A PROTOTYPE OF KNOWLEDGE BASED FUZZY ANALYTIC NETWORK PROCESS SYSTEM FOR SUSTAINABLE MANUFACTURING INDICATOR

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Abstrak

Sektor pembuatan lestari merupakan paradigma pembuatan yang masih baharu namun paling kompleks. Kekompleksan ini wujud kerana paradigma ini merangkumi tiga aspek kelestarian yang saling bergantung iaitu ekonomi, alam sekitar dan sosial. Dalam memulakan usaha pembuatan lestari, pembentukan indikator merupakan perkara yang perlu diberi perhatian berbanding perkara lain. Malangnya, indikator sedia ada mempunyai beberapa kelemahan yang mungkin menghad ketepatan penilaian prestasi kelestarian sesebuah organisasi. Sementelah, hanya terdapat sebilangan kecil mekanisme indikator piawai yang mampu untuk menangani keperluan spesifik pelbagai organisasi pembuatan. Sehubungan itu, kajian ini mencadangkan Sistem Proses Rangkaian Analitik Kabur Berasaskan Pengetahuan (KBFANP) yang baharu, dan mampu untuk membantu proses pembuatan keputusan dalam pengurusan pembuatan lestari dengan membangunkan satu mekanisme indikator. Sistem KBFANP ini mengandungi empat fasa utama iaitu Pendahuluan, Pemilihan, Penilaian dan Pengutamaan. Sistem ini menyatukan kelebihan Sistem Berasaskan Pengetahuan, Teori Set Kabur dan Proses Rangkaian Analitik sebagai satu kaedah gabungan indikator piawai yang dapat digunakan dalam semua jenis konteks permasalahan. Satu prototaip Sistem KBFANP telah dibina, diuji dan dianalisis ke atas tiga set data eksperimen dan dua persekitaran pembuatan sebenar. Sistem ini mampu memberi penyelesaian terhadap bahagian yang perlu ditambah baik pada tahap keutamaan yang berbeza-beza. Kajian ini juga menyokong idea pembuatan langsing dan pembuatan hijau sebagai teras dalam pelaksanaan pembuatan lestari. Sistem KBFANP yang dicadangkan boleh bertindak sebagai Sistem Sokongan Keputusan penasihatan yang mampu memberi manfaat kepada ahli akademik dan pengamal industri.

Kata kunci: Indikator pembuatan lestari, Sistem berasaskan pengetahuan, Proses rangkaian analitik kabur

Abstract

Sustainable manufacturing is a relatively new but a very complex manufacturing paradigm. The complexity arises as this paradigm covers three interdependent yet mutually supporting sustainability dimensions of economic, environmental and social. In a further step to embark on the essence of sustainable manufacturing, the development of appropriate indicators needs to be emphasized as compared to other efforts. Regrettably, the existing indicators have several drawbacks that may hamper the accuracy of sustainability performance assessment of an organization. As such, there are only a few standardized indicator mechanisms which can suit specific requirements of various manufacturing organizations. Hence, this study suggests a novel Knowledge-Based Fuzzy Analytic Network Process (KBFANP) system which can assist the decision making process of sustainable manufacturing by developing a new indicator mechanism. The KBFANP system comprises of four major phases, namely Initialization, Selection, Evaluation and Prioritization. The system incorporates the advantages of Knowledge-Based System Fuzzy Set Theory and Analytic Network Process into a single unified approach as a standardized indicator, which is applicable to all types of problem setting. A prototype of KBFANP system was developed, tested and analyzed on three experimental data sets and two real manufacturing settings. The system was able to provide solutions on the areas that need improvement with different levels of priority. This study also supports the notion of lean and green manufacturing as the elementary foundation of sustainable manufacturing implementation. The proposed KBFANP system can act as an advisory Decision Support System which is beneficial to both academia and industrial practitioners.

