Customer	(0.08, 0.12, 0.17)	0.13	C1: Customers' satisfaction	(0.50, 0.82, 0.88)	0.73
			C2: Quality	(0.13, 0.18, 0.34)	0.22
Internal Business Process	(0.16, 0.20, 0.52)	0.29	P1: Material Intensity	(0.16, 0.24, 0.35)	0.25
			P2: Hazardous material ratio	(0.50, 0.67, 0.68)	0.62
			P3: Direct emission	(0.07, 0.09, 0.14)	0.10
Learning & Growth	(0.05, 0.06, 0.08)	0.07	L1: Training Hours/ Employee	(0.50, 0.82, 0.88)	0.74
			L2: Management's Commitment	(0.13, 0.18, 0.34)	0.22

Table 5.20: Fuzzy and crisp Performance rating values

Indicators	Decision makers' opinion	TFN	Crisp Value
F1: Cost	Very Good	(75,100,100)	91.6
F2: Debt Ratio	Good	(50,75,100)	75
C1: Customers' satisfaction	Moderate	(25, 50, 75)	50
C2: Quality	Good	(50,75,100)	75
P1: Material intensity	Good	(50,75,100)	75
P2: Hazardous Material Ratio	Very Good	(75,100,100)	91.6
P3: Direct Emission	Moderate	(25, 50, 75)	50
L1: Training hours/ Employee	Poor	(0, 25, 50)	25
L2: Management's Commitment	Good	(50,75,100)	75

Two virtual companies have been considered for comparing the performance of ABC. One was introduced as best-performing company and another was worst performing company. The outputs of ABC were compared with these two virtual companies at each stage. Finally, sustainability scores or indexes of the target Company along with the virtual companies have been computed as shown in Table 5.21.

Table 5.21: Validation of proposed model

Enterprises	Assessment result (Sustainability score)				
	COM	MOM	SOM	LOM	BOM
Ideal	75	75	75	75	75
ABC	50	50	50	50	50
Non-ideal	08	00	00	00	07

The working of FIS models is represented by the rule viewers. To demonstrate the structure of rule viewer, one FIS at second stage is chosen as shown in Figure 5.13. In this rule viewer, each input variable is plotted along column and each rule along a row. Input variable values can be changed by moving the red line, and output can be observed from output column. For all FIS in the proposed model, there are two input variables and five membership functions resulting into 25 (5^2) rules.

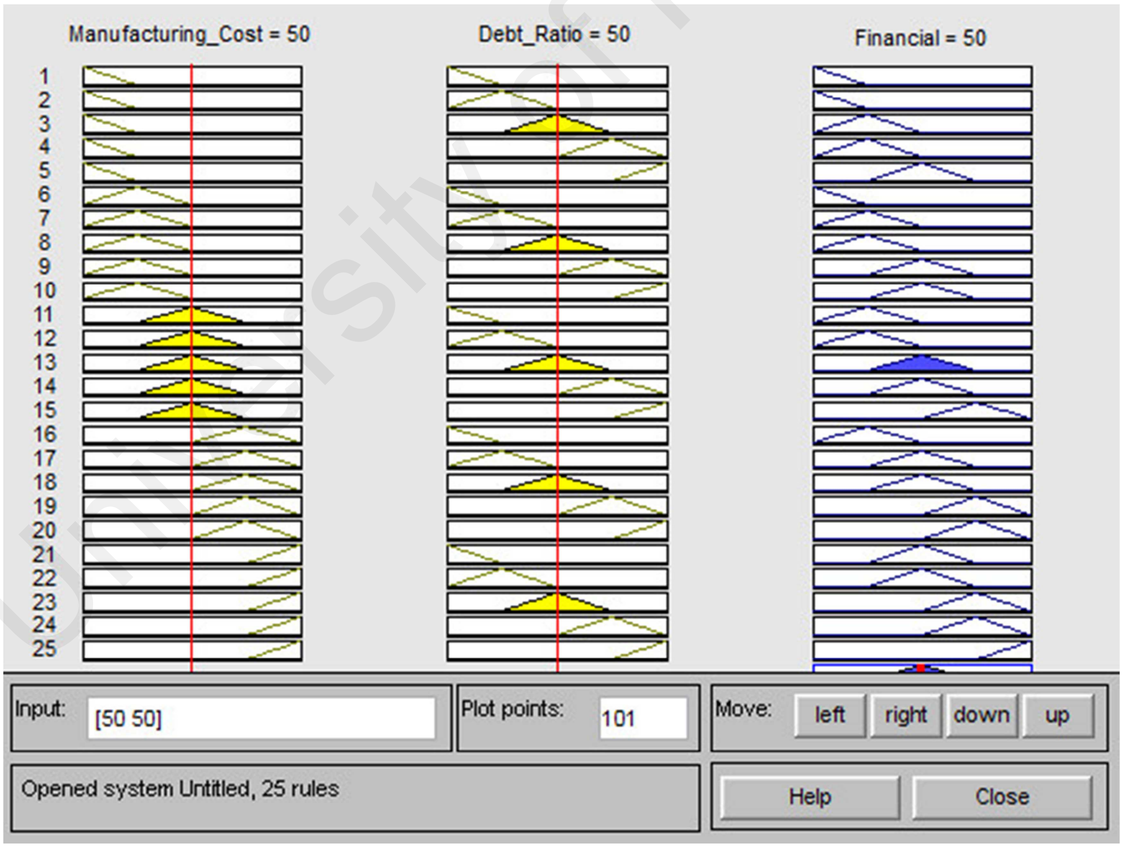


Figure 5.13: Rule Viewer for case company (Stage 1)

The monotonic behaviour of proposed hierarchal FIS is verified by varying the input values and observing the output values. The output surface of the second stage FIS is shown in Fig 5.14. It is seen that increasing the input values result in increased value of outputs for each FIS. The robustness of this model has been validated by two methods. First, this model has been validated by applying different defuzzification methods. Second, performance rating of the case company is in between worst and best performing companies. As shown in Table 5.21, assessment results for all three enterprises are same in all defuzzification modes and prove the validity of this model. The result of overall sustainability performance of ABC is found to be moderate. It is also found that there is scope of improvement in financial performance, but measures such as customers, internal business process and learning and growth require more attention for overall sustainability improvement. From the customer aspect of BSC, customer's satisfaction requires more focus than quality to improve the score of this aspect. Material intensity and direct emission require more focus than hazardous material ratio to improve performance of the internal business process aspect. From learning and growth perspective, more efforts require for enhancing skills of employee.

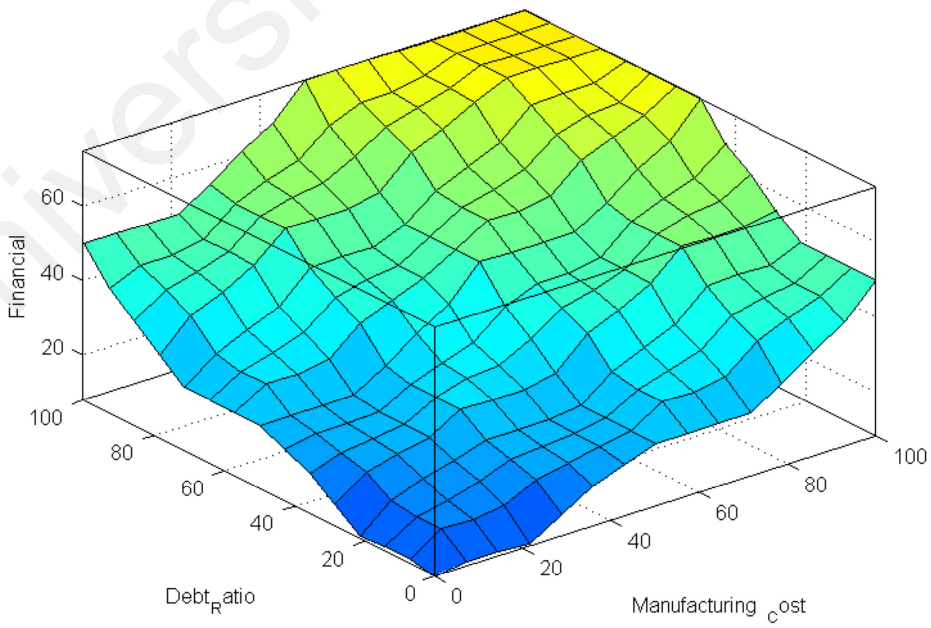


Figure 5.14: Output surfaces of FIS for case company

5.4.10.3 Sensitivity analysis

Sensitivity analysis plays an important role in the decision making process by determining the effects of change in a decision parameter on overall performance. This section attempts to help decision-makers to select the appropriate strategy by sustainability evaluation in given scenario. A scenario is defined by the available set of sustainability indicators. The change in the values of indicators and resulting change in the sustainability scores observed, the decision makers could identify the most important indicators to improve the sustainability performance.

Sensitivity analysis requires the computation of the gradient of sustainability score with respect to each indicator. A gradient gives the increase of sustainability score per unit increase of an indicator. In order to perform sensitivity analysis, the method suggested by (Phillis and Davis (2009)) was adopted. The steps of the sensitivity analysis are as follows:

1. Calculation of the sustainability score: For a given organization, obtain the performance values with respect to each indicator using the proposed method. Start from stage 1 of the hierarchal FIS and proceed successively to obtain the sustainability score.
2. Introduction of perturbation: For an indicator, say, *i*, increase its weighted performance value (x_i) by some fixed amount (δ), for example, 10%. If the result is greater than 100 (i.e. maximum sustainability score), then truncate it to 100 to avoid overshooting the permissible region of the indicators.
3. Sensitivity analysis: evaluate the sustainability score with the same set of data in step 1 except for indicator '*i*' whose value is now $x_i+\delta$. Denote the new evaluation as SS $_{(xi+\delta)}$. The gradient of SS with respect to i^{th} indicator is defined by forward difference

$$\Delta_i = SS_{(xi+\delta)} - SS \quad (5.21)$$

Reset the value of indicator to x_i.

4. Loop: repeat step 2 and 3 for all indicators.
5. Ranking: identify the gradient with the largest values, which corresponds to the indicators which affects most in given scenario.

During the sensitivity analysis, biasness towards indicators which belongs to small groups was observed. For example, financial aspect depends on only two indicators. Therefore, an increase in the debt ratio has nearly direct effect on SS. Internal business process has three indicators, an improvement in one of these indicators results in small improvement of SS. To avoid this bias, the indicator '*i*' is ranked according to scaled gradient (D_i).

$$D_i = (100 - x_i)\Delta_I \quad (5.22)$$

Where (100- x_i) is the distance of the i^{th} indicator from sustainable value and Δ_i is gradient of sustainability score with respect to i^{th} indicator. Therefore, indicators that affect the SS most and are farther from sustainable region are identified and ranked to improve the sustainability performance. The results of sensitivity analysis for ABC are shown in Table 5.22.

Table 5.22: Most important indicators for sustainability improvement in case company

Indicator (*i*)	Scaled gradient (D_i)
Customers' satisfaction (C1)	0.416
Training hours/ Employee (L1)	0.199
Debt ratio (F2)	0.132
Material intensity (P1)	0.099
Direct emission (P3)	0.083
Quality (C2)	0.049
Management's commitment (L2)	0.016

The overall sustainability performance of ABC was found to be moderate. At present scenario, as can be seen from Table 5.22, the order of importance of indicators is C1>L1>F2>P1>P3>C2>L2. As manufacturing cost (F1) and hazardous material ratio (P2) are already within sustainable region (i.e., distance from sustainable value is zero or near zero), these indicators are not identified as the important indicators. In this case study, the company is an SME and not a bigger organization, the lower score of management commitment is not surprizing in the case of SMEs although this indicator is very important. Based on this analysis, decision makers can devise the strategy to improve its sustainability performance.

5.5 Summary

This chapter presents two FIS-based sustainability evaluation models for manufacturing SMEs to cater for the different needs of decision makers. The first model considers the absolute weights of indicator based on the Triple Bottom Line framework. The second model is an integrated FAHP-FIS method for sustainability assessment based on BSC framework considers the relative importance of indicators. The relative importance of indicators and measures were obtained by FAHP method. Considering the characteristics of SMEs, the indicators for sustainability performance evaluations are identified during an empirical study (see chapter 4) were used in these models. Performance assessment of enterprise with respect to each indicator and weightage of corresponding indicator and measure were used as inputs in hierarchal FIS system. Proposed models can accommodate any number of indicators. These models are validated using different defuzzification methods. During implementation in manufacturing SMEs, these models were found to be useful in assessing and identifying weak areas. These models can be generalized for all SMEs with some modification at the lower hierarchy of model by changing the performance indicators. These models serve as the tools for decision-makers to evaluate the effectiveness and alter sustainability strategies to achieve enhanced overall sustainability performance.

CHAPTER 6: STRATEGY SELECTION FOR SUSTAINABLE MANUFACTURING WITH INTEGRATED AHP -VIKOR METHOD UNDER INTERVAL-VALUED FUZZY ENVIRONMENT

6.1 Introduction

There are numerous strategies to enhance the sustainability of manufacturing organizations (Maxwell et al., 2006), but researchers are more focused on the strategies related to resource usage and waste minimization(Abdul Rashid et al., 2008). Some of the often cited labels for manufacturing strategies are pollution prevention, product stewardship, lean manufacturing, waste reduction, resource usage reduction, 3R (Reduce, Reuse and Recycle), 6R (reduce, reuse, recover, redesign, remanufacture, recycle), substitution (new resource or technology), material efficiency, resource efficiency, and eco-efficiency(Womack et al., 2007; Abdul Rashid et al., 2008; Jayal et al., 2010; Despeisse et al., 2012). It is also observed that improvement in material utilization contributes towards the increase in the energy-efficiency (Worrell et al., 2009). In view of the importance of resource usage towards sustainability of manufacturing organizations, four clearly separated strategies have been identified for sustainable manufacturing, which are waste minimization, material efficiency, resource efficiency and eco-efficiency (Abdul Rashid et al., 2008). The selection of an appropriate strategy plays an important role towards achieving success in sustainability initiatives.

In the case of strategy selection for sustainable manufacturing, major challenges are to determine the relative weights of each criterion and evaluate all the strategies with respect to various criteria that are usually incommensurable and conflicting (Azadegan et al., 2011; Vinodh et al., 2013b). Selection criteria for sustainable manufacturing strategy should be able to reflect the performance ratings of strategies with respect to three aspects of sustainability (i.e. economic, environmental and social). Furthermore, in a group decision making, each decision maker has different knowledge and opinion about the criteria weights and performance rating of strategies with respect to each criterion. Therefore, strategy selection for sustainable manufacturing becomes a Multi-Criteria Decision Making (MCDM) problem, which involves uncertainties such as interval value and fuzziness. Due to such nature of the problem, the methods of MCDM are reasonably derived to suit the specific needs of strategy selection problems (Sanayei et al., 2010).

MCDM is divided into two different branches. The first one is multi-attribute decision making (MADM) that focuses on selection activities and second branch is multi-objective programming in which alternatives are not predetermined but a set of objective functions is optimized to a set of constraints (San Cristóbal, 2011). MADM method selects the best solution among several strategies considering the same attributes. Some of the popular approaches in MADM are Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Analytical Hierarchal Process (AHP), ELimination Et Choix Traduisant la REalité (ELECTRE), Simple Additive Weighting (SAW), VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR), and Preference Ranking Organisation METHod for Enrichment Evaluations (PROMETHEE).

In recent decades, MADM and methods based on its extensions have been applied widely in various disciplines ranging from renewable energy, quality control, water management, human resource management, transportation, product design and manufacturing (San Cristóbal, 2011). To utilize the advantages of various methods, researchers either integrate two or more methods together or extend the applicability of these methods to new environment to develop a hybrid or innovative method.

Vahdani and Hadipour (2011) extended the applicability of ELECTRE method to the interval-valued fuzzy environment. Liu et al. (2014) presented a hybrid TOPSIS method for failure mode and effect analysis under intuitionistic fuzzy environment. Vinodh et al. (2014) applied fuzzy VIKOR method for fit concept selection in a manufacturing organization. Thakker et al. (2008) combined the three well known methods; the Cambridge Material Selector based method, the adapted value engineering techniques, and the TOPSIS to propose a new way for material selection strategy. Zaerpour et al. (2009) presented an integrated AHP and TOPSIS method for partitioning of products under fuzzy environment. Kaya and Kahraman (2010) applied integrated fuzzy VIKOR & AHP method for selection of the best renewable energy alternative. Zamani et al. (2014) proposed a hybrid method by combining AHP and VIKOR under fuzzy environment for contractor selection. Fouladgar et al. (2012) proposed a fuzzy AHP-VIKOR method for project portfolio selection. Integrated VIKOR and AHP methods have been developed and applied in various disciplines. However, there is no published literature that combines AHP and VIKOR methods under interval-valued fuzzy (IVF) environment to rank the sustainable manufacturing strategies.

The AHP method provides a basis to obtain the relative weights of criteria. The VIKOR method developed to solve MCDM problems involving incommensurable and conflicting criteria (Opricovic & Tzeng, 2004), may provide a basis of strategy selection method that can effectively deal with the nature of this problem. We used the concepts of IVF sets theory and linguistic variables to cope with uncertainty and qualitative factors. Then, a novel hierarchal MCDM method based on IVF sets theory and combined AHP-VIKOR method is proposed to deal with sustainability strategy selection problems in manufacturing organization. A sensitivity analysis was carried out to ascertain the stability of the ranking. This method can easily be extended to other disciplines as a decision making method for selection of the best alternatives or strategies.

The remainder of this chapter is structured as follows: Section 6.2 presents an overview and background of VIKOR, AHP, and IVF Set theory. This is followed by section 6.3, which presents an illustrative list of selection criteria for sustainable manufacturing. In section 6.4, the proposed method is presented. Using a case study, applicability of this method is illustrated in section 6.5. In final section, the summary of this chapter is presented.

6.2 Brief Overview of VIKOR and IVF Set Theory

As this study applied the AHP and VIKOR methods under IVF environment, this section presents basic concepts and definitions of VIKOR method and IVF sets. The overview of the AHP method is already provided in section 5.2.2.

6.2.1 VIKOR Method

The compromised ranking method called VIKOR was developed by Opricovic (1998) and Opricovic and Tzeng (2002) for multi-criteria optimization of complex systems (Opricovic & Tzeng, 2004). This method determines the compromise solution for a problem. VIKOR focuses on ranking and selection from a set of alternatives in presence of conflicting criteria. It introduces the multi-criteria ranking index based on the particular measure of ‘‘closeness” to the ‘‘ideal” solution (Opricovic, 1998). In a compromise programming method, the L_p-metric used as an aggregation function to obtain the multi-criteria measure for compromise ranking (Opricovic & Tzeng, 2004).

In VIKOR method, the various *J* alternatives are represented as $A_1, A_2, ..., A_j$. The rating of alternative A_j with respect to i^{th} criterion is denoted by f_{ij}; where *n* is number of criteria. The development of VIKOR method begins with following form of *Lp*-metric.

$$L_{p,j} = \left\{ \sum_{i=1}^{n} [w_i (f_i^+ - f_{ij}) / (f_i^+ - f_i^-)]^p \right\}^{1/p} \quad (6.1)$$

Where, $1 \le p \le \infty; j = 1, 2, \ldots. J$.

If criteria symbolizes benefit then, $f_i^+ = \max_j f_{ij}$ and $f_i^- = \min_j f_{ij}$

For VIKOR method, $L_{1,j}$ (as $S_j$in Eqs. (6.20)) and $L_{\infty,\mathrm{j}}$ (as R_j in Eqs. (6.21)) are used to formulate the ranking measures. The solution based on $\min_j S_j$ is maximum group utility i.e. based on the majority rule; and solution obtained by $\min_j R_j$ is the minimum regret of opponent. The compromise solution is a feasible solution that is closest to ideal solution, and a compromise means an agreement established by mutual agreements.

6.2.2 Interval-Valued Fuzzy Sets Theory

The idea of fuzzy set theory was conceived by Lotfi Zadeh about five decades ago as a method to cope with human reasoning in decision making(Zadeh, 1965). Bellman and Zadeh (1970) developed fuzzy set theory for MCDM problems to handle the uncertainties associated with the relative weights of criteria and performance ratings. In fuzzy MCDM methods, importance weights of criteria and performance ratings are represented in terms of fuzzy numbers. Fuzzy numbers are convex set defined by real numbers as membership function in the interval of [0 1]. Using fuzzy sets theory, it is often difficult for decision-makers to precisely quantify his or her preference as a number in an interval [0,1] (Karnik & Mendel, 2001). Therefore, it is more appropriate to represent the degree of certainty by an interval (Chen, 2014; Naim & Hagras, 2014). Gorzałczany (1987) andTurksen (1986) extended the concept of fuzzy set theory to develop the interval-valued fuzzy sets. Later on, Guijun and Xiaoping (1998) proposed the definition and arithmetic operations of IVF sets. The IVF-logic based applications have been used in various studies. Examples includeLu et al. (2010) for water resource management,Rashid et al. (2014) for robot selection, Samantra et al. (2013) for reverse logistics alternative selection and many more. In the following, some important definitions and notations of IVF sets theory will be reviewed for references.

Figure 6.1 shows an example of IVF set $\tilde{A}$ labelled as "Mean High". According to Di Martino and Sessa (2014), the membership function of outer fuzzy set is called Upper Membership Function of $\tilde{A}$ (for short, $UMF(\tilde{A})$); the membership of inner fuzzy set is called Lower Membership Function of $\tilde{A}$ (for short, $LMF(\tilde{A})$). The area between $LMF(\tilde{A})$ and $UMF(\tilde{A})$ is called Footprint of Uncertainty of $\tilde{A}$ (for short, $FOU(\tilde{A})$). Symbolically, an IVF fuzzy set $\tilde{A}$ can be represented as $(LMF(\tilde{A}), UMF(\tilde{A}))$.

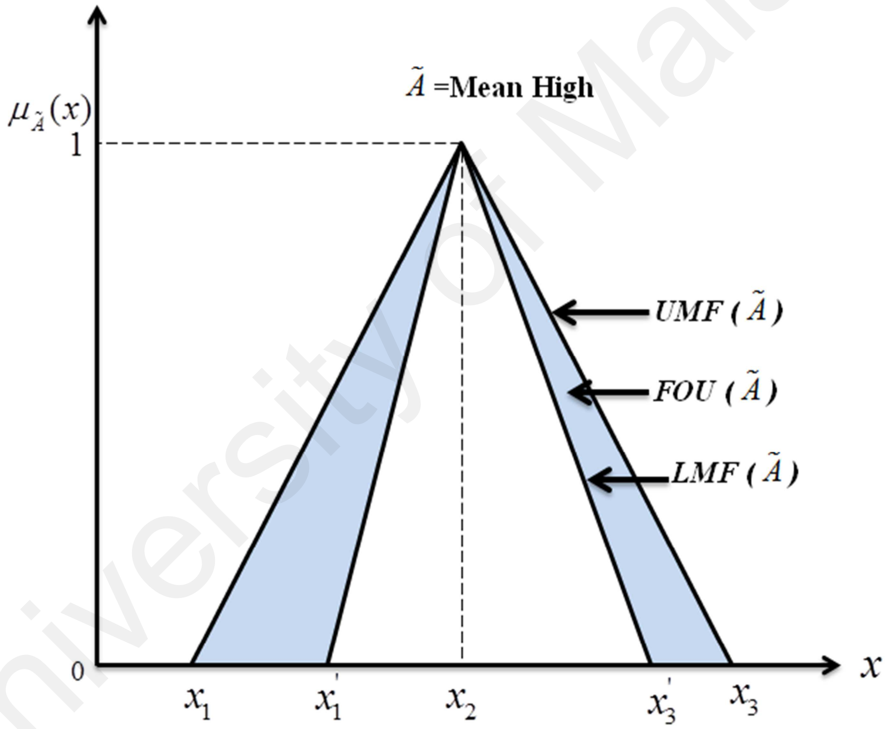


Figure 6.1: Example of triangular IVF set (Di Martino & Sessa, 2014)

Consequently, the symbology presented by Kuo (2011) and Vahdani et al. (2012) to represent a triangular IVF set are used in this study. As can be seen in Figure 6.1, we have $\tilde{A} = (LMF(\tilde{A}), UMF(\tilde{A}))$, where we put, for simplicity, $LMF(\tilde{A}) = (x_1', x_2, x_3')$ and $UMF(\tilde{A}) = (x_1, x_2, x_3)$, thus $\tilde{A} = [(x_1, x_1'); x_2; (x_3', x_3)]$. The IVF set is defined by setting the central value (x_2), the lower bound values of interval ($x_1, x_1^{'}$) and upper bound values of interval ($x_3^{'}, x_3$) with $x_1 \le x_1^{'} \le x_2 \le x_3^{'} \le x_3$.

6.3 Selection Criteria for Sustainable Manufacturing Strategy

The criteria for strategy selection are required to be consistent, relevant, practical, and effective with the overall objective. There is significant number of criteria for ranking the strategies for sustainability, but the suitability of these criteria for strategy selection in manufacturing depends on how these criteria consider characteristics of manufacturing organizations. Sustainability issue is exclusively related to cost-reduction practices in manufacturing organizations (Williamson et al., 2006). Furthermore, from the business perspective, cost is the fundamental principle and driving force for any business activity. Cost can be minimized by reducing the manufacturing cost, waste minimization, decreasing resource usage, and increasing the productivity of work force. Major resources used in manufacturing sectors are material, energy, and water. Thus, selection criteria should be able to assess the effect of strategies on the productivity of these resources. Customers' satisfaction and market accessibility are also important criteria for manufacturing organizations to remain competitive. Therefore, selection criteria should represent the effect of strategies on competitiveness and community engagement. The lack of awareness towards new technology and sustainability has further contributed to the increase in the problem of acceptance of strategy by the employees. Considering these characteristics, the selection criteria should be able to reflect the performance of strategies with respect to cost, quality, competitiveness, market share, waste minimization, resource productivity, human productivity, employee acceptance, and community involvement.

The illustrative list of criteria for strategy selection for sustainable manufacturing is identified from the literature as shown in Table 6.1. These criteria are identified considering the characteristics of manufacturing organizations as discussed above.

Table 6.1: List of selection criteria for strategy selection

Aspect	Criteria	(Robèrt et al., 2002)	(Howarth & Hadfield, 2006)	(Hu & Bidanda, 2009)	(Vinod h et al., 2013a)	(Nezami & Yildirim)	(Achan ga et al., 2006)
Economic							
	Implementation Cost	×	×	×	×		×
	Increase in profit (Return on investment)			×	×		×
	Competitiveness		×	×		×	
	Increase in market share	×			×	×	
	Technical capability					×	×
	Resource requirement					×	×
	Adaptability				×		×
Environmental							
	Decrease in waste	×	×		×	×	
	Decrease in emissions	×	×		×	×	
	Decrease in material usage	×	×		×	×	
	Decrease in energy usage	×			×	×	
	Decrease in water usage	×			×	×	
Social							
	Employee acceptance						×
	Increase in Employment opportunity		×		×		×
	Health and safety		×		×	×	
	Regulation completeness	×		×	×	×	
	Community engagement	×			×		
	Skills enhancement				×		×

6.4 Proposed Model for Strategy Selection

This section proposes a systematic approach to extend the applicability of VIKOR method to solve the strategy or alternative selection problems under IVF environment. The framework of proposed method is shown in Figure 6.2. In Manufacturing, importance weights of criteria and performance rating values of strategies usually have a lot of ambiguity and uncertainties(Vinodh & Balaji, 2011b). Thus, relative weights and performance rating values are considered as linguistic variables and represented by triangular IVF numbers in this method as shown in Table 6.3 &6.4. This method combines two MCDM approaches, which are AHP and VIKOR methods under IVF environment. The IVF-AHP is used to obtain the IVF weight for each criterion. The fuzzy weights obtained from IVF-AHP method and IVF performance ratings obtained from various decision makers are aggregated. The aggregated IVF numbers are defuzzified, then used as inputs to the VIKOR method to obtain the final ranking of strategies.

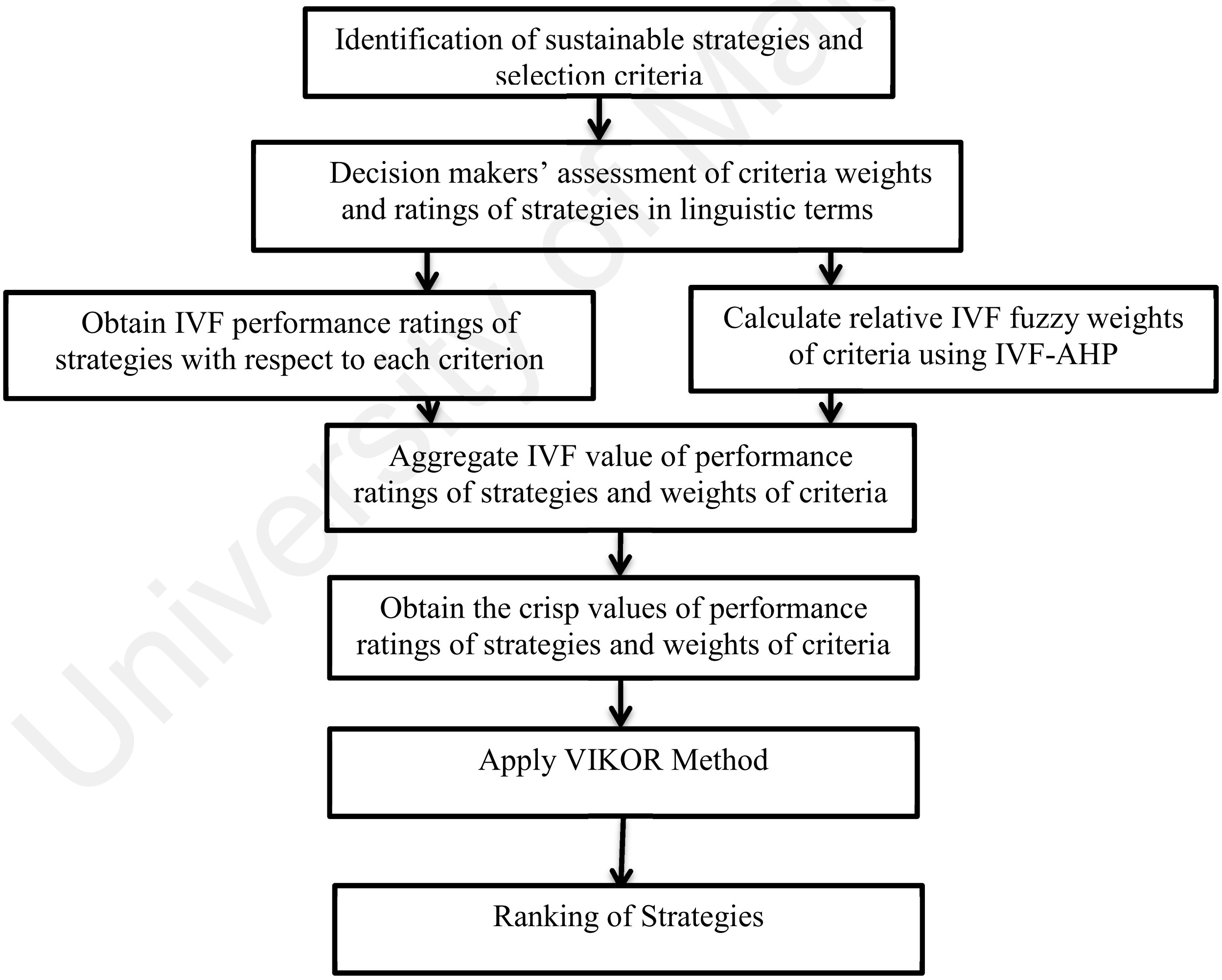


Figure 6.2: Strategy selection framework

If $\tilde{A} = [\tilde{f}_{ij}]_{m\times n}$ is a fuzzy decision matrix for an MCDM problem in which $A_1, A_2, \ldots,$ A_m are m possible strategies and $C_1, C_2, \ldots, C_n$ are n criteria. The performance of strategy A_j with respect to criterion C_i is indicated by triangular IVF number, $\tilde{f}_{ij} = [(f_{1ij}, f'_{1ij}); f_{2ij}; (f'_{3ij}, f_{3ij})]$. Let the relative importance weight of i^{th} criterion be represented by triangular IVF number, $\tilde{w}_i = [(w_{1i}, w'_{1i}); w_{2i}; (w'_{3i}, w_{3i})]$.

Table 6.2: Linguistic scale for criterion importance used for IVF-AHP comparisons (Chen-Tung & Kuan-Hung, 2010)

Level of Importance	Triangular IVF number
Equal importance (VL)	[(1,1);1;(1,1)]
Moderate importance (MI)	[(1,2);3;(4,5)]
Strong importance (SI)	[(3,4);5;(6,7)]
Very strong importance (VSI)	[(5,6);7;(8,9)]
Extreme importance (EI)	[(7,8);9;(9,9)]

Table 6.3: Definitions of linguistic variables for the performance ratings (Vahdani et al., 2010)

Level of Performance	Triangular IVF number
Very poor (VP)	[(0,0);0;(1,1.5)]
Poor (P)	[(0,0.5);1;(2.5,3.5)]
Moderately poor (MP)	[(0,1.5);3;(4.5,5.5)]
Fair (F)	[(2.5,3.5);5;(6.5,7.5)]
Moderately good (MG)	[(4.5,5.5);7;(8,9.5)]
Good (G)	[(5.5,7.5);9;(9.5,10)]
Very good (VG)	[(8.5,9.5);10;(10,10)]

6.4.1 Steps of Proposed Model

Step 1. Define the hierarchal structure for the selection problem based on different aspects and relevant criteria.

Step 2. Obtain the decision makers' opinions in terms of linguistic variables about performance ratings of possible strategies with respect to each criterion (see Table 6.3), and pair-wise comparison among criteria and sub-criteria at the respective level of hierarchy (see Table 6.2).

Step 3. Replace the linguistic variables by corresponding triangular IVF numbers for performance ratings of strategies with respect to each criterion to construct the IVF decision matrices (using Table 6.3).The decision matrix can be represented as $\tilde{A}^k = [\tilde{f}_{ij}^k] = [(f_{1ij}^k, f_{1ij}^{'k}); f_{2ij}^k; (f_{3ij}^{'k}, f_{3ij}^k)]$, where $\tilde{f}_{ij}^k$ is the performance rating of j^{th} strategy with respect to i^{th} criterion as obtained from decision maker 'k'.

Step 4. Obtain IVF weights of criteria using IVF-AHP method.

The IVF weights for criteria and aspects can be calculated by using IVF-AHP method. The calculation steps of IVF-AHP method are as follows:

i. Construct the fuzzy positive reciprocal matrix.

Using Table 6.3, replace the linguistic variables' scores of pair-wise comparison by triangular IVF numbers to construct the IVF positive reciprocal matrices. According to Buckley (1985), fuzzy positive reciprocal matrix for decision maker '*k*' can be defined as follows:

$$\tilde{C}^k = [\tilde{c}_{ij}^k]_{n \times n} \; ; \; i, j = 1, 2, 3, .., n$$

$$\tilde{c}_{ij}^k = 1, \text{ for } i = j$$

$$\tilde{c}_{ji}^k = \frac{1}{\tilde{c}_{ij}^k}, \text{ for } i \neq j$$

Where $\tilde{c}_{ij}^k$, a triangular IVF number is represented as $\tilde{c}_{ij}^k = [(c_{1ij}^k, c_{1ij}^{'k}); c_{2ij}^k; (c_{3ij}^{'k}, c_{3ij}^k)]$ and n is the number of criteria considered in the matrix. The reciprocal of IVF number $\tilde{c}_{ij}^k$ is

$\frac{1}{\tilde{c}_{ij}^k}$ and defined as $\frac{1}{\tilde{c}_{ij}^k}=[(\frac{1}{c_{3ij}^k},\frac{1}{c_{3ij}^{'k}});\frac{1}{c_{2ij}^k};(\frac{1}{c_{1ij}^{'k}},\frac{1}{c_{1ij}^k})]$. Naturally the reciprocal IVF number of $\tilde{c}_{ij}^k$ has sense if any real number involved in the definition of $\tilde{c}_{ij}^k$ is different from zero.

ii. Compute the interval-valued fuzzy weights of criteria and sub-criteria.

To facilitate the weight computations, apply α-cut to decompose the IVF reciprocal matrix into crisp matrices. For decision maker *'k'*, let $\alpha=1$ to construct a matrix $C_2^k=[c_{2ij}^k]_{n\times n}$ and let $\alpha=0$ to construct four matrices; $C_1^k=[c_{1ij}^k]_{n\times n}, C_1^{'k}=[c_{1ij}^{'k}]_{n\times n}, C_3^k=[c_{3ij}^k]_{n\times n}$ and $C_3^{'k}=[c_{3ij}^{'k}]_{n\times n}$ in accordance with fuzzy reciprocal numbers. For example, C_1^k is defined by Eq.(6.4).

$$C_1^k=[c_{1ij}^k]_{n\times n}=\begin{bmatrix} 1 & c_{112}^k & \dots & c_{11n}^k \\ c_{121}^k & 1 & \dots & c_{12n}^k \\ \dots & \dots & \dots & \dots \\ c_{1n1}^k & c_{1n2}^k & \dots & 1 \end{bmatrix} \quad (6.2)$$

To ensure the consistency of decision makers' opinions towards the criteria weights, calculate the $\lambda_{\max}$ for each crisp matrix. Then, the consistency index (*CI*) for each matrix can be computed using Eq. (6.3). Based on the *CI* and random index (*RI*), calculate the consistency ratio (*CR*) using Eq. (6.2). If $CR \geq 0.1$, then, the decision makers should be asked to reconsider their opinions.

Using AHP method on crisp matrices obtained in step A, determine the five crisp weight matrices $W_1^k=[w_{1i}^k], W_1^{'k}=[w_{1i}^{'k}], W_2^k=[w_{2i}^k], W_3^{'k}=[w_{3i}^{'k}]$ and $W_3^k=[w_{3i}^k]$ for i= 1, 2, …, *n*. For example, W_1^k matrix is obtained as:

$$W_1^k = [w_{1i}^k] = \begin{bmatrix} w_{11}^k \\ w_{12}^k \\ \vdots \\ w_{1n}^k \end{bmatrix} \tag{6.3}$$

To obtain the IVF weight matrix, it is required that these five crisp weight matrices are combined to obtain the five values (lower-bound values $(w_{1i}^k, w_{1i}^{'k})$, central value (w_{2i}^k) and upper bound values $(w_{3i}^{'k}, w_{3i}^k)$) of IVF weight of each criterion.