Keywords: Sustainable manufacturing indicator, Knowledge-based system, Fuzzy analytic network process

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Table of Contents

List of Tables

List of Figures

List of Appendices

List of Abbreviations

ACO	Ant Colony Optimization
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
ANN	Artificial Neural Network
ANP	Analytic Network Process
CBR	Case Based Reasoning
CI	Computational Intelligence
DEA	Data Envelopment Analysis
DJSI	Dow Jones Sustainability Index
ELECTRE	ELimination Et Choix Traduisant la REalité - ELimination and Choice Expressing Reality
EMS	Environmental Management System
EPA	Environmental Protection Agency
EPI	Environmental Performance Index
ES	Expert System
FAHP	Fuzzy Analytic Hierarchy Process
FANP	Fuzzy Analytic Network Process
FKBS	Fuzzy Knowledge Based System
FLSP	Fuzzy Least Squares Priority
FLLS	Fuzzy Logarithmic Least Squares
FPP	Fuzzy Preference Programming
FMCDM	Fuzzy Multi Criteria Decision Making
FRGS	Fundamental Research Grant Scheme
FST	Fuzzy Sets Theory
GA	Genetic Algorithm
GhG	Greenhouse gas emission
GMM	Green Manufacturing Management
GRI	Global Reporting Initiative
IEA	International Energy Agency
IS	Intelligent System

ISP	Indicators of Sustainable Production
JIT	Just in Time
KBFANP	Knowledge Based Fuzzy Analytic Network Process
KETTHA	Kementerian Tenaga, Teknologi Hijau Dan Air
KPI	Key Performance Index
KBS	Knowledge Based System
LCA	Life Cycle Assessment
LCSP	Lowell Centre for Sustainable Production
LMM	Lean Manufacturing Management
LP	Linear Programming
MADM	Multi Attribute Decision Making
MCDM	Multi Criteria Decision Making
MODM	Multi Objective Decision Making
MOHE	Ministry of Higher Education
NN	Neural Network
OECD	Organization for Economic Co-operation and Development
OEE	Overall Equipment Effectiveness
PDCA	Plan, Do, Check, Act
PDSA	Plan, Do, Study, Act
QFD	Quality Function Deployment
QMS	Quality Management System
SA	Simulated Annealing
SOP	Standard of Practice
SWOT	Strength, Weakness, Opportunities, Threats
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TPS	Toyota Production System
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
VSM	Value Stream Mapping

CHAPTER ONE

INTRODUCTION

At the exact time when this thesis first sentence is being written, the total number of the current world population is 7,201,815,103 and keeps on growing at the current rate of 1.14% (Worldometers, 2013). Based on the latest United Nation (UN) projection, a continued increase in population in the future is anticipated as shown in Figure 1.1. Although there exist a steady decline in the population growth rate, the global population is still expected to reach between 8.3 and 10.9 billion by the year 2050 (UN, 2013). At a glance, this figure means nothing if we look this as a single variable. However, it means a global catastrophe if we considered it with the trending issues of scarcity of non-renewable natural resources, emerging natural environment health problems of climate change, increasing energy security and potential global famine (OECD, 2008).

Scientists have debated that current global population expansion and resource consumption increment will indeed threatened the world's economy as well as ecosystem (Nature, 2009). Nevertheless, the existing environmental problems, such as rising levels of greenhouse gas (GhG) emissions, global warming, and various types of pollution, are being further provoked by the population expansion matter (Desonie, 2008). In addition, several experts claimed that overpopulation's real casualty is our environment which as a matter of fact is not true in some point of view because human, economy and environment co-exists as separate yet unified entities that are dependent among each other (TIME, 2011; UN, 2005).