It is seen that combining weight matrices ($W_1^k, W_1^{'k}, W_2^k, W_3^{'k}$ and W_3^k) to obtain the IVF weights may result into IVF sets that are not normal IVF sets. To ensure the IVF weights are still normal IVF sets; use the equations (6.4)-(6.11) to adjust the weights. According to the method suggested by Csutora and Buckley (2001), constants ($Q_1^{'k}$) and ($Q_3^{'k}$) are computed by using Eqs. (6.4) & (6.5). These constants are used to adjust the lower and upper bounds of the Lower Membership Functions of the weights using Eqs (6.6) & (6.7).

$$Q_1^{'k} = \min\{\frac{w_{2i}^k}{w_{1i}^{'k}} \mid 1 \le i \le n\} \tag{6.4}$$

$$Q_3^{'k} = \max\{\frac{w_{2i}^k}{w_{3i}^{'k}} \mid 1 \le i \le n\} \tag{6.5}$$

After computing $Q_1^{'k}$ and $Q_3^{'k}$; the adjusted weight matrices, $W_{1i}^{'k*}$ and $W_{3i}^{'k*}$ can be calculated as follows:

$$W_{1i}^{'k*} = [w_{1i}^{'k*}], \text{ where; } w_{1i}^{'k*} = Q_1^{'k} w_{1i}^{'k}, i = 1,2,3\ldots.., n \tag{6.6}$$

$$W_{3i}^{'k*} = [w_{3i}^{'k*}], \text{ where; } w_{3i}^{'k*} = Q_3^{k} w_{3i}^{'k}, i = 1,2,3\ldots.., n \tag{6.7}$$

Now, use the adjusted weight matrices ($W_{1i}^{'k*}$ and $W_{3i}^{'k*}$) to compute the constants (Q_1^k) and (Q_3^k) by using Eqs (6.8) & (6.9). The adjusted lower and upper bounds of Upper Membership Functions (*UMFs*) of the weights are computed by using Eqs (6.10) & (6.11).

$$Q_1^k = \min\{\frac{w_{1i}^{'k*}}{w_{1i}^k} \mid 1 \le i \le n\} \tag{6.8}$$

$$Q_3^{'k} = \max\{\frac{w_{3i}^{'k*}}{w_{3i}^k} \mid 1 \le i \le n\} \tag{6.9}$$

Using the constants Q_1^k and Q_3^k, the adjusted lower and upper bound values (W_{1i}^{k*} and W_{3i}^{k*}) of the *UMFs* of weights can be obtained as:

$$W_{1i}^{k*} = [w_{1i}^{k*}], \text{ where; } w_{1i}^{k*} = Q_1^k w_{1i}^k, i = 1,2,3\ldots.., n \tag{6.10}$$

$$W_{3i}^{k*} = [w_{3i}^{k*}], \text{ where; } w_{3i}^{k*} = Q_3^k w_{3i}^k, i = 1,2,3\ldots.., n \tag{6.11}$$

Combining adjusted weight matrices ($W_{1i}^{k*}, W_{1i}^{'k*}, W_{2i}^{k*}, W_{3i}^{'k*}, W_{3i}^{k*}$), the IVF weight for decision maker '*k*' can be obtained as follows:

$$\tilde{W}_i^k = [w_{1i}^{k*}, w_{1i}^{'k*}, w_{2i}^{k*}, w_{3i}^{'k*}, w_{3i}^{k*}], i = 1,2,3\ldots.., n \tag{6.12}$$

Step 5. Calculate the aggregate weights ($\tilde{w}_i$) and performance ratings ($\tilde{f}_{ij}$)

The aggregate weight of each criterion and performance ratings of strategies with respect to each criterion are computed by using equations (6.13) and (6.14), respectively. The Min-Max aggregation method is applied to achieve balance between pessimistic and optimistic evaluations by considering disjunctive and conjunctive behaviours of decision makers (Detyniecki et al., 2000). The upper and lower bound values of *UMF* of IVF numbers are obtained by Min and Max aggregation methods, respectively. Other values of IVF numbers are aggregated by using the arithmetic mean operator that does not represent any behavioural property (Detyniecki et al., 2000).

The relative IVF weight of i^{th} criterion can be represented by $\tilde{w}_i = [(w_{1i}, w_{1i}^{'}); w_{2i}; (w_{3i}^{'}, w_{3i})]$, i= 1,2,3…,n and computed as

$$w_{1i} = \min\,(w_{1i}^{k*}),\ \ w_{1i}^{'} = \frac{1}{p}\sum_{k=1}^{p} w_{1i}^{'k*},\ w_{2i} = \frac{1}{p}\sum_{k=1}^{p} w_{2i}^{k*},\ w_{3i}^{'} = \frac{1}{p}\sum_{k=1}^{p} w_{3i}^{'k*},\ \ w_{3i} = \max\,(w_{3i}^{k*}) \quad (6.13)$$

Where $k = 1, 2, ..., p$ and p is the numbers of decision makers.

The performance rating of j^{th} strategy with respect to i^{th} criterion can be represented by

$\tilde{f}_{ij} = [(f_{1ij}, f_{1ij}^{'}); f_{2ij}; (f_{3ij}^{'}, f_{3ij})]$, i= 1,2,3….., n and j=1,2,3…..,m and computed as

$$f_{1ij} = \min\,(f_{1ij}^{k}),\ \ f_{1ij}^{'} = \frac{1}{p}\sum_{k=1}^{p} f_{1ij}^{'k},\ f_{2ij} = \frac{1}{p}\sum_{k=1}^{p} f_{2ij}^{k},\ f_{3ij}^{'} = \frac{1}{p}\sum_{k=1}^{p} f_{3ij}^{'k},\ \ f_{3ij} = \max\,(f_{3ij}^{k}) \quad (6.14)$$

Where $k = 1, 2, ..., p$ and p is the numbers of decision makers.

It should be noted that Eq. (6.13) provides the local weights of indicators or aspects at the respective level of hierarchy. Once local weights are calculated, global weights can be calculated by combining local weights with respect to all successive hierarchal levels(Liberatore, 1987).

Step 6.Defuzzify the IVF criteria weights ($\tilde{w}_i$) and performance ratings ($\tilde{f}_{ij}$) of strategies with respect to each criterion to get the crisp values.

In this study, centre of area (COA) defuzzification method was applied to obtain crisp values. For an IVF set $\tilde{A}$ with a membership function $\mu_{\tilde{A}}(x)$; $x \in X$, the centroid (

$C_{\tilde{A}}$) can be computed in terms of $[c_l, c_r]$. The c_l and c_r are respectively maximum and minimum of centroids of all embedded type-1 fuzzy sets in the Footprint of Uncertainty (*FOU*) of set $\tilde{A}$. Karnik and Mendel (2001) demonstrated that c_l and c_r can be computed from the *LMF* and *UMF* of IVF set $\tilde{A}$ as follows:

Steps for calculating the parameter c_l

For each IVF set, we initialize the value of θ_i by setting

$$\theta_i = \frac{1}{2}(LMF(\tilde{A} \mid x_i) + UMF(\tilde{A} \mid x_i)), i = 1, 2, ...N \tag{6.15}$$

and then compute the value

$$c_i = \frac{\sum_{i=1}^{N} x_i \theta_i}{\sum_{i=1}^{N} \theta_i} \tag{6.16}$$

Without loss of generality, we assume that $x_1 \leq x_2 \leq ..... \leq x_N$. Formula (6.16) implies that we can find an index $L \in \{1, ..., N-1\}$ such that $x_L \leq c_i \leq x_{L+1}$.

Set $\theta_i = UMF(\tilde{A} \mid x_i)$ if $i \leq L$ and $\theta_i = LMF(\tilde{A} \mid x_i)$ if $i \geq L+1$. Then calculate the value of c_l as

$$c_l = \frac{\sum_{i=1}^{L} x_i UMF(\tilde{A} \mid x_i) + \sum_{i=L+1}^{N} x_i LMF(\tilde{A} \mid x_i)}{\sum_{i=1}^{L} UMF(\tilde{A} \mid x_i) + \sum_{i=L+1}^{N} LMF(\tilde{A} \mid x_i)} \tag{6.17}$$

If $c_l = c_i$ then stop else $c_i := c_l$ and go to step 3.

Steps for calculating the parameter c_r

For each IVF set, we initialize the value of θ_i by Formula (6.15) and calculate the value of c_i by Formula (6.16).

Without loss of generality, we assume that $x_1 \le x_2 \le ..... \le x_N$. Formula (6.16) implies that we can find an index $R \in \{1,...., N\text{-}1\}$ such that $x_R \le c_i \le x_{R+1}$ (Initially *R*=*L*).

Set $\theta_i = LMF(\tilde{A} \mid x_i)$ if $i \le R$ and $\theta_i = UMF(\tilde{A} \mid x_i)$ if $i \ge R+1$. Then calculate the value of c_r as

$$c_r = \frac{\sum_{i=1}^{R} x_i LMF(\tilde{A} \mid x_i) + \sum_{i=R+1}^{N} x_i UMF(\tilde{A} \mid x_i)}{\sum_{i=1}^{R} LMF(\tilde{A} \mid x_i) + \sum_{i=R+1}^{N} UMF(\tilde{A} \mid x_i)} \tag{6.18}$$

If $c_r = c_i$ then stop else $c_i := c_r$ and go to step 3.

The value of centroid ($C_{\tilde{A}}$) of the IVF set $\tilde{A}$ is computed as follows:

$$C_{\tilde{A}} = \frac{c_l + c_r}{2} \tag{6.19}$$

Considering the computational complexity involved with defuzzification of IVF numbers, MATLAB® based IT2FLS (Interval type-2 fuzzy logic system, a free available software from '*http://sipi.usc.edu/~mendel/software/*')was used for the implementation of KM algorithm.

Step 7. Determine the best rating f_i^+ and worst rating f_i^- for all the criteria.

If criteria symbolize benefit, then

$f_i^+ = \max_j f_{ij}$ and $f_i^- = \min_j f_{ij}$

Step 8. Measure the utility (S_j), Regret (R_j) and VIKOR indices (Q_j) for j=1, 2… m by using the following equations;

$$S_j = \sum_{i=1}^{n} \frac{w_i\,(f_i^+ - f_{ij})}{(f_i^+ - f_i^-)} \qquad (6.20)$$

$$R_j = \max_i \left(\frac{w_i\,(f_i^+ - f_{ij})}{(f_i^+ - f_i^-)}\right) \qquad (6.21)$$

$$Q_j = \frac{v(S_j - S_j^+)}{(S_j^- - S_j^+)} + \frac{(1-v)(R_j - R_j^+)}{(R_j^- - R_j^+)} \qquad (6.22)$$

where;

$S^+ = \min_j S_j$, $\qquad S^- = \max_j S_j$

$R^+ = \min_j R_j$, $\qquad R^- = \max_j R_j$

and 'v' is the weight of decision making strategy or the maximum group utility. The compromise can be selected with "voting by majority" (v>0.5), with "consensus" (v=0.5), or with "veto" (v<0.5). The strategy having smallest VIKOR value (Q_j) is considered to be best solution.

Step 9. Rank the strategies by sorting each S_j, R_j and Q_j values in increasing order.

The outcome is a set of three ranking lists. Propose the strategy j_1 equivalent to Q_1 (smallest among Q_j values) as a compromise solution if

Condition 1[C1]: The strategy j_1 has an acceptable advantage; e.g. $Q_2 - Q_1 \geq DQ$,where; $DQ = \frac{1}{m-1}$ and m is number of strategies.

Condition 2[C2]: The strategy $j_1$is stable within the decision-making process. In other words, it is also the best ranked in S or R ranking lists.

If one of the above conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

Alternatives j_1 and j_2 , $Q_{j_2} = Q_2$ where if and only when condition **[C2]** is not satisfied.

Alternatives $j_1, j_2, ..., j_m$ if the condition **[C1]** is not satisfied; and j_m is ascertained by the relation $Q_m - Q_1 \geq DQ$ for maximum *m* where, $Q_{j_m} = Q_m$.

The best strategy ranked by Q is the one with the minimum value of Q . Ranking of strategies may be performed by different value of weight of maximum group utility (*v*). The compromise solution obtained with initial maximum group utility (*v*) value will be replaced if (*v*) is not within the stability interval. VIKOR is a helpful tool in multi-criteria decision-making, particularly in a situation where the decision-maker is not able or does not know how to express their preferences at the beginning of system design (Opricovic & Tzeng, 2004).

6.5 Illustrative Example

The proposed method has been designed for sustainable manufacturing strategy selection from a holistic and comprehensive approach. In this section, a case study is used to illustrate the application of this method. Case company (hereafter known as ABC due to confidentiality issue) is a manufacturing small and medium enterprise that strives to select a suitable strategy to enhance overall sustainability. The proposed method is designed considering the uncertainties in decision making related to sustainable manufacturing in ABC. The usage of materials and resources are considered very important for sustainable manufacturing in ABC. Therefore, in this study, sustainable strategies are considered to include waste minimization, material efficiency, resource efficiency, and eco-efficiency. In order to implement proposed method, data collection has been carried out to get the inputs to the proposed method aimed at selecting the best strategy for sustainable manufacturing.

6.5.1 Data Collection

There are three decision makers in the ABC from whom inputs have been collected. Decision makers in this company are either managers or senior managers, and they are the head of respective departments. Three decision makers (who participated in this study) are Manager (quality assurance), who is also responsible for sustainability initiatives in the company, Senior Manager (finance) and Manager (production). The procedure for data collection has been illustrated as follows:

a. Decision makers have been asked to identify the selection criteria pertinent to ABC Company from economic, environmental, and social aspects. The hierarchy of the problem is shown in Figure 6.3.

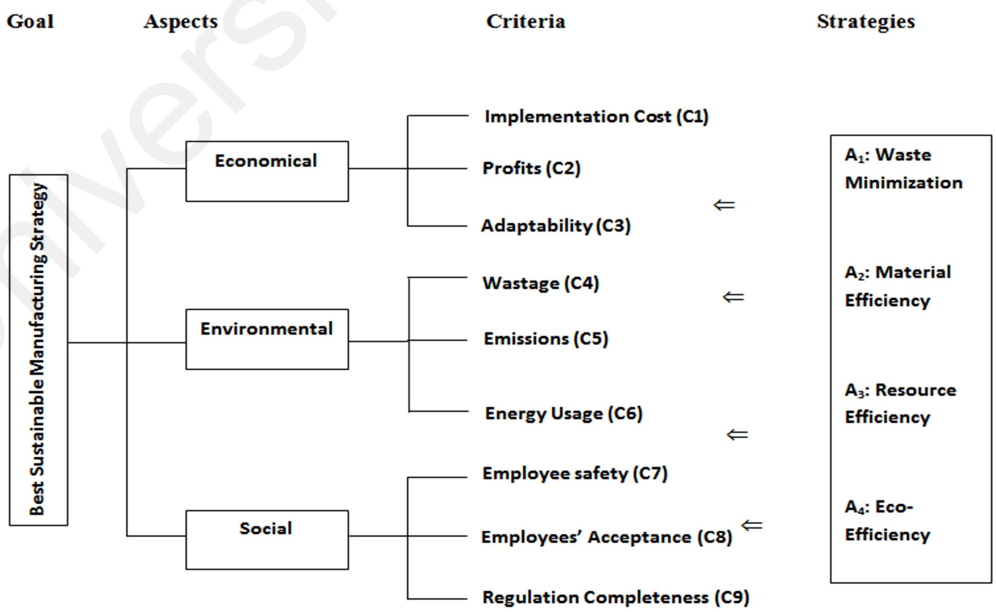


Figure 6.3: Hierarchy structure for the case study

b. Decision makers' opinion towards the pair-wise comparison importance weights of criteria and aspects must be recorded in terms of linguistic variables. Decision makers were also asked for their perception towards rating of strategies against selected criteria as shown in Figure 6.3.

The pair-wise comparison matrix in terms of linguistic variables from decision makers' opinion has been recorded as shown in Table 6.4. Decision makers were asked to evaluate the performance rating of strategies for the selected criteria using linguistic variables (Table 6.5).

Table 6.4: Fuzzy comparison matrixes for aspects and criteria

Aspects					Economic criteria				
		ECO	ENV	SOC			C1	C2	C3
DM1	ECO	VL	MI	SI	DM1	C1	VL	VL	VSI
	ENV		VL	MI		C2		VL	EI
	SOC			VL		C3			VL
DM2	ECO	VL	SI	SI	DM2	C1	VL	MI	EI
	ENV		VL	MI		C2		VL	VSI
	SOC			VL		C3			VL
DM3	ECO	VL	VL	MI	DM3	C1	VL	MI	EI
	ENV		VL	MI		C2		VL	VSI
	SOC			VL		C3			VL

Environmental Criteria					Social criteria				
		C4	C5	C6			C7	C8	C9
DM1	C4	VL	VL	MI	DM1	C7	VL	SI	MI
	C5		VL	VL		C8		VL	SI
	C6			VL		C9			VL
DM2	C4	VL	MI	SI	DM2	C7	VL	VSI	MI
	C5		VL	MI		C8		VL	VSI
	C6			VL		C9			VL
DM3	C4	VL	MI	MI	DM3	C7	VL	SI	SI
	C5		VL	MI		C8		VL	SI
	C6			VL		C9			VL

Table 6.5: Decision Makers' (DMs) assessments of strategies based on each criterion

		C1	C2	C3	C4	C5	C6	C7	C8	C9
DM1	A1	G	MG	VG	VG	VG	G	G	MG	VP
	A2	VG	F	MP	MG	MP	VG	MP	F	F
	A3	MG	G	G	VG	VG	VG	G	P	G
	A4	F	VG	G	MG	F	VG	G	VP	P
DM2	A1	VG	F	VG	G	VG	G	MG	G	VP
	A2	VG	MP	F	MG	P	MG	F	P	MP
	A3	G	MG	G	VG	VG	G	G	P	G
	A4	MG	G	VG	F	MG	MG	VG	VP	VP
DM3	A1	MG	G	G	VG	VG	VG	MG	F	P
	A2	G	MG	F	G	MP	G	MP	MG	F
	A3	F	VG	MG	G	VG	MG	VG	P	G
	A4	MP	VG	MG	MG	P	F	VG	VP	MP

6.5.2 Implementation and Results

During the implementation and the result extraction process, linguistic values obtained during the data collection process were replaced by corresponding IVF numbers as shown in Table 6.2&6.3. The AHP method was applied to calculate the IVF weighs as discussed in section 6.4.1 (Step 4). All crisp matrices were examined for consistency by obtaining the consistency index of corresponding positive reciprocal matrixes. In the case of inconsistency, decision makers were asked to re-evaluate their opinions. This process was continued until the consistency ratio for all comparison matrixes became less than or equal to 0.10.

Using Min-Max aggregation method(Section 6.4.1, Step 5), varied opinions of decision makers were combined to obtain IVF weights of aspects and criteria and performance rating of strategies with respect to these criteria as shown in Table 6.6&6.7.

Table 6.6: Interval valued fuzzy weights of aspects and criteria

Aspects / Criteria	Local Weights	Global weights
Economical	**[(0.34,0.57);0.58;(0.58,0.69)]**	**[(0.34,0.57);0.58;(0.58,0.69)]**
Implementation cost (C1)	[(0.44,0.53);0.58;(0.58,0.71)]	[(0.15,0.30);0.34;(0.34,0.49)]
Profits (C2)	[(0.27,0.31);0.36;(0.38,0.47)]	[(0.09,0.20);0.21;(0.22,0.32)]
Adaptability (C3)	[(0.05,0.06);0.06;(0.06,0.07)]	[(0.02,0.03);0.03;(0.03,0.05)]
Environmental	**[(0.16,0.29);0.29;(0.30,0.43)]**	**[(0.16,0.29);0.29;(0.30,0.43)]**
Wastages (C4)	[(0.32,0.51);0.55;(0.57,0.63)]	[(0.05,0.15);0.16;(0.17,0.27)]
Emissions (C5)	[(0.21,0.28);0.29;(0.30,0.36)]	[(0.03,0.08);0.08;(0.09,0.16)]
Energy usage (C6)	[(0.11,0.15);0.16;(0.17,0.32)]	[0.02,0.04);0.05;(0.05,0.14)]
Social	**[(0.10,0.12);0.13;(0.15,0.29)]**	**[(0.10,0.12);0.13;(0.15,0.29)]**
Employee safety (C7)	[(0.47,0.59);0.61;(0.63,0.66)]	[(0.05,0.07);0.08;(0.09,0.19)]
Employee Acceptance (C8)	[(0.24,0.28);0.28;(0.29,0.32)]	[(0.02,0.03);0.04;(0.04,0.09)]
Regulation completeness (C9)	[(0.09,0.10);0.10;(0.12,0.21)]	[(0.01,0.01);0.01;(0.02,0.06)]

Table 6.7: Aggregated fuzzy interval values of strategies' ratings

Strategies → Criteria ↓	A1	A2	A3	A4
C1	[(4.5,7.5);8.67;(9.17,10)]	[(5.5,8.83);9.67;(9.83,10)]	[(2.5,5.5);7;(8,10)]	[(0,3.5);5;(6.33,9.5)]
C2	[(2.5,5.5);7;(8,10)]	[(0,3.5);5;(6.33,9.5)]	[(4.5,7.5);8.67;(9.17,10)]	[(5.5,8.83);9.67;(9.83,10)]
C3	[(5.5,8.83);9.67;(9.83,10)]	[(0,2.83);4.33;(5.83,7.5)]	[(4.5,6.83);8.33;(9,10)]	[(4.5,7.5);8.67;(9.17,10)]
C4	[(5.5,8.83);9.67;(9.83,10)]	[(4,6.17);7.67;(8.5,10)]	[(5.5,8.83);9.67;(9.83,10)]	[(2.5,4.83);6.33;(7.5,9.5)]
C5	[(8.5,9.5);10;(10,10)]	[(0,1.17);2.33;(3.83,5.5)]	[(8.5,9.5);10;(10,10)]	[(0,3.17);4.33;(5.67,9.5)]
C6	[(5.5,8.17);9.33;(9.67,10)]	[(4.5,7.5);8.67;(9.17,10)]	[(4.5,7.5);8.67;(9.17,10)]	[(2.5,6.17);7.33;(8.17,10)]
C7	[(4.5,6.17);7.67;(8.5,10)]	[(0,2.17);3.67;(5.17,7.5)]	[(5.5,8.17);9.33;(9.67,10)]	[(5.5,8.88);9.67;(9.83,10)]
C8	[(2.5,5.5);7;(8,10)]	[(0,2.83);4.33;(5.83,7.5)]	[(0,0.5);1;(2.5,3.5)]	[(0,0);0;(1,1.5)]
C9	[(0,0.17);0.33;(1.5,3.5)]	[(0,2.83);4.33;(5.83,7.5)]	[(5.5,7.5);9;(9.5,10)]	[(0,0.67);1.33;(2.67,5.5)]

In order to obtain the crisp values of strategies' ratings and criteria weights based on centre of area method (COA), Karnik-Mendal (KM) algorithms for IVF numbers was applied in this study (Section 6.4.1, Step 6). The Crisp values for strategies' performance ratings with respect to each criterion and weights of criteria are shown in Table 6.8.

Table 6.8: Crisp values of strategies' ratings with respect to criteria and weights of criteria

	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	8.03	6.64	8.78	8.78	9.63	8.61	7.41	6.64	1
A2	8.78	4.79	4.12	7.41	2.53	8.03	3.69	4.12	4.12
A3	6.64	8.03	7.81	8.78	9.63	8.03	8.61	1.42	8.34
A4	4.87	8.78	8.03	5.21	4.52	6.86	8.78	0.42	1.94
weights	0.32	0.20	0.03	0.16	0.09	0.06	0.09	0.04	0.02

Using step 7 (Section 6.4.1), the best values f_i^+ and worst values f_i^- of crisp performance ratings of strategy with respect to each criterion were identified and are shown in Table 6.9.

Table 6.9: Best rating f_i^+ and worst rating f_i^- for each criterion

	C1	C2	C3	C4	C5	C6	C7	C8	C9
f_i^+	8.78	8.78	8.78	8.78	9.63	8.61	8.78	6.64	8.34
f_i^-	4.87	4.79	4.12	5.21	2.53	6.86	3.69	0.42	1

As per step 8 (section 6.4.1),using equations (6.20), (6.21) and (6.22), the utility *(S),* regret *(R)* and VIKOR index ($Q_{v=0.5}$) of all strategies were calculated as shown in Table 6.10. As mentioned above, *v* is the weight of the strategy of the majority of criteria. Here, we can use *v*=0.50 for final ranking (Opricovic & Tzeng, 2004; Sanayei et al., 2010).

Table 6.10: The values of *S* (utility), *R* (Regret) and $Q_{v=0.5}$ (VIKOR value) for all strategies

	Strategies for sustainable manufacturing			
	A_1	A_2	A_3	A_4
S	0.221	0.542	0.286	0.683
R	0.111	0.207	0.178	0.325
$Q_{v=0.5}$	0	0.828	0.354	1

Based on the *S, R* and *Q* values (Section 6.4.1, Step 9), strategies were ranked as shown in Table 6.11.

Table 6.11: The ranking of strategies by *S, R* and *Q* values in increasing order

	Ranking of strategies			
	1	2	3	4
By S	A_1	A_3	A_2	A_4
By R	A_1	A_3	A_2	A_4
By $Q_{v=0.5}$	A_1	A_3	A_2	A_4

The compromise solution, closest to ideal solution was achieved as strategyA_1. The difference in VIKOR values ($Q_{v=0.5}$) of A_1 and A_3 (strategy with minimum value and strategy next to this) is 0.354> ($\frac{1}{m-1}$) where *m* is the number of strategies. Strategy A_1 is selected for implementation based on its smallest VIKOR value *(Q)* with *v*=0.5 and is a stable solution as it satisfies the condition 2 mentioned in step 9 of section 6.4.1.

6.5.3 Sensitivity Analysis

As mentioned above, the proposed method is based on combining concepts of VIKOR and AHP in an IVF environment, where this method can be applied to individual or group of evaluators according to their own preferences to select their ideal strategy. In this section, the results of the proposed method concerning rationality and discriminatory ability are examined. Here, the analytic technique was borrowed from the concepts of sensitivity analysis.

Table 6.12: Values of Q_j for different values of $v(0 \le v \le 1)$

v	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Q1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Q2	0.743	0.760	0.777	0.794	0.811	0.828	0.846	0.863	0.880	0.897	0.914
Q3	0.358	0.357	0.356	0.356	0.355	0.354	0.353	0.353	0.352	0.351	0.350
Q4	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

The proposed method is verified for rationality and stability by using the concept of sensitivity analysis when maximum utility values *(v)* do not affect the results. This analysis is performed by decreasing and increasing the *v* value from 0 to 1 by the step of 0.1. Table 6.12 illustrates the results of sensitivity analysis for four strategies under consideration. Also, Fig 6.4 illustrates a graphical representation of these strategies. According to sensitivity analysis results, ranking of strategies is as same as previous main ranking. The strategies show a straight line or nearly straight-line trend, and their positions are stable in new ranking, while changing the value of maximum utility value (v).Based on the above results from the proposed method, this study can show that the proposed method can easily select the best strategy.

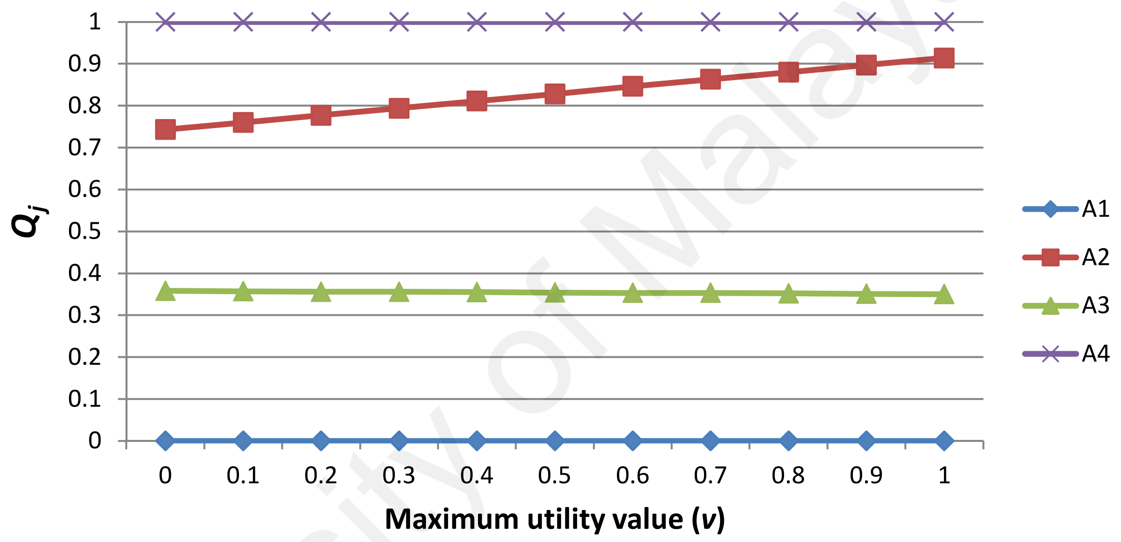


Figure 6.4: Ranking of preference order of strategies after sensitivity analysis

6.6 Summary

The strategy selection problem for sustainable manufacturing is often influenced by uncertainty in real situations, and in such a situation, interval-valued fuzzy set theory is an appropriate tool to cope with this kind of problems. This chapter presented an integrated AHP-VIKOR method to select sustainability strategy for manufacturing organization under IVF environment to deal with incommensurable and conflicting criteria. The rationality and validity of the proposed method were established by performing a sensitivity analysis. It can be seen that this method has some advantages, which may be useful in dealing with a strategy selection problem for sustainable manufacturing. This method enables us to determine the ranking of sustainability strategies for manufacturing organizations. The proposed method for strategy selection can also be easily extended to other disciplines as a decision-making tool for alternative/strategy selection.

CHAPTER 7: DEVELOPMENT OF AN EXPERT SYSTEM FOR PERFORMANCE ASSESSMENT AND STRATEGY SELECTION FOR SUSTAINABLE MANUFACTURING

7.1 Introduction

Sustainable manufacturing decision making problems in manufacturing SMEs are complex problem which requires expert's reasoning about knowledge. Generally, manufacturing SMEs lack the manpower of these skill sets and also accessibility to the tools available for decision making. Therefore, a web-based expert system is of a great help to manufacturing SMEs to carry out the decision making related to sustainable manufacturing. An expert system is a computer system that emulates the decision making ability of a human expert. The expert system is also known as knowledge-based system which is composed of two sub-systems: (1) knowledge base and (2) inference engine (Smith, 1985). The knowledge base represents the facts about the real world. The inference engine evaluates the current state of knowledge base, applies relevant rules and arrives at particular conclusion. This chapter proposes a fuzzy rule-based expert system for sustainable manufacturing decision making in SMEs.

The proposed expert system has two components: (1) sustainability evaluation and (2) strategy selection. The initial set of measures and metrics which are important and applicable were identified by conducting an empirical study among the Malaysian manufacturing SMEs (See chapter 4). The measures for performance assessment were classified based on the three aspects of Triple Bottom Line (TBL) which are economic, environmental and social. Sixteen metrics for each aspect were identified and categorized under four economic, five environmental and three social measures. Considering the involvement of human reasoning in the decision making process of manufacturing SMEs, it is proposed to gather the performance ratings of the organization with respect to metrics and importance weights of metrics in terms of linguistic variables. The fuzzy rule-based expert system is proposed to elicit the performances of all the aspects and overall sustainability of the organization. Using a sensitivity analysis during performance assessment, the system is able to identify the important measures to improve the sustainability performance.

The second component of this expert system is based on the VIKOR method to select the best strategy. The important measures obtained during sustainability evaluation process have been considered as selection criteria for strategy selection. The perceived improvement in performance ratings of these measures due to respective strategies is considered as performance ratings of strategies. The expert system also examines the stability of the ranking results using a sensitivity analysis. The implementation results of a manufacturing SME as case company shows the applicability of the proposed system.

The organization of this chapter is as follows. Section 7.2 describes the research design while section 7.3 discusses the development of the web-based expert system. A case study is used to demonstrate and evaluate the expert system in section 7.4, and the results obtained are discussed in section 7.5. Finally, summary and recommendations are presented in the section 7.6.

7.2 Research Design

The purpose of this study is to develop a web-based expert system that will aid decision makers in the sustainability performance assessment of their manufacturing system and then select the suitable strategy for further improvement. The performance assessment system is based on the evaluation framework adopted from Chapter 4 as shown in Figure 7.1. The strategy selection methodology is based on the perceived improvements in the performance measures due to various strategies under consideration.

The system consists of two modules, first for performance evaluation of sustainable manufacturing and other for strategy selection for further improvement. Sustainability performance assessment is divided into economic, environmental and social performance evaluation. The economic dimension of performance measurement recognizes the metrics effectively measuring relations with customers and suppliers that results in achieving financial goals (Presley et al., 2007). The measures for economic performance are manufacturing cost, quality, responsiveness and flexibility. The environmental performance is all about how well an organization manages the environmental aspects of its activities, products, and services (ISO 14001: 2004).

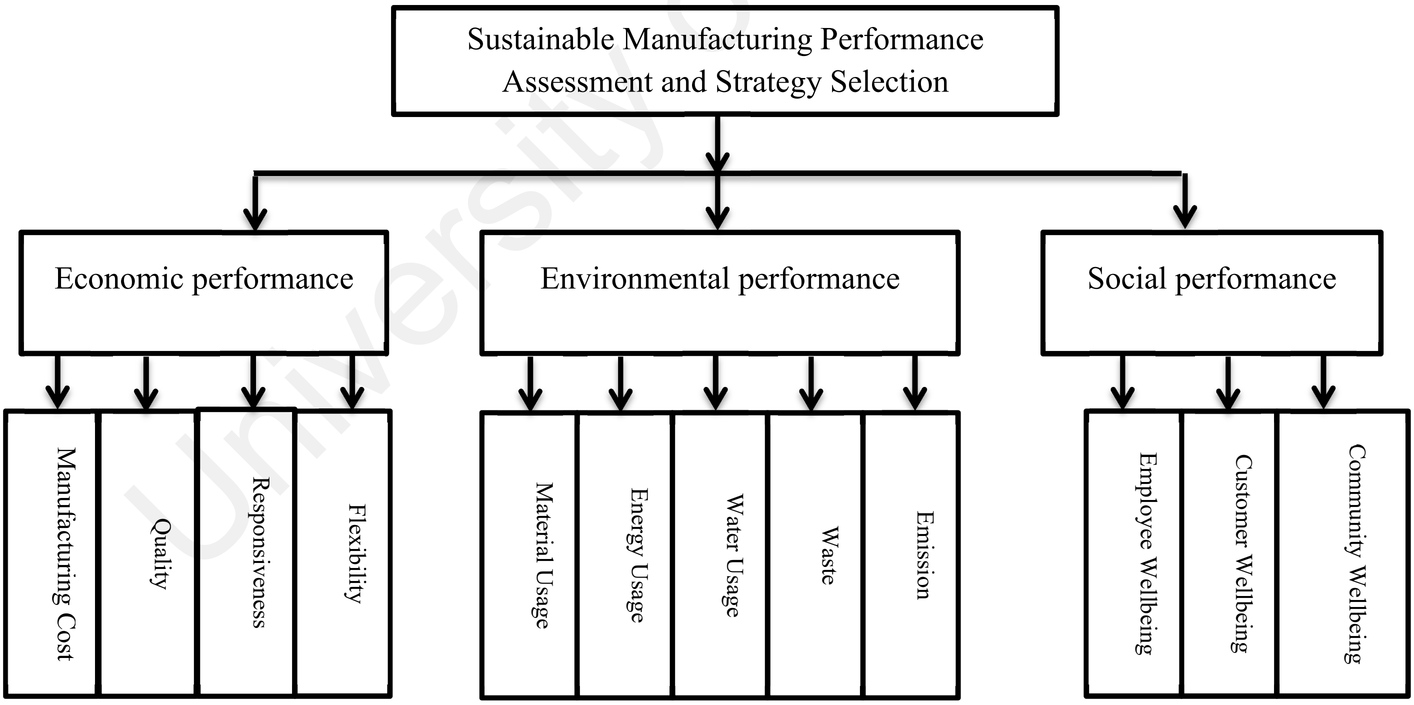


Figure 7.1: Framework for expert system

The measures considered for the environmental aspect of sustainability are material usage, energy usage, water usage, waste, and emission. Social performance assesses how well an organization has translated its social goals into practice. Social performance can be evaluated in terms of the impact of organization's decisions and activities on society that contribute towards sustainable development including health and welfare of society, stakeholder's expectations, compliance with applicable law and integration throughout the organization (ISO 26000: 2010).In this study, the measures for social performances are employee wellbeing, customer wellbeing, and community wellbeing.

The measures and their corresponding metrics that have been considered for development of this expert system for sustainability assessment is presented in Table 7.1 are adopted from Chapter 4. Considering the involvement of human reasoning in manufacturing decision-making, the sustainability evaluation module is based on the fuzzy logic concepts. Using a sensitivity analysis, the evaluation module can also identify the most important measures for sustainability improvement. The important measures identified during the evaluation process can be a suitable basis for strategy selection.

The other module focuses on the selection of best sustainable manufacturing strategy considering the perceived improvements in the important measures that are identified during the evaluation process. Each measure is considered as a selection criterion and the perceived improvement in the performance of the measure is considered as performance rating with respect to that criteria. The compromise solution method, VIKOR, is used to design the strategy selection method. The strategy selection module of the expert system provides the ranking of various strategies under consideration. The system is also able to validate the ranking results by checking the stability of results using sensitivity analysis.

Table 7.1: Performance measures and metrics for sustainable manufacturing

Aspects/ Measures	Metrics
Economic performance	
Manufacturing Cost	Reduction in material cost, cost associated with labour, decrease in energy cost, decrease in delivery cost, increased in recycling cost, reduction in waste disposal cost, increase in environment protection cost
Quality	Increase in delivery reliability, percentage decrease in level of scrap, percentage decrease in level of rework
Responsiveness	Decrease in order lead time, decrease in manufacturing lead time, decrease in product development time
Flexibility	Increase in demand flexibility, increase in delivery flexibility, increase in production flexibility
Environmental performance	
Material Usage	Decrease in material intensity, percentage decrease in virgin material usage, increase in recycled/ remanufactured/ reused material usage, percentage decrease in hazardous material usage
Energy Usage	Decrease in total energy consumption, percentage increase in renewable energy usage, percentage increase in energy saving
Water Usage	Decrease in water total consumption, percentage increase in recycled water usage
Waste	Decrease in total waste generated, increase in level of recyclable/remanufacture/ reusable waste, percentage decrease in landfill, percentage decrease in hazardous material in waste, percentage decrease in waste water
Emission	Decrease in CO_2 emission, decrease in BFCs emission.
Social performance	
Employee Wellbeing	Average number of training hour, decrease in turnover ratio, decrease in number of accidents, increase in job satisfaction, improvement in working conditions, level of employee participation in decision making
Customers Wellbeing	Increase in customers' satisfaction, disclosure of product & service information, level of health and safety assessment of product, availability of take back / warranty
Community Wellbeing	Number of community projects, decrease in number of non-compliance, availability of child labour policy, composition of work force, salary compared to local minimum wages, community involvement in decision making

7.3 Proposed Expert System

This study provides decision makers with a fuzzy-based expert system to evaluate the sustainability performance and then select the suitable strategy on the basis of sustainability evaluation results. The expert system has two modules: (1) sustainability evaluation system and (2) strategy selection system. The following sub-sections present the methodology considered for these two modules.

7.3.1 Sustainability Evaluation System

The evaluation method applied in the expert system is based on the hierarchal fuzzy inference system. In each fuzzy inference system, a set of rules is used to draw the conclusion. In a fuzzy rule-based system, every combination of variables requires a different rule, thus increasing the linguistic variable results into the rule explosion. The linguistic variables used for performance ratings are poor, fair and good, and for importance weights of measures are low, moderate and high.

7.3.1.1 Hierarchal fuzzy model

In order to obtain the final sustainability performance score, the system is divided into two stages as shown in the Figure 7.2. At the first stage, there are three categories of hierarchal fuzzy systems to compute the performances of the three aspects (i.e. Economic performance, environmental performance and social performance). To avoid the rule explosion, it is proposed to use two inputs and three membership functions for each fuzzy system at this stage. The weighted performance of the organization with respect to each measure is considered as input to the fuzzy systems at this stage. The weighted performance values and importance weights of the measures were determined on the basis of performance ratings and importance weights of corresponding indicators. To determine the weighted performance ratings of measures, the following formula has been used in this study.

$$\text{Weighted performance rating of measure} = \frac{\sum_{i=1}^{n} p_i \times w_i}{\sum_{i=1}^{n} w_i} \qquad (7.1)$$

And importance weight of measure= $\frac{1}{n}\sum_{i=1}^{n} w_i$ (7.2)

Where p_i is the performance rating and w_i is the importance weight of corresponding ith indicator, respectively. The performance ratings and importance weights of the indicators will be input by the users when they are using the fuzzy rule-based system to evaluate their sustainability performance.

It should be noted that after selecting two by two inputs if one input variable remains, it would be considered as an output variable of a fuzzy system in that category as shown in Figure 7.2. The first stage is continued until all input variables are accommodated and number of outputs for each category is reduced to one. There are three output variables at first stage, which are considered as input variables at the second stage. At the second stage, the three input variables represent economic, environmental and social aspects. Thus, it is proposed to use three inputs and three membership functions for a fuzzy system at this stage. The output of the second stage of the fuzzy system provides the overall sustainability score (SS) of the performance of the organization.

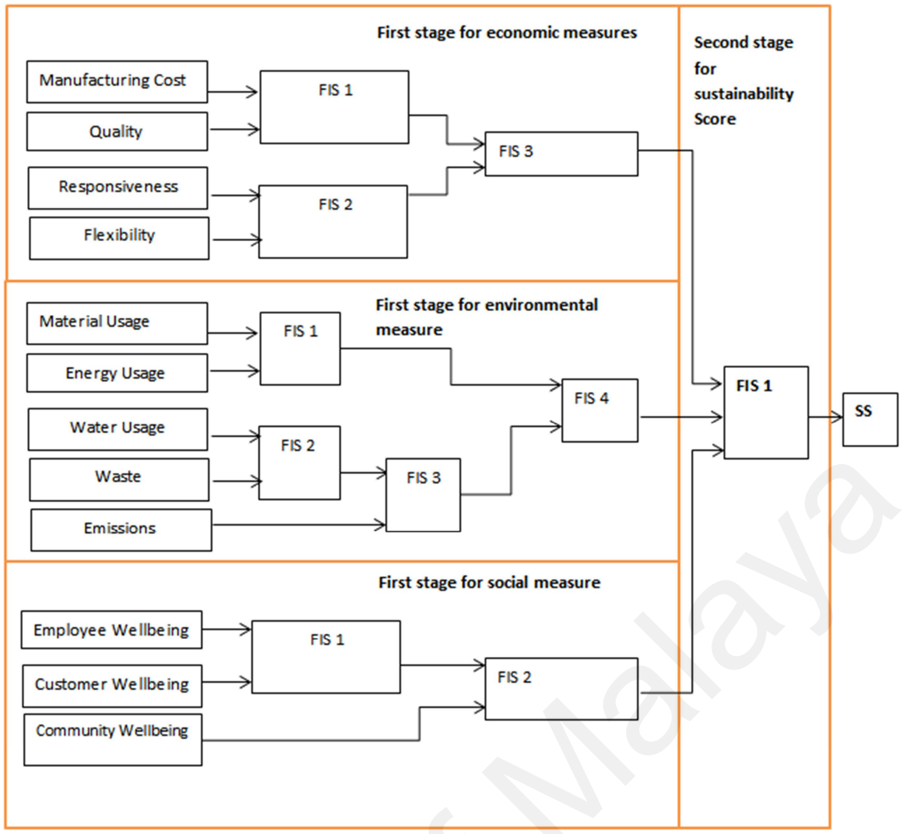


Figure 7.2: Hierarchal structure of fuzzy assessment system

In the rule-based system, the terms following the IF statements of the rule are called the premises while the THEN part of the rule is called the conclusion. The fuzzy AND operator is applied to combine the premise variables. The resulting degree of membership of the logically combined premises is called the adaptability of the premises to the conclusion of the rule ((Olugu & Wong, 2012)Kaufmann, Tobias, & Schulin, 2009). The conclusion part of each rule is a fuzzy singleton, expressed as a word that is associated with a distinct numerical value (Kaufmann et al., 2009). The influence of the premise on the conclusion is given by the implication functions.

The next step involved establishing the full sets of 'If and Then' rules for each system. The fuzzy rule bases for fuzzy systems at first and second stages are presented in Table 7.2 & Table 7.3. A group of experts in the field of sustainable manufacturing were contacted to lend their opinion on the conclusion of the rules.

Table 7.2: Fuzzy rule base matrix for first stage

First Input → / Second Input ↓	Poor	Fair	Good
Poor	Poor	Poor	Fair
Fair	Poor	Fair	Fair
Good	Fair	Fair	Good

Table 7.3: Fuzzy rule base matrix at second stage

First Input	Second Input	Third Input	Output	First Input	Second Input	Third Input	Output
Poor	Poor	Poor	Poor	Fair	Fair	Good	Fair
Poor	Poor	Fair	Poor	Fair	Good	Poor	Fair
Poor	Poor	Good	Poor	Fair	Good	Fair	Fair
Poor	Fair	Poor	Poor	Fair	Good	Good	Fair
Poor	Fair	Fair	Fair	Good	Poor	Poor	Poor
Poor	Fair	Good	Fair	Good	Poor	Fair	Fair
Poor	Good	Poor	Poor	Good	Poor	Good	Fair
Poor	Good	Fair	Fair	Good	Fair	Poor	Fair
Poor	Good	Good	Fair	Good	Fair	Fair	Fair
Fair	Poor	Poor	Poor	Good	Fair	Good	Fair
Fair	Poor	Fair	Fair	Good	Good	Poor	Fair
Fair	Poor	Good	Fair	Good	Good	Fair	Fair
Fair	Fair	Poor	Fair	Good	Good	Good	Good
Fair	Fair	Fair	Fair				

The approach adopted to obtain the conclusion part of the rules involved in the application of the fuzzy methodology. The methodology used the weighted performance ratings of the measures to obtain the 'conclusion' for each rule. The first step was to represent the weighted performance ratings of the measures with fuzzy numbers as shown in Table 7.4. Finally, a defuzzification was carried out to obtain a crisp value of the conclusion for each rule.

Table 7.4: Fuzzy numbers for estimating linguistic variable values

Performance Ratings	
Linguistic variable	Triangular Fuzzy number
Poor	(1, 1, 4)
Fair	(2,4,6)
Good	(4,7,7)

7.3.1.2 Sensitivity analysis

Sensitivity analysis plays an important role in the decision making process of determining the effects of a change in the decision parameter on overall performance. This section attempts to help decision-makers to select the appropriate strategy by sustainability evaluation in given scenario. A scenario is defined by the available set of sustainability indicators. The change in the values of indicators and resulting change in the sustainability scores observed, the decision makers could identify the most important indicators to improve the sustainability performance. The sustainability assessment sub-system is able to perform the sensitivity analysis on the concept built upon in Section 5.4.10.3.

7.3.2 Strategy Selection System

Once performance assessment results are obtained, then the next step for sustainability improvement is to select the suitable strategy to make the required adjustment in the existing practices. The selection of best strategy is proposed on the basis of perceived improvement in the performance of measures. The list of important measures obtained during the sensitivity analysis can be considered as selection criteria for strategy selection. The measures with higher values of scaled gradient have more impact on the overall sustainability improvement. However, this system provides flexibility to user to include or exclude any measure for further analysis.

7.3.2.1 Strategy selection model

For strategy selection, assuming that there are j number of strategies named as A_1, A_2... A_j under consideration. The proposed system requires the importance weighted and perceived improvements in the performance of all criteria (i.e. Measures with high scaled gradient values) due to the implementation of various strategies. Importance weights of measures based on the importance of corresponding indicator were obtained during the performance assessment phase as:

Importance weight of measure= $\frac{1}{n}\sum_{i=1}^{n} w_i$

Where w_i is the importance weightage of i[th] indicator of corresponding measure.

The level of perceived improvement in the performance of measures with respect to various strategies will be input by the user when they are using the strategy selection module of the system to select the best strategy. The level of perceived improvements of measures are inputs in linguistic terms using 7-point Likert's scale (1=No improvement, 2=Very Poor, 3=Poor, 4= Fair, 5=Good, 6=Very Good, and 7=Excellent).

After obtaining, perceived improvement in performances of measures with respect to strategies, the linguistic variables are converted into corresponding Crisp values using Likert's scale.

Now, the crisp values of importance weights (w_i) and perceived improvement (f) in the performance of measures with respect to various strategies are used in VIKOR method. For example, f_{ij} is the perceived improvement of measure *i* with respect to strategy A*j*. This system applies VIKOR methodology for selection of best strategy. After obtaining the perceived improvement (f_{ij}) and importance weights (w_i), this sub-system applied the Step7-9 of the VIKOR method as discussed in Section 6.4.1.

7.3.2.2 Stability of the ranking results

As mentioned above, the proposed strategy selection system is based on the concepts of VIKOR method. In this section, the results of the proposed method concerning rationality and discriminatory ability are examined. Here, the analytic technique was borrowed from the concepts of sensitivity analysis.

The proposed system is able to verify the results of strategy selection for rationality and stability by using the concept of sensitivity analysis when maximum utility values *(v)* do not affect the results. This analysis is performed by decreasing and increasing the *v* value from 0 to 1 by the step of 0.1. According to sensitivity analysis results, ranking of strategies should be same for all values of maximum utility value (*v*).

7.4 Programing Framework

PHP.net based Joomla was utilized to build the fuzzy based system because it is widely used for managing web content and its proper presentation. Various tasks like user management, content management, etc. can be done easily using this platform. JavaScript is used to design the front-end dynamic feature for the web-based system. For backend data processing and management MYSQL has been used. PHP.net is truly revolutionary and gives programmers a much more capable, efficient and flexible way to design the web based systems. In addition, it also supports the integration of various tools such as JavaScript and MYSQL. The entire programming code of the expert system is not provided with this dissertation. However, it can be made available if asked.

The web-based system accepts the measurements from expert assessment of the manufacturing SMEs using a seven-point Likert scale (1-7). This scale is aimed to gather the performance level (1-Not at all important, 2-Low important, 3-Slightly important, 4-Moderate important, 5-Fairly important, 6- Very important and 7-Extremely important) and importance level of each metric (1-Unavailable, 2-Very poor, 3-Poor, 4- Fair, 5-Good, 6-Very good and 7-Excellent). Once the performance and importance level of each metric corresponding to the each measure are input into the system, it will compute the weighted performance rating using Eqs. (4) and importance weight using Eqs. (5) for each measure. Based on the performance evaluation score obtained for each measure, the system will classify the scores with a linguistic variable. The linguistic variables, Poor, Fair and good are represented by fuzzy membership functions (1,2.5,4), (2.5,4,5.5) and (4,5.5,7) respectively. Based on the fuzzy logic methodology, the system uses the membership functions and fuzzy rules based on expert opinions to find the conclusions at both stages. These conclusions from stage one are used inputs for stage 2 to determine the overall sustainability score of the organization. Using a sensitivity analysis as discussed in section 7.3.1.2, this system also helps the decision makers to identify the most important indicators to improve the sustainability performance. Based on this analysis, decision makers can select the best strategy to improve their sustainability performance.

The next module of the expert system is designed for strategy selection. The strategy selection module is based on a widely used multi-attribute decision making method, VIKOR. This system accepts the linguistic values of perceived improvements in the indicators' performance ratings which are based on a Likert scale (1-7). The VIKOR method requires the importance of selection criteria and performance ratings of strategies with respect to these criteria. The most important measures identified during sustainability evaluation sensitivity analysis are considered as criteria. The importance weights of the measures are considered as weights of criteria and the perceived improvement in the performance of indicators due to implementation of a strategy are considered as performance ratings of the strategies with respect to measures. This system presents the ranking of strategies and a stability check of results using sensitivity analysis.

The screenshots of the system is presented in Figure7.3-7.18; the sustainability assessment module of the system is based on the framework presented in Figure 7.2. The overall sustainability performance depends on the three aspects, i.e., economic, environmental and social performances of the organization. At the beginning of the assessment, this system presents the list of measures and corresponding metrics associated with three aspects. For each indicator, the performance rating and importance weight are to be selected in linguistic terms. Once the values for each indicator is entered, by a click on the 'calculate the performance', it will show the performance levels of each measure, each aspect and overall sustainability performance. The performance ratings will be displayed in both crisp and fuzzy grades. The results also display the output of sensitivity analysis which aims at determining the list of the most important indicators for the improvement in overall sustainability.

After the sustainability evaluation, the decision maker can proceed in strategy selection by a click on the 'select strategy' button. The strategy selection page presents a data collection form to gather the opinion of the decision maker about the perceived improvement in the performance ratings of measures with respect to corresponding strategies. The decision maker can add desired number of strategies for evaluation by clicking on 'add more' button. Once all the strategies and corresponding perceived improvement data are input, and then click on the 'Evaluate strategies' to obtain the results of the selection process. The result presents the ranking of strategies and the stability of the ranking.

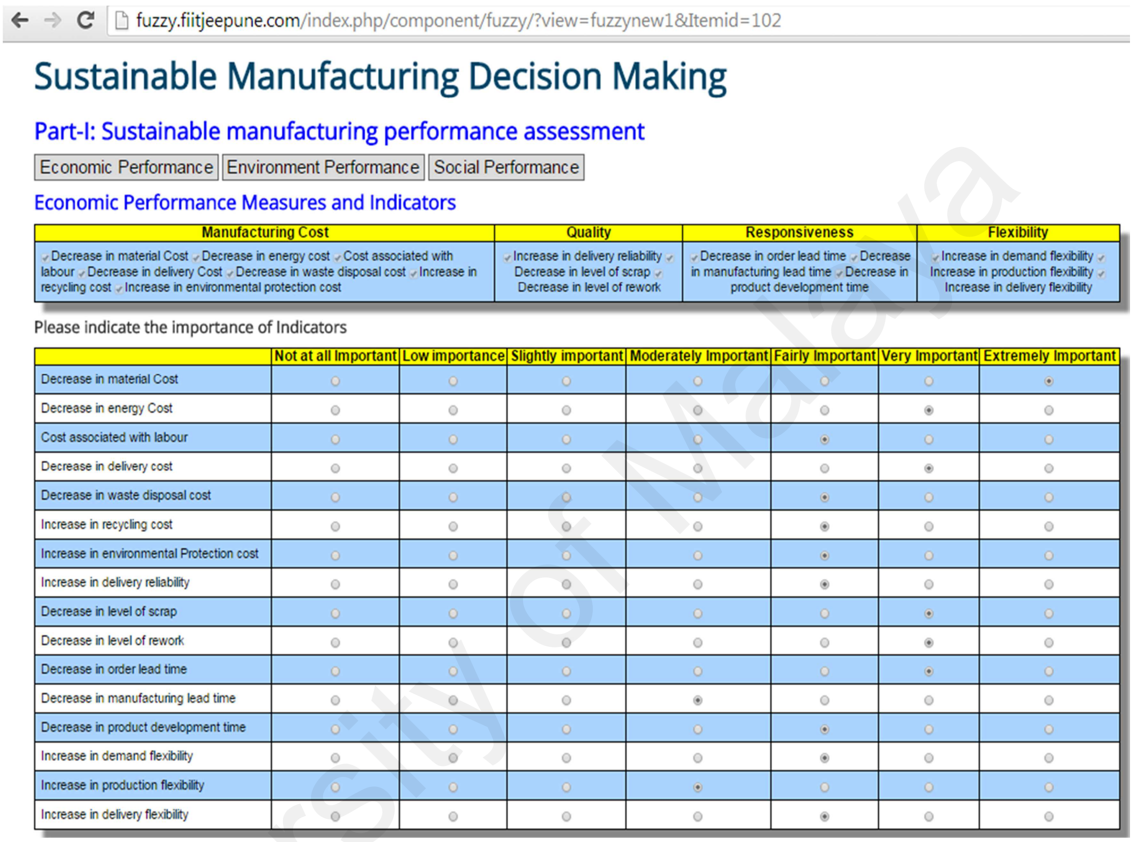
7.5 Validation Study

The proposed expert system has been designed for performance assessment and strategy selection for sustainable manufacturing in SMEs from a holistic and comprehensive approach. In this section, a case study is used to exhibit the utilization of the expert system. An electrical and electronic part manufacturing SME in India has been selected for testing and evaluation of the expert system. The chosen company was established in 1970. Its staff strength is 341. The system was presented to the unit head of the company to assess the sustainability performance and then select the suitable strategy from a manufacturer's perspective. A team of three managers was formed who belongs to quality control, accounts and production departments. The system was presented to these managers of the company to assess the sustainability performance and then select the best strategy from manufacturer perspective. For the sustainability performance evaluation, they scored all the importance and performance of all indicators for each aspect in terms of linguistic values and their mutually agreed scores were input into the system. The performance assessment system came up with the final performance values and list of important measures for sustainability improvement.

For strategy selection system, all decision makers agreed to consider all the measures as selection criteria. The usage of materials and resources were considered very important for sustainable manufacturing in the company. Therefore, four sustainable strategies were considered for evaluation as waste minimization, material efficiency, resource efficiency and eco-efficiency. The perceived improvement in the performance rating of measures with respect to each strategy were discussed among the decision makers and their mutually agreed scores were input in this system. The strategy selection system came up with the ranking of these strategies and also shows the stability of ranking using the concept of sensitivity analysis.

7.6 Results and Discussion

The screenshots of the sustainability evaluation and strategy selection conducted for manufacturing SME are represented by Figure 7.3-7.12 and Figure 7.13-7.18 respectively. It is seen that system is user-friendly and applicable in sustainability evaluation and suitable for strategy selection. The users were required to input the values of importance weights and performance ratings in linguistic terms using radio buttons as seen in Figure 7.3-7.9.The results of sustainability evaluation can be seen from Figure 7.9-7.11.



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Sustainable Manufacturing Decision Making

Part-I: Sustainable manufacturing performance assessment

Economic Performance | Environment Performance | Social Performance

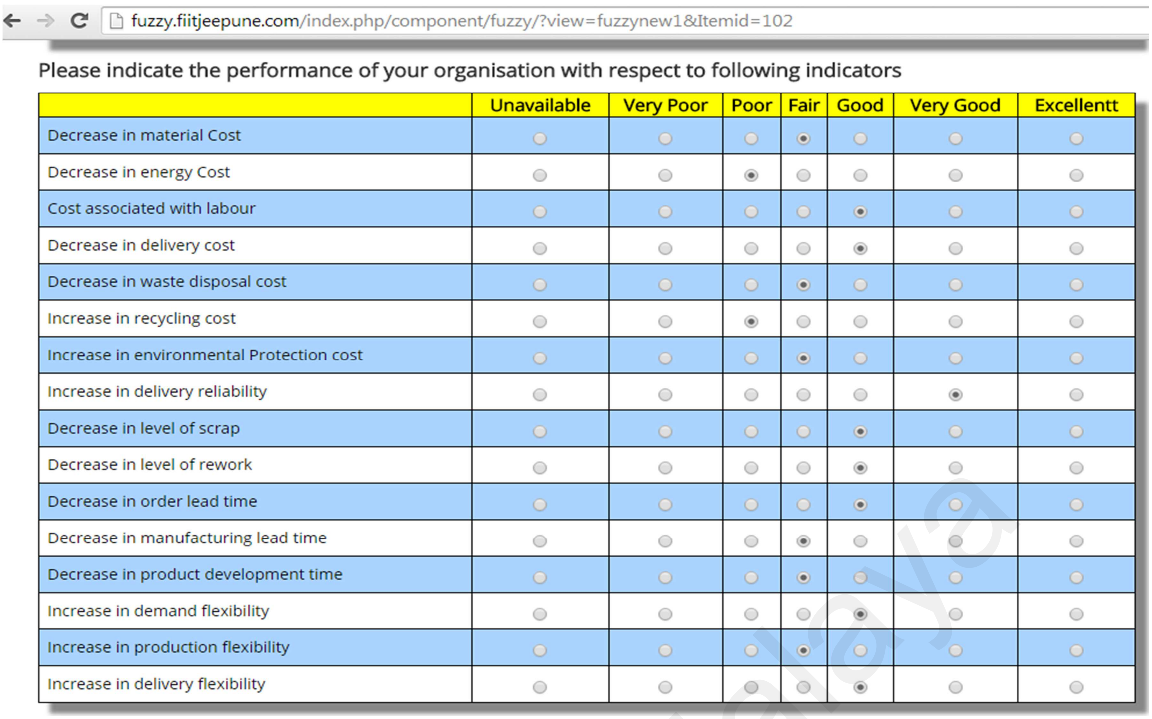
Economic Performance Measures and Indicators

Manufacturing Cost	Quality	Responsiveness	Flexibility
Decrease in material Cost, Decrease in energy cost, Cost associated with labour, Decrease in delivery Cost, Decrease in waste disposal cost, Increase in recycling cost, Increase in environmental protection cost	Increase in delivery reliability, Decrease in level of scrap, Decrease in level of rework	Decrease in order lead time, Decrease in manufacturing lead time, Decrease in product development time	Increase in demand flexibility, Increase in production flexibility, Increase in delivery flexibility

Please indicate the importance of Indicators

	Not at all Important	Low importance	Slightly important	Moderately Important	Fairly Important	Very Important	Extremely Important
Decrease in material Cost							●
Decrease in energy Cost						●	
Cost associated with labour					●		
Decrease in delivery cost						●	
Decrease in waste disposal cost					●		
Increase in recycling cost					●		
Increase in environmental Protection cost					●		
Increase in delivery reliability					●		
Decrease in level of scrap						●	
Decrease in level of rework						●	
Decrease in order lead time						●	
Decrease in manufacturing lead time				●			
Decrease in product development time					●		
Increase in demand flexibility					●		
Increase in production flexibility				●			
Increase in delivery flexibility					●		

Figure 7.3: Screenshot of economic performance indicators (Importance rating)



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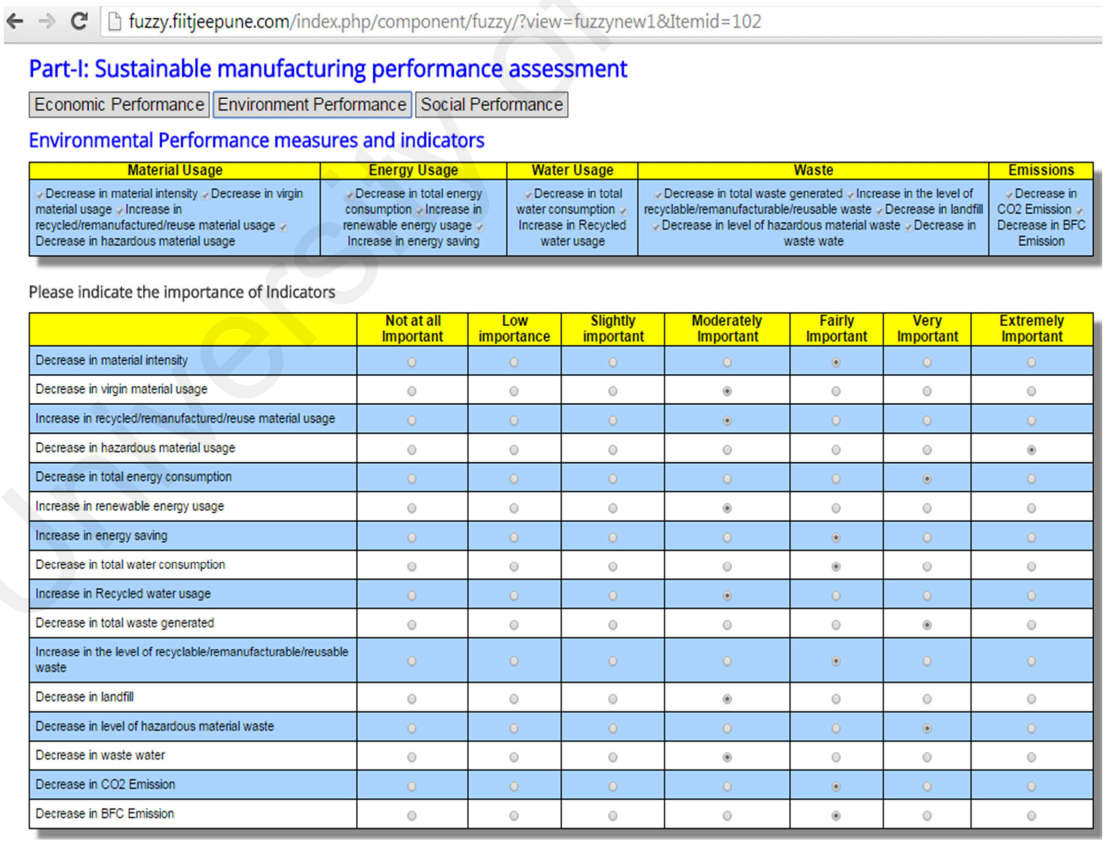
Please indicate the performance of your organisation with respect to following indicators

	Unavailable	Very Poor	Poor	Fair	Good	Very Good	Excellentt
Decrease in material Cost	○	○	○	●	○	○	○
Decrease in energy Cost	○	○	●	○	○	○	○
Cost associated with labour	○	○	○	○	●	○	○
Decrease in delivery cost	○	○	○	○	●	○	○
Decrease in waste disposal cost	○	○	○	●	○	○	○
Increase in recycling cost	○	○	●	○	○	○	○
Increase in environmental Protection cost	○	○	○	●	○	○	○
Increase in delivery reliability	○	○	○	○	○	●	○
Decrease in level of scrap	○	○	○	○	●	○	○
Decrease in level of rework	○	○	○	○	●	○	○
Decrease in order lead time	○	○	○	○	●	○	○
Decrease in manufacturing lead time	○	○	○	●	○	○	○
Decrease in product development time	○	○	○	●	○	○	○
Increase in demand flexibility	○	○	○	○	●	○	○
Increase in production flexibility	○	○	○	●	○	○	○
Increase in delivery flexibility	○	○	○	○	●	○	○

Figure 7.4: Screenshot of economic performance indicators (performance rating)



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Part-I: Sustainable manufacturing performance assessment

Economic Performance | Environment Performance | Social Performance

Environmental Performance measures and indicators

Material Usage	Energy Usage	Water Usage	Waste	Emissions
✓Decrease in material intensity ✓Decrease in virgin material usage ✓Increase in recycled/remanufactured/reuse material usage ✓Decrease in hazardous material usage	✓Decrease in total energy consumption ✓Increase in renewable energy usage ✓Increase in energy saving	✓Decrease in total water consumption ✓Increase in Recycled water usage	✓Decrease in total waste generated ✓Increase in the level of recyclable/remanufacturable/reusable waste ✓Decrease in landfill ✓Decrease in level of hazardous material waste ✓Decrease in waste wate	✓Decrease in CO2 Emission ✓Decrease in BFC Emission

Please indicate the importance of Indicators

	Not at all Important	Low importance	Slightly important	Moderately Important	Fairly Important	Very Important	Extremely Important
Decrease in material intensity	○	○	○	○	●	○	○
Decrease in virgin material usage	○	○	○	●	○	○	○
Increase in recycled/remanufactured/reuse material usage	○	○	○	●	○	○	○
Decrease in hazardous material usage	○	○	○	○	○	○	●
Decrease in total energy consumption	○	○	○	○	○	●	○
Increase in renewable energy usage	○	○	○	●	○	○	○
Increase in energy saving	○	○	○	○	●	○	○
Decrease in total water consumption	○	○	○	○	●	○	○
Increase in Recycled water usage	○	○	○	●	○	○	○
Decrease in total waste generated	○	○	○	○	○	●	○
Increase in the level of recyclable/remanufacturable/reusable waste	○	○	○	○	●	○	○
Decrease in landfill	○	○	○	●	○	○	○
Decrease in level of hazardous material waste	○	○	○	○	○	●	○
Decrease in waste water	○	○	○	●	○	○	○
Decrease in CO2 Emission	○	○	○	○	●	○	○
Decrease in BFC Emission	○	○	○	○	●	○	○

Figure 7.5: Screenshot of environmental performance indicators (importance rating)

fuzzy.fiitjeepune.com/index.php/component/fuzzy/?view=fuzzynew1&Itemid=102

Please indicate the performance of your organisation with respect to following indicators

	Unavailable	Very Poor	Poor	Fair	Good	Very Good	Excellentt
Decrease in material intensity	○	○	○	●	○	○	○
Decrease in virgin material usage	○	○	○	○	●	○	○
Increase in recycled/remanufactured/reuse material usage	○	○	○	○	●	○	○
Decrease in hazardous material usage	○	○	○	○	○	●	○
Decrease in total energy consumption	○	○	○	○	●	○	○
Increase in renewable energy usage	○	○	●	○	○	○	○
Increase in energy saving	○	○	○	●	○	○	○
Decrease in total water consumption	○	○	○	●	○	○	○
Increase in Recycled water usage	○	○	●	○	○	○	○
Decrease in total waste generated	○	○	○	●	○	○	○
Increase in the level of recyclable/remanufacturable/reusable waste	○	○	●	○	○	○	○
Decrease in landfill	○	○	○	●	○	○	○
Decrease in level of hazardous material waste	○	○	○	○	○	●	○
Decrease in waste water	○	○	○	○	●	○	○
Decrease in CO2 Emission	○	○	○	○	●	○	○
Decrease in BFC Emission	○	○	○	●	○	○	○

Figure 7.6: Screenshot of environmental performance indicators (performance rating)

fuzzy.fiitjeepune.com/index.php/component/fuzzy/?view=fuzzynew1&Itemid=102

Part-I: Sustainable manufacturing performance assessment

Economic Performance | Environment Performance | Social Performance

Social Performance measures and indicators

Employee wellbeing	Customer wellbeing	Community wellbeing
✓Decrease in number of accidents per annum ✓Increase in average hours of training/year ✓Decrease in employee turnover ✓Increase in job satisfaction index ✓Improvement in working condition ✓Increase in employee participation in decision making	✓Increase in customer satisfaction index ✓Life cycle assessments for health and safety impacts ✓Availability of warranty ✓Disclosure of Product and sevice information	✓Decrease in number of non-compliance ✓Salary compared to local minimum wage ✓Compositon of worforce by gender/age ✓Child labour policy ✓Number of community projects orinitiatives ✓Community involvement in decision making

Please indicate the importance of Indicators

	Not at all Important	Low importance	Slightly important	Moderately Important	Fairly Important	Very Important	Extremely Important
Decrease in number of accidents per annum	○	○	○	○	●	○	○
Increase in average hours of training/year	○	○	○	●	○	○	○
Decrease in employee turnover	○	○	○	○	●	○	○
Increase in Job satisfaction index	○	○	○	●	○	○	○
Improvement in working condition	○	○	○	●	○	○	○
Increase in employee participation in decision making	○	○	●	○	○	○	○
Increase in customer satisfaction index	○	○	○	○	●	○	○
Life cycle assessments for health and safety impacts	○	○	●	○	○	○	○
Availability of warranty	○	○	○	○	●	○	○
Disclosure of Product and sevice information	○	○	●	○	○	○	○
Decrease in number of non-compliance	○	○	○	○	○	●	○
Salary compared to local minimum wage	○	○	○	●	○	○	○
compositon of worforce by gender/age	○	○	○	●	○	○	○
child labour policy	○	○	○	○	●	○	○
Number of community projects orinitiatives	○	○	●	○	○	○	○
Community involvement in decision making	○	●	○	○	○	○	○

Figure 7.7: Screenshot of social performance indicators (importance rating)

fuzzy.fiitjeepune.com/index.php/component/fuzzy/?view=fuzzynew1&Itemid=102

Please indicate the performance of your organisation with respect to following indicators

	Unavailable	Very Poor	Poor	Fair	Good	Very Good	Excellentt
Decrease in number of accidents per annum	○	○	○	○	●	○	○
Increase in average hours of training/year	○	○	○	●	○	○	○
Decrease in employee turnover	○	○	●	○	○	○	○
Increase in Job satisfaction index	○	○	●	○	○	○	○
Improvement in working condition	○	○	○	●	○	○	○
Increase in employee participation in decision making	○	○	●	○	○	○	○
Increase in customer satisfaction index	○	○	○	●	○	○	○
Life cycle assessments for health and safety impacts	○	●	○	○	○	○	○
Availability of warranty	○	○	○	●	○	○	○
Disclosure of Product and sevice information	○	○	●	○	○	○	○
Decrease in number of non-compliance	○	○	○	○	○	●	○
Salary compared to local minimum wage	○	○	○	●	○	○	○
compositon of worforce by gender/age	○	○	○	●	○	○	○
child labour policy	○	○	○	○	○	●	○
Number of community projects orinitiatives	○	○	●	○	○	○	○
Community involvement in decision making	○	○	●	○	○	○	○

calculate the performance

Figure 7.8: Screenshot of social performance indicators (performance rating)

Performance ratings and weights of Economic measures

Name of Measures	Value	Grade
Performance Rating of Manufacturing Cost	4.00	Fair
Importance Weightage of Manufacturing Cost	5.57	
Performance Rating of Responsiveness	4.40	Fair
Importance Weightage of Responsiveness	5.00	
Performance Rating of Flexibility	4.71	Fair
Importance Weightage of Flexibility	4.67	
Performance Rating of Quality	5.29	Good
Importance Weightage of Quality	5.67	
Overall Economic Performance		Fair(4.349)

Figure 7.9: Screenshot of economic performance assessment

Performance ratings and weights of Environmental measures

Name of Measures	Value	Grade
Performance Rating of Material Usage	5.10	Good
Importance Weightage of Material Usage	5.00	
Performance Rating of Energy Usage	4.13	Fair
Importance Weightage of Energy Usage	5.00	
Performance Rating of Water Usage	3.56	Fair
Importance Weightage of Water Usage	4.50	
Performance Rating of Waste	4.44	Fair
Importance Weightage of Waste	5.00	
Performance Rating of Emmission	4.50	Fair
Importance Weightage of Emmission	5.00	
Overall Environmental Performance		Fair(4.362)

Figure 7.10: Screenshot of environmental performance assessment

Performance ratings and weights of Social measures

Name of Measures	Value	Grade
Performance Rating of Employee Well Being	3.72	Fair
Importance Weightage of Employee Well Being	4.17	
Performance Rating of Customer Well Being	3.44	Fair
Importance Weightage of Customer Well Being	4.00	
Performance Rating of Community Well Being	4.71	Fair
Importance Weightage of Community Well Being	4.00	
Overall Social Performance		Fair(3.953)

Final Performance is Fair(Crisp value 4.36)

Recommendation is to Improve

Figure 7.11: Screenshot of social and overall sustainability performance assessment

As can be seen from Figure 7.9, the overall economic performance of the case company was fair. The performance rating of the quality was good, whereas other measures were rated fair. Furthermore, quality was rated, most important, followed by manufacturing cost, flexibility and responsiveness. This could be attributed to the fact that manufacturing SME is an ISO 9001 certified company since 2005 and quality management system is well in place.

The environmental performance of the case company was fair as shown in Figure 7.10. The performance rating of material usage was good, whereas other measures were rated fair. The importance of the material usage, energy usage, waste and emissions were almost same whereas the importance of water usage was low. Water usage showed a comparatively low importance score among environmental performance measures. This might be because; the managers believed that it is difficult to assess the water treatment & recovery in the performance measurement of sustainable manufacturing. The high performance rating of material usage could be due to pressure from various suppliers to discard the hazardous substances since the case company is a supplier to various bigger manufacturing organizations.

The social performance of the company was fair as shown in Figure 7.11. The performance ratings of all the measures were fair which required considerable improvement. It can be also seen that the importance of these measures are low compared to economic and environmental measures. This is in line with a corporate social responsibility study conducted by Lu (2013) on manufacturing SMEs. The comparative low score of importance for social measures might be due to conflicting interests and various concerns of stakeholders. The overall sustainability performance of the company was fair and the system's recommended future action is to improve.

Most important measures for sustainability improvement (Based on sensitivity analysis)

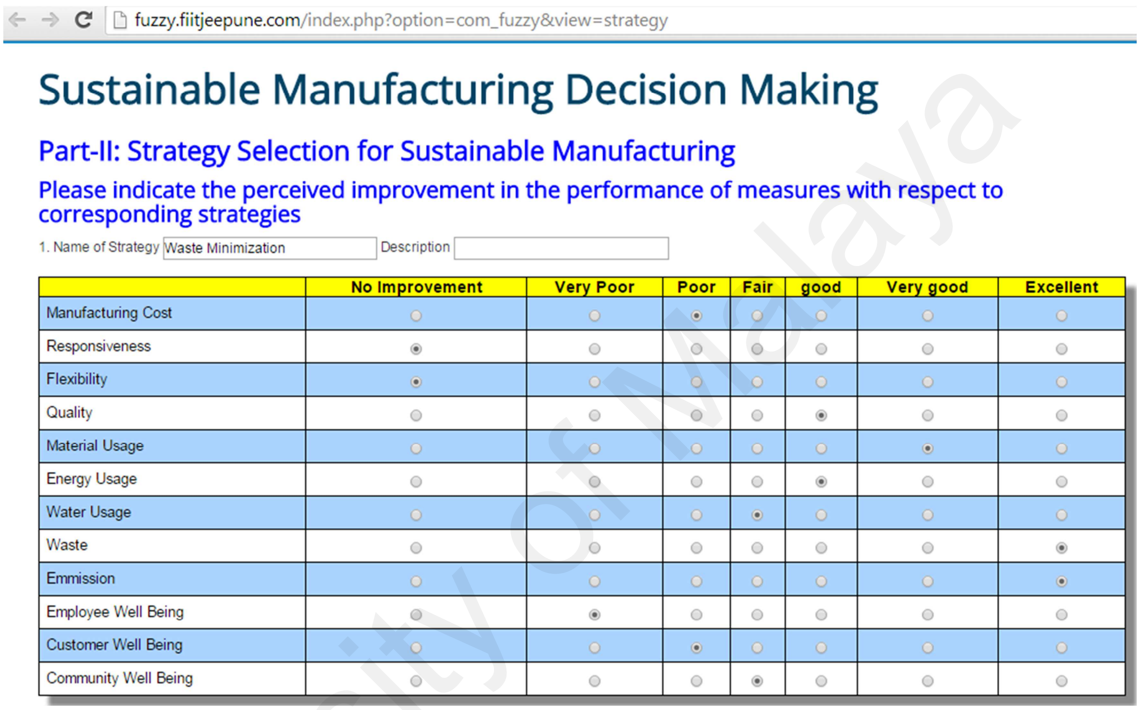
S.N.	Select	Measure Name	Scaled Gradient
1.	☑	Manufacturing Cost	0.2892004153686383
2.	☑	Water Usage	0.2679127725856694
3.	☑	Energy Usage	0.24835583246798168
4.	☑	Customer Well Being	0.24645205953617136
5.	☑	Employee Well Being	0.23671858774662252
6.	☑	Waste	0.23219106957424732
7.	☑	Responsiveness	0.22499134648667327
8.	☑	Emmission	0.21633783316026278
9.	☑	Flexibility	0.1850865351332643
10.	☑	Quality	0.1678037383177571
11.	☑	Material Usage	0.16441675320179974
12.	☑	Community Well Being	0.15853236413984056

Select Strategy

Figure 7.12: Screenshot of importance of measures for sustainability improvement

The Figure 7.12 presents the result of sensitivity analysis conducted to identify the relative importance of the performance measures. The measures are ranked on the basis of scaled gradient values (see section 7.3.1.2), which identify the measures those affect the overall sustainability most and are farther from sustainable region are identified and ranked to improve the sustainability performance. In the case company, the manufacturing cost was identified as most important measure followed by water usage. As can be seen from Figure 7.12, the order of importance of measures is manufacturing cost>water usage>energy usage> customer wellbeing >employee wellbeing >waste > responsiveness>emissions> flexibility> quality > material usage > community wellbeing. This analysis shows that improvement in the performance rating of manufacturing cost provides greater opportunity for overall sustainability improvements. This information can be very useful to select the sustainable strategies as a future course of action.

As explained above, this system provides flexibility to the users to include or exclude any measure for strategy selection based on the result of the sensitivity analysis conducted above. The managers from the case company agreed to consider all the measures for evaluating the four strategies under considerations. Considering the impact of material and other resource usage, the four strategies identified by their managers were waste minimization, material efficiency, resource efficiency and eco-efficiency. The Figure 7.13-7.16 represents the screenshots of the perceived improvement in the performance ratings of the measures with respect to these strategies.


fuzzy.fiitjeepune.com/index.php?option=com_fuzzy&view=strategy

Sustainable Manufacturing Decision Making

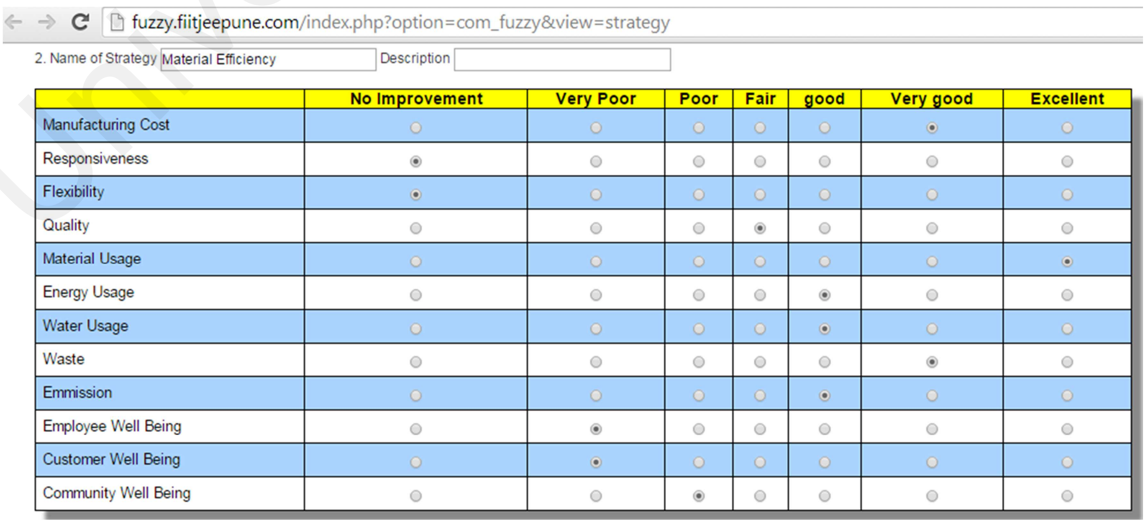
Part-II: Strategy Selection for Sustainable Manufacturing

Please indicate the perceived improvement in the performance of measures with respect to corresponding strategies

1. Name of Strategy: Waste Minimization Description:

	No Improvement	Very Poor	Poor	Fair	good	Very good	Excellent
Manufacturing Cost	○	○	●	○	○	○	○
Responsiveness	●	○	○	○	○	○	○
Flexibility	●	○	○	○	○	○	○
Quality	○	○	○	○	●	○	○
Material Usage	○	○	○	○	○	●	○
Energy Usage	○	○	○	○	●	○	○
Water Usage	○	○	○	●	○	○	○
Waste	○	○	○	○	○	○	●
Emmission	○	○	○	○	○	○	●
Employee Well Being	○	●	○	○	○	○	○
Customer Well Being	○	○	●	○	○	○	○
Community Well Being	○	○	○	●	○	○	○

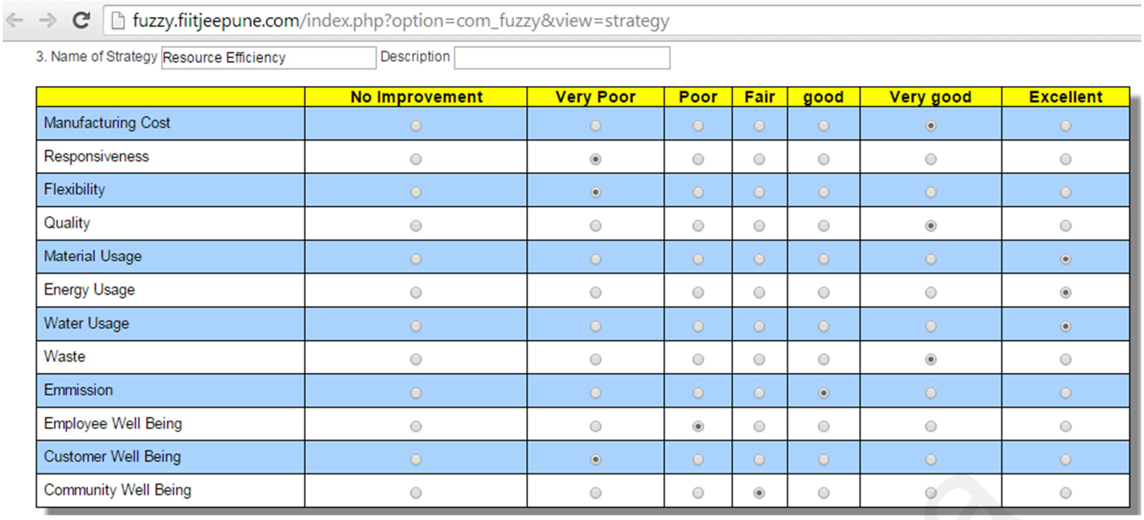
Figure 7.13: Screenshot of waste minimization strategy


fuzzy.fiitjeepune.com/index.php?option=com_fuzzy&view=strategy

2. Name of Strategy: Material Efficiency Description:

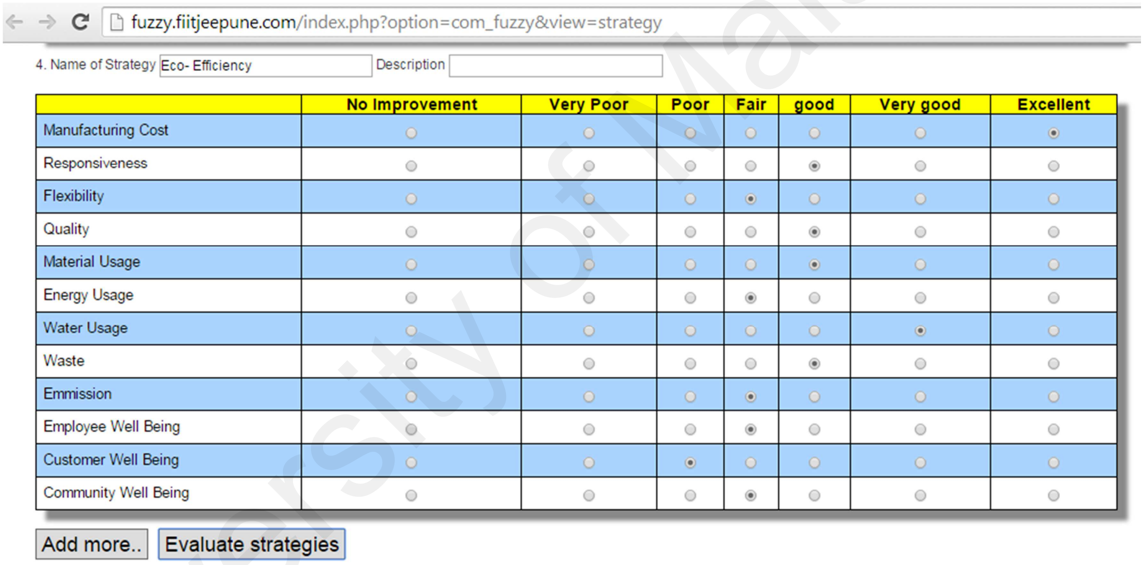
	No Improvement	Very Poor	Poor	Fair	good	Very good	Excellent
Manufacturing Cost	○	○	○	○	○	●	○
Responsiveness	●	○	○	○	○	○	○
Flexibility	●	○	○	○	○	○	○
Quality	○	○	○	●	○	○	○
Material Usage	○	○	○	○	○	○	●
Energy Usage	○	○	○	○	●	○	○
Water Usage	○	○	○	○	●	○	○
Waste	○	○	○	○	○	●	○
Emmission	○	○	○	○	●	○	○
Employee Well Being	○	●	○	○	○	○	○
Customer Well Being	○	●	○	○	○	○	○
Community Well Being	○	○	●	○	○	○	○

Figure 7.14: Screenshot of material efficiency strategy



	No Improvement	Very Poor	Poor	Fair	good	Very good	Excellent
Manufacturing Cost	○	○	○	○	○	●	○
Responsiveness	○	●	○	○	○	○	○
Flexibility	○	●	○	○	○	○	○
Quality	○	○	○	○	○	●	○
Material Usage	○	○	○	○	○	○	●
Energy Usage	○	○	○	○	○	○	●
Water Usage	○	○	○	○	○	○	●
Waste	○	○	○	○	○	●	○
Emmission	○	○	○	○	●	○	○
Employee Well Being	○	○	●	○	○	○	○
Customer Well Being	○	●	○	○	○	○	○
Community Well Being	○	○	○	●	○	○	○

Figure 7.15: Screenshot of resource efficiency strategy



	No Improvement	Very Poor	Poor	Fair	good	Very good	Excellent
Manufacturing Cost	○	○	○	○	○	○	●
Responsiveness	○	○	○	○	●	○	○
Flexibility	○	○	○	●	○	○	○
Quality	○	○	○	○	●	○	○
Material Usage	○	○	○	○	●	○	○
Energy Usage	○	○	○	●	○	○	○
Water Usage	○	○	○	○	○	●	○
Waste	○	○	○	○	●	○	○
Emmission	○	○	○	●	○	○	○
Employee Well Being	○	○	○	●	○	○	○
Customer Well Being	○	○	●	○	○	○	○
Community Well Being	○	○	○	●	○	○	○

Figure 7.16: Screenshot of Eco-efficiency strategy

Figure 7.17 represents the screenshot of the ranking of the strategies result. The ranking of the strategies was based on the VIKOR values using $v=0.5$. The resource efficiency was ranked as a first strategy with minimum VIKOR value equals to zero. The eco-efficiency was ranked second, followed by waste minimization and material efficiency. The compromise solution, closest to the ideal solution was achieved as resource efficiency as a sustainable strategy for further improvement. The difference in VIKOR values ($Q_{v=0.5}$) of resource efficiency and eco-efficiency (strategy with minimum value and strategy next to this) is 0.46> ($1/m-1$). The resource efficiency strategy was selected for implementation based on its smallest VIKOR value *(Q)* with *v*=0.5and is a stable solution as it satisfies the condition 2 mentioned in step 2 of section 7.3.2.1. The stability of this ranking was further verified by performing a sensitivity analysis. This analysis was performed by decreasing and increasing the *v* value from 0 to 1 by the step of 0.1. As can be seen from Figure7.18, the strategies show a straight line or nearly straight-line trend, and their positions are stable in new ranking while changing the value of maximum utility value (*v*). Based on the above results from the proposed system, this study has demonstrated that the proposed system can easily evaluate the sustainability performance and then select the best strategy for its improvement.

Ranking of Strategies (Based on vikor values)

Rank(v)	Criteria Name	S	smax	smin	R	Rmax	Rmin	Vikor
1	Resource Efficiency	20.27	41.17	20.27	4.00	5.67	4.00	0.00
2	Eco- Efficiency	24.54	41.17	20.27	5.20	5.67	4.00	0.46
3	Waste Minimization	32.58	41.17	20.27	5.57	5.67	4.00	0.76
4	Material Efficiency	41.17	41.17	20.27	5.67	5.67	4.00	1.00

Figure 7.17: Screenshot of ranking of strategies

stability of ranking of strategies (based on sensitivity analysis)

SN	Strategy Name	v=0.1	v=0.2	v=0.3	v=0.4	v=0.5	v=0.6	v=0.7	v=0.8	v=0.9	v=1.0
1	Waste Minimization	0.91	0.87	0.83	0.80	0.76	0.73	0.69	0.66	0.62	0.59
2	Material Efficiency	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3	Resource Efficiency	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Eco- Efficiency	0.67	0.62	0.56	0.51	0.46	0.41	0.36	0.31	0.26	0.20

Figure 7.18: Screenshot of stability of the ranking of strategies

7.7 Summary

Till recently, there are very few studies on sustainability evaluation of manufacturing SMEs. This chapter presents an expert system for sustainability evaluation and then strategy selection for manufacturing SMEs. The varied importance of indicators is considered in this study that is very often in the decision making in the manufacturing organization. Due to the vagueness in manufacturing decision-making, the decision makers express their opinions into linguistic terms instead of crisp values. Therefore, fuzzy logic based system was proposed to deal with the subjectivity involved in performance evaluation of manufacturing SMEs. Using a sensitivity analysis, the expert system identified the most important indicators for sustainability performance. The strategy selection system is based on VIKOR method which considers the most important measures as selection criteria and perceived improvement in their performance ratings of strategies with respect to measures under consideration. To validate the ranking of strategies, this system is able to perform a stability check of results using the concept of sensitivity analysis.

CHAPTER 8: CONCLUSIONS

8.1 Introduction

This chapter summarizes the research process, research findings, contributions and limitations of this study and future research direction arising from this study. The aim of this research study is as presented in chapter 1, which states as follows:

> *This research study is aimed at developing and investigating the suitability of general sustainable manufacturing model on the sustainable manufacturing practices of small and medium scale enterprises (SMEs). In essence, this study will enhance the understanding of requirements and framework for an efficient sustainable manufacturing practice in the SMEs of developing countries and propose suitable decision-making models for sustainable manufacturing.*

This research aim has been achieved by completing the following three research objectives that were presented in chapter 1. The objectives of this research study were:

1. *To identify the set of key performance measures for sustainability assessment of manufacturing SMEs.*
2. *To develop sustainable manufacturing decision-making.*
3. *To develop an expert system for performance assessment and strategy selection for manufacturing SMEs.*

On the basis of literature review, best strategies and performance assessment methods and metrics for sustainable manufacturing were identified. An empirical study was conducted to investigate the importance and applicability of the performance metrics for sustainability assessment of manufacturing SMEs. Considering the involvement of human reasoning in decision making in manufacturing SMEs, the fuzzy-based sustainability assessment and strategy selection models were developed. The performance measures and metrics identified during the empirical study were used as input in these model to obtain the sustainability score of the manufacturing organizations. Finally, a web based expert system was developed to evaluate the sustainability performance and then select the best strategy. This expert system is based on the set of indicators identified during the empirical study. Considering the vagueness in decision making in manufacturing SMEs, the performance evaluation and strategy selection module of this system is based on the fuzzy logic concept. The expert system is also validated by implementation in manufacturing SMEs.

8.2 Summary of Research Findings

1. The concept of sustainable manufacturing is found to be introduced recently in manufacturing SMEs. However, It is seen that the practices of sustainable manufacturing has been gradually adopted by manufacturing SMEs due to pressure from various bodies such as regulatory bodies, larger organizations and financial institutions.It is also seen that manufacturing SMEs which are suppliers to multi-national companies have compartively greater exposure of these practices.
2. It is found that manufacturing SMEs in Malaysia are relatively more concerned about economic performance followed by environmental and social performances.The importance and applicability of social performance measures were found low. This might be due to comparatively more subjectivity of social measures and issues related to fair allocation of benefits among the employee and community.
3. Due to lack of awareness and knowledge about the sustainable manufacturing practices among the decision makers, the decision-making methods based on the fuzzy concepts are found to be more suitable. It is seen that decision makers face

difficulty in providing their opinions in crisp values of input variables.The managers (involved in case studies) acknowledged that the availability of sustainability evaluation and strategy selection methods profoundly helped them to analyse and decide the best strategy for the sustainable manufacturing.

4. Besides the sustainability asssessment, a sensitivity analysis to identify the most important indicators in a given scenario for sustainability improvements was also recognised as a goodtool to aid the decision-making process in manufacturing SMEs.
5. The empirical study on the investigations of the importance and applicability of sustainable manufacturing indicators presented the key performance measures for manufacturing SMEs.
6. Two sustainability assessment model based on fuzzy logic are found to fit to the various scenario of performance evaluation.A novel strategy selection method based on the fuzzy logic concept is also found to be suitable for decision making in manufacturing SMEs. The sustainability evaluation and strategy selection expert system was found to be easily accessible and user friendly to the practitioners from manufacturing SMEs.

8.3 Contribution to the Body of Knowledge

In literature, it is highlighted that very few studies have addressed issues of sustainable manufacturing related to performance assessment and strategy selection in small-and medium-scale enterprises. However, no literature can provide an investigation of importance and applicability of sustainable manufacturing performance measures in SMEs especially from Malaysian perspective. Previous studies by various authors did not considered the TBL framework of sustainability. They considered either one or two aspects of sustainability only (see Rao et al. (2006), Rao et al. (2009), Wyrick et al. (2013), Natarajan (2012), Henriques and Catarino (2014)). There were also researchers who looked upon the sustainability performance evaluation considering the three aspects but not focussed on the SMEs (see Joung et al. (2013), Yuan et al. (2012), Amrina and Yusof (2011), Vinodh and Jeya Girubha (2012)). There was no other study found in the literature that investigates the importance and applicability of sustainable manufacturing measures for manufacturing SMEs. Researchers have applied FIS-based assessment model in various area (see Amindoust et al. (2012), Ordoobadi (2009). However, FIS-based sustainability evaluation model is not developed for manufacturing SMEs. In addition, there is lack of the literature on sustainability assessment models which applied fuzzy inference system using Balanced Scorecard framework. Further, considering the characteristics of decision making in manufacturing SMEs which consist of uncertainty, there is a lack of strategy selection models for sustainable manufacturing under IVF environment in literature. It is also seen that there is a lack of an easy to access expert system for sustainable manufacturing decision making in SMEs.

In conclusions, it is emphasised that there are no similar studies that can fulfil the gaps addressed by the study using an empirical and three case studies from an emerging economy, thus emphasising the value of this study in adding to the body of the knowledge. The research study makes contribution to knowledge in following ways:

1. The study makes a contribution to body of knowledge through an empirical study to investigate the importance and applicability of sustainable performance measures for manufacturing SMEs. The set of key performance measures has been identified which can be used for sustainability evaluation of manufacturing SMEs. This study also provides an insight to practitioners about the relative importance and applicability of various performance measures.

2. This study contributes to sustainable manufacturing performance evaluation methods by proposing two FIS-based models to suit the different needs of the manufacturing SMEs. The first model is based on TBL framework of sustainability which requires the absolute weight of indicators and performance rating of indicators to determine the economic, environmental, social and overall sustainability performance. The second model is based on BSC framework, which requires relative weights of indicators and performance ratings of the indicators. The fuzzy AHP method is integrated with FIS to accommodate the relative weights of indicators to obtain the sustainability performance.
3. This study contributes to strategy/ alternative selection method by proposing a novel integrated AHP-VIKOR method under interval-valued fuzzy environment. The IVF environment provides more flexibility to decision makers when they are not sure about their opinions. This method can be used as a decision-making tool for alternative or strategy selection in other areas where uncertainties are inherent.
4. The research study presents an expert system for sustainability evaluation and strategy selection. The expert is based on the fuzzy logic concepts to deal with the uncertainties involved in manufacturing decision making in SMEs. There are two modules: 1. Performance evaluation and 2. Strategy selection. Based upon the results of the performance evaluation, the best strategy can be selected for sustainability improvement.

8.4 Implications for Practitioners

For successful implementation of the sustainable manufacturing practices, manufacturers from SMEs should be aware of the pertinent performance measures, how to assess the current level of performance and a tool to select the best strategy for improvement in sustainability performance. This research study provides knowledge, decision-making models, and an expert system to achieve the success in their sustainability initiative. The implications for the practitioners are summarized as followed:

1. This study presents a set of sustainable manufacturing performance measures and corresponding metrics. The knowledge about the importance and applicability provides an insight to the decision maker in selecting the performance metrics for their organizations. It will also guide the decision makers on prioritising their effort towards sustainable manufacturing practices and strategy selection.
2. This study provides two FIS-based sustainability evaluation models to cater for the different needs of decision makers. The development of these models considered the vagueness involve in the decision making related to sustainable manufacturing in SMEs. These models require input from practitioners in terms of linguistic variables which can be made easily available compared to crisp values of inputs. The practitioners have flexibility to choose the one or another model depending on the suitability to their existing manufacturing system.
3. This study provides a sustainable manufacturing strategy selection model to select the best strategy for making the adjustment in their manufacturing system. The IVF environment provides a comparatively more flexible environment to the decision makers to provide their opinions. This model combines the FAHP and VIKOR methods to accommodate the incommensurate and conflicting criteria for the strategy selection which are inherent in decision making in the manufacturing SMEs.
4. This study presents a web-based free expert system that assist the decision-maker to evaluate the sustainable performance and select the best strategy for further improvement. This system requires inputs from practitioners in terms of

linguistic variables. The knowledge base of this expert system is based on the empirical study conducted among the manufacturing SMEs. In order to achieve the final recommendation, fuzzy rule base are used as inference engine. This system does not require specialized skills or understanding of complex methods of sustainable manufacturing decision making. Thus, the decision makers are needed not to be an expert. The web-based accessibility to the expert system reduces the difficulty in the obtaining the decision making tools related to sustainable manufacturing for SMEs. In addition, the web-based expert system provides flexibility to the decision maker to assess the performance and select the strategy expert system from anywhere at any time. The usability and user friendliness of the expert system were evaluated during the validation study. Based upon the suggestions and comments received from practitioners, the system was fine-tuned and finally, it is found to be good.

8.5 Limitations and Future Research Directions

The limitation of this study is that it focuses on manufacturing SMEs from emerging economies only, and results may not be applicable to manufacturing SMEs from developed economies. Furthermore, this study focuses on the investigation of the importance and applicability of sustainability performance measures and metrics and does not propose any structural model. The TBL structure of sustainability was utilized to propose sustainability evaluation model. The study was aimed to provide a holistic view of sustainable manufacturing practices in manufacturing SMEs. Thus, inter-sector and intra-sector analysis of the importance and applicability of metrics and measures was not included in this study.

This study presented the set of the key performance measures for sustainability evaluation of manufacturing SMEs. As manufacturing SMEs covers many sectors, further research can be taken up to investigate the importance of the indicator specific to each sector. Another research can be taken up to find the gaps in sustainability performance of various sectors using intra/ inter sector gap analysis. The results of this study are applicable to manufacturing SMEs in general. However, the importance and applicability of performance measures may vary from one sector to another. For sustainability performance assessment, application of type-2 fuzzy inference system is still a research gap. Researchers can focus on the using the type-2 FIS which provides more flexibility than Mamdani's FIS.

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List of Publications and Papers Presented

Published or Accepted Papers

1. S Singh, EU Olugu, A Fallahpour. (2014). Fuzzy-based sustainable manufacturing assessment model for SMEs. *Clean Technologies and Environmental Policy, 16*(5), 847-860 (ISI-Cited)

2. S Singh, EU Olugu, S Nurmaya, AB Mahat. (2015), Fuzzy-based sustainability evaluation method for manufacturing SMEs using balanced scorecard framework.*, Journal of Intelligent Manufacturing,* doi: 10.1007/s10845-015-1081-1(ISI-Cited)

3. S Singh, EU Olugu, S Nurmaya, AB Mahat, KY Wong. (2015), Strategy selection for sustainable manufacturing in SMEs by integrated AHP and VIKOR based on interval valued fuzzy numbers,*International Journal of Advanced Manufacturing Technology* (ISI-Cited)

Under Review Papers

1. S Singh, EU Olugu, S Nurmaya, AB Mahat. (Under Review).Investigation of the importance and applicability of sustainable manufacturing performance measures for Malaysian SMEs . *International Journal of Production Research* (ISI-Cited)

2. S Singh, EU Olugu, S Nurmaya, SK Singh. (Under Review) A fuzzy based expert system for performance evaluation and strategy selection for sustainable manufacturing in SMEs. *Expert Systems with Applications*(ISI-Cited)

Conference Proceeding

1. S Singh, EU Olugu, *Sustainable supply chain performance measurement: metrics and models* at 17^{th} International conference on Industrial Engineering Theory, Applications and Practices, Busan, Korea (2013)

2. S Singh, EU Olugu, S Nurmaya, AB Mahat (2014). *Proposition of key performance measures for sustainable manufacturing in SMEs.* Paper presented at the MSME Conclave Cum Conference on Sustainable Supply Chain Capabilities of Micro, Small and Medium Enterprises: Influences, practices, Training needs and Employment opportunities., Doon University, Dehradun, 10th May 2014 (Best Research Paper Award)

3. S Singh, EU Olugu, S Nurmaya. (Accepted). *Development of sustainable manufacturing performance evaluation expert system for small and medium enterprises.* 13th Global Conference on Sustainable Manufacturing - Decoupling Growth from Resource Use, HoChi Minh City / Binh Duong, Vietnam on 16th - 18th September, 2015 (Scopus-cited)

Appendix 'A'

Survey questionnaire on Importance and applicability of sustainable manufacturing performance metrics

Dear Respondent,

This is a survey to assess the viewpoint of practitioners from Small and Medium manufacturing Enterprises regarding the importance and interrelationships of various issues for sustainable manufacturing – as part of research project being carried out at the University of Malaya with collaboration with SME Bank.

As you are aware, Sustainable manufacturing strives to produce goods by minimizing negative environmental impact and reducing resources' consumption. It also focuses at safety of employee and community while making product available on an affordable cost. Therefore, **the objective of the survey is to assess the importance and applicability various measures and metrics for sustainability performance of manufacturing SMEs** in order to improve performance of **manufacturing SMEs**.

We would like to share the results of this study with participating SMEs which may be helpful to increase understanding of sustainable manufacturing initiatives in SMEs as well as the industries in general.

Based on the findings, an ***expert system is being developed to assist the decision makers*** for the SMEs. All participants of this survey are eligible for ONE ***free copy of expert system application***, which may help you to identify the weak performing areas for further sustainability improvement.

The outcome of this study would assist industrial policy makers in setting up of environmental regulations and implementing best innovative practices to achieve desired economic performance without compromising environmental and societal concerns.

This study requires an accurate database to meet the above objectives and outcome. In this connection, a questionnaire is developed to acquire data. We request you to kindly support this study by your participation through answering this questionnaire. It would take approximately 15 minutes to complete all sections. We thank you, beforehand, in spending your valuable time and co-operation in filling the questionnaire.

Please feel free to contact us in case of any query.

Regards,

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PLEASE PROVIDE RESPONSES RELIGIOUSLY AS THESE RESPONSES ARE ONLY MEANT FOR RESEARCH PURPOSE AND YOUR IDENTITY WILL NOT BE REVEALED.

A survey on Sustainable Manufacturing

Part- A: Basic Information

Name of Company:

E-mail:

Product type:

Number of employee:

Certifications (if any):

Part-B: Importance of indicators for sustainable manufacturing performance assessment

Importance of the indicator means significance of the indicator towards the corresponding measure. For Example: Manufacturing cost (as a measure) consist of various cost elements (indicators) such as material cost, labor cost, tooling cost and many more. To determine the manufacturing cost, each cost component may have varying importance indicated by legends as given below. You are requested to evaluate the level of importance of these indicators to corresponding Measures.

Legends: 0- No idea, 1- Very Low importance, 2- Low importance, 3- Moderate importance, 4- High importance, 5- Very High importance

Measures	**Indicators**	**Level of Importance**					
		0	**1**	**2**	**3**	**4**	**5**
Profit	Net Profit						
	Total Revenue						
	Investments						
Manufacturing Cost	Material cost						
	Labor cost						
	Energy cost						
	Delivery cost						
	Inventory Cost						
	Waste treatment cost						
	Recycling cost						
	Environment Protection cost						
Quality	Delivery reliability						
	Level of Scrap						
	Level of rework						
Responsiveness	Order lead time						
	Manufacturing lead time						
	Product development time						
Flexibility	Demand Flexibility						
	Delivery flexibility						
	Production flexibility						
Material usage	Material Intensity						
	Specific virgin material ratio						
	Specific recycled/remanufactured/reused material						
	Reclaimed packaging material						
	Hazardous material ratio						
Energy usage	Total energy consumption						
	Specific energy consumption						
	Renewable energy ratio						
	Amount of energy saved						

Measures	**Indicators**	**Level of Importance**					
		0	**1**	**2**	**3**	**4**	**5**
Water usage	Total water consumption						
	Recycled water ratio						
Waste	Total solid waste generated						
	Level of recyclable/remanufacture/ reused waste						
	Ratio of disposable waste/ landfill						
	Level of hazardous materials in waste						
	Amount of total waste water						
Pollutants	CO_2 emissions						
	BFCs Emission						
Employee wellbeing	Hours of training per year						
	Number of accidents						
	Employee turnover ratio						
	Job satisfaction assessment						
	Employee involvement in decision making						
	Workplace conditions						
	Human rights training						
Customer wellbeing	Customers' satisfaction assessment						
	Life cycle assessment for health and safety						
	Availability of warranty/ take back policy						
	Number of customers complaints						
Community wellbeing	Community involvement in decision making						
	Number of non-compliances						
	Salary compared local minimum wage						
	Composition of work force						
	Child labor policy						
	Number of community projects initiatives						

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Part-B: Applicability of indicators for sustainable manufacturing performance assessment

How applicable an indicator is to determine the value of corresponding measure in your organization. For Example: Manufacturing cost (as a measure) consist of various cost elements (indicators) such as material cost, labor cost, tooling cost and many more. To determine the manufacturing cost, each cost component may have varying applicability as shown by legends below. You are requested to evaluate the level of importance of these indicators to corresponding Measures.

Legends: 0- No idea, 1- Very Low applicability, 2- Low applicability, 3- Moderate applicability, 4- High applicability, 5- Very High applicability

Measures	Indicators	Level of applicability					
		0	1	2	3	4	5
Profit	Net Profit						
	Total Revenue						
	Investments						
Manufacturing Cost	Material cost						
	Labor cost						
	Energy cost						
	Delivery cost						
	Inventory Cost						
	Waste treatment cost						
	Recycling cost						
	Environment Protection cost						
Quality	Delivery reliability						
	Level of Scrap						
	Level of rework						
Responsiveness	Order lead time						
	Manufacturing lead time						
	Product development time						
Flexibility	Demand Flexibility						
	Delivery flexibility						
	Production flexibility						
Material usage	Material Intensity						
	Specific virgin material ratio						
	Specific recycled/remanufactured/reused material						
	Reclaimed packaging material						
	Hazardous material ratio						
Energy usage	Total energy consumption						
	Specific energy consumption						
	Renewable energy ratio						
	Amount of energy saved						

Measures	Indicators	Level of applicability					
		0	1	2	3	4	5
Water usage	Total water consumption						
	Recycled water ratio						
Waste	Total solid waste generated						
	Level of recyclable/remanufacture/ reused waste						
	Ratio of disposable waste/ landfill						
	Level of hazardous materials in waste						
	Amount of total waste water						
Pollutants	CO_2 emissions						
	BFCs Emission						
Employee wellbeing	Hours of training per year						
	Number of accidents						
	Employee turnover ratio						
	Job satisfaction assessment						
	Employee involvement in decision making						
	Workplace conditions						
	Human rights training						
Customer wellbeing	Customers' satisfaction assessment						
	Life cycle assessment for health and safety						
	Availability of warranty/ take back policy						
	Number of customers complaints						
Community wellbeing	Community involvement in decision making						
	Number of non-compliances						
	Salary compared local minimum wage						
	Composition of work force						
	Child labor policy						
	Number of community projects initiatives						

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Data collection form for fuzzy-based sustainability assessment

1. Importance of aspects and measures

Please indicate the level of importance of following indicators for sustainability assessment of your organization by ticking the relevant column.

Aspects	Measures	Level of Importance			
		Not importantat all	**Low**	**Moderate**	**High**
Economic					
	Cost				
	Quality				
	Responsiveness				
	Flexibility				
Environmental					
	Material Intensity				
	Reused material ratio				
	Recyclable material ratio				
	Hazardous material ratio				
	Waste material Ratio				
	Renewable Energy Ratio				
	Energy Intensity				
	Water consumption				
	Waste water ratio				
	Land usage				
	Direct Emissions				
	Indirect Emissions				
Social					
	Employee turnover ratio				
	Labor intensity				
	Training hours/ employee				
	Customers' satisfaction				
	Community Involvement				

2. **Performance ratings of organization with respect to indicators.**

Please indicate the performance of your organization with respect to the following indicators for sustainability assessment of your organization by ticking the relevant column.

Indicators	Level of Importance			
	Not Available	Poor (P)	Fair (F)	Good (G)
Cost				
Quality				
Responsiveness				
Flexibility				
Material Intensity				
Reused material ratio				
Recyclable material ratio				
Hazardous material ratio				
Waste material Ratio				
Renewable Energy Ratio				
Energy Intensity				
Water consumption				
Waste water ratio				
Land usage				
Direct Emissions				
Indirect Emissions				
Employee turnover ratio				
Labor intensity				
Training hours/ employee				
Customers' satisfaction				
Community Involvement				

Appendix 'C'

Data collection form for balanced scorecard (BSC) based sustainability assessment.

1. Importance of indicators: Please indicate the relative importance of indicator using pair-wise comparison. Please add rows and column to accommodate the more indicators.

	Indicator1	**Indicator2**	**Indicator3**	**Indicator4**
Indicator1				
Indicator2				
Indicator3				
Indicator4				

Legends:

Fuzzy numbers	**Linguistic value**
$\tilde{9}$	**Absolutely Important**
$\tilde{7}$	**Very strongly Important**
$\tilde{5}$	**Essentially Important**
$\tilde{3}$	**Weakly Important**
$\tilde{1}$	**Equally Important**
$\tilde{2},\tilde{4},\tilde{6},\tilde{8}$	**Intermediate value between two adjacent judgments**

2. **Performance ratings of organization with respect to indicators.**

Please indicate the performance of your organization with respect to the following indicators for sustainability assessment of your organization by ticking the relevant column.

Indicators		Level of Importance			
	Very Poor (VP)	Poor (P)	Fair (F)	Good (G)	Very Good (VG)
Indicator 1					
Indicator 2					
Indicator 3					
Indicator 4					
Indicator 5					
Indicator 6					
Indicator 7					
Indicator 8					
Indicator 9					
Indicator 10					
Indicator 11					
Indicator 12					
Indicator 13					
Indicator 14					
Indicator 15					
Indicator 16					
Indicator 17					
Indicator 18					
Indicator 19					
Indicator 20					
Indicator 21					

Note: please add rows to accommodate more indicators.

Appendix 'D'

Data collection form for strategy selection.

Please indicate the perceived performance of the following strategies with respect to given criteria.

	Strategy 1	Startegy 2	Strategy 3	Strategy 4
Criteria 1				
Criteria 2				
Criteria 3				
Criteria 4				
Criteria 5				
Criteria 6				
Criteria 7				

Note: please add rows and columns to accommodate more number of the strategies and criteria.

Legends:

Level of Performance Ratings
Very poor (VP)
Poor (P)
Moderately poor (MP)
Fair (F)
Moderately good (MG)
Good (G)
Very good (VG)

Appendix E

Brief profile of companies and experts involved in this study:

1. Demographic Characteristics of the respondents (Comapanies) involved in empirical study

Demographic Variables	Category	Frequency	Percentage
Type of SMEs	Automotive	8	14
	Electrical and electronics	15	26
	Chemical	7	12.5
	Food	4	7
	Manufacturing/ Others	22	39
No. of Employees	Less than 5	2	4
	Between 5 to 50	23	41
	Between 51 to 150	31	55

2. Brief profile of the experts involved in the validation of decision making models.

For confidentiality reason, full details of the experts from industry cannot be provided. The profile of the managers participated in the study are given below.

Model	Company	Description	Experts' Profile
Sustainability assessment Model-I/ Strategy selection Model	Company-I	Company-I is a tier-2 original equipment manufacturer (OEM) supplier for more than 20 vehicle and Genset manufacturers	1. Quality Assurance Manager 2. Senior Finance Manager 3. Production Manager
Sustainability assessment Model-I/ Expert System	Company-II	Comapny-II is a Medium scale OEM involved in manufacturing of electical parts for various automotives.	1. Manager- Quality Control 2. Account Officer 3. 3. Production manager