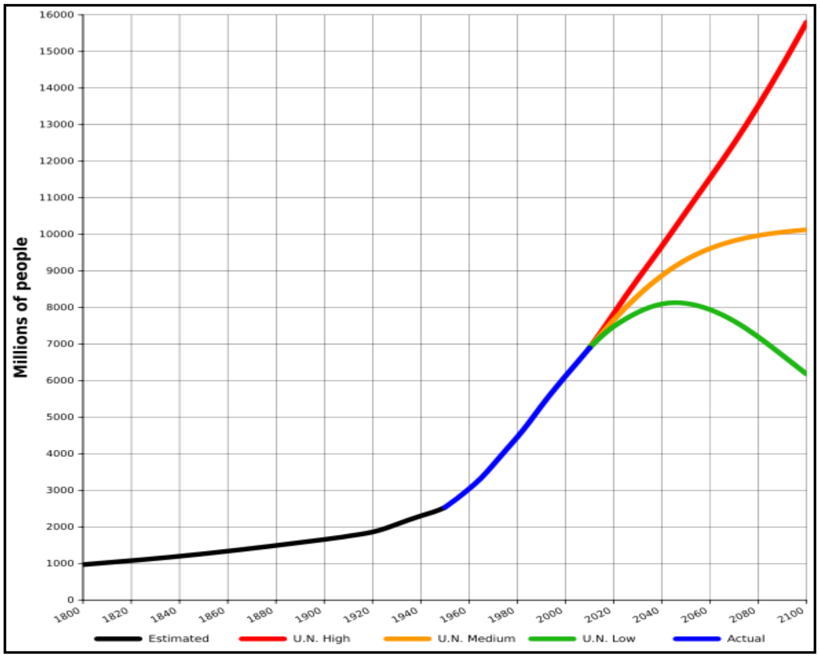

Figure 1.1. World-Population 1800-2100

Note: Reprinted from UN (2013).

As the global community is moving in the direction towards environmental preservation, several academicians and industry practitioners have already started shifting their attention towards sustainability proposition, where the scope is further enhanced with the inclusion of the economy and society future improvement (Khalili, 2011). The concept of sustainability is being propagated today and started to emerge literally everywhere starting from our household until the large scale manufacturing and service industries' operations.

Today's manufacturing is heavily linked as one of the top cause for our environmental degradation which has become a serious distress to our mother nature as well as to the global manufacturing community (Dornfeld, 2013; UN, 2005). This is certainly true as manufacturing industry consumes more energy, produces more hazardous and invaluable waste compared to other industries. From the perspective of global energy consumption, the demand for energy of manufacturing industry has been increasing exponentially for nearly a third of today's global energy usage (OECD, 2008). To make matters worse, the industry is also being held accountable for about 9.17% of global carbon dioxide (CO2) emission which is the second highest after transportation industry (IEA, 2012).

In response to this damaging phenomenon, manufacturing industry accompanied with various advancements has recently shown more interest in sustainable manufacturing paradigm (Seliger, Jawahir, & Kraisheh, 2011). From sustainability viewpoint, the manufacturing operation should consider a holistic development of an organization and its current and future potential impact towards stakeholders and external indirect parties which are affected by it. The sustainable revolution in manufacturing has just begun and there exist abundant research opportunity in the research area and yet numerous problem needs to be solved (Nasr, Hilton, & German, 2011; Seliger et al., 2011).

Driven by this new paradigm, various discipline including manufacturing is still in the point of departure, to search for the best knowledge of the sustainable practice (Onsrud & Simon, 2013; Searcy, 2009). In addition to this, relevant knowledge of sustainable manufacturing must being made accessible by the organization to assist in the decision making process. Making right decision at each process of the design, implementation and evaluation is essential to promote a vigorous sustainable development into the industry (Bonsoivin, 2013; UNEP, 2009; UNESCO, 2006).

Intrigued by this notion, this research is inspired to focus on the area of sustainability decision making process into the manufacturing practice. It includes relevant concept in the build-up of sustainable manufacturing practice and the discussion on apposite method to be used to enhance organizational decision making regarding this new paradigm. The outcome of this research expectantly will be a useful guide especially for the manufacturing organization to assist in their corporate decision making, in pursuit of a sustainability perfection.

1.1 Overview of Sustainable Manufacturing

In order to understand the concept of sustainable manufacturing, it is definite importance to know first the general concept of sustainability (Rosen & Kishawy, 2012). There are numerous definitions of sustainability suggested in the literature but the most well acknowledged definition was indeed the pioneer definition by the Brundtland Commission of the United Nations on March 20, 1987 (UN, 1987) which specified as follows:

"*The development that meets the needs of the present without compromising the ability of future generations to meet their own needs which contains two key concepts:*

1. *The concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and*
2. *The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.*"

UN (1987) suggested that sustainability should be categorized into three interdependent yet mutually supporting pillars of economic, environmental and social. Economic sustainability concerns on the section of the production, distribution, usage and management of resources which includes profit, cost saving, economic growth and research and development. Environmental sustainability focuses more on the natural environment physical aspects such as natural consumption of atmosphere, water, and soil, environmental management and pollution prevention. Finally, social sustainability addresses more on human development elements such as standard of living, education, community and equality (Khalili, 2011; UN, 1987). Between these three elements, there exists inter-relationship between each of the components as presented into two general models in Figure 1.2 and Figure 1.3.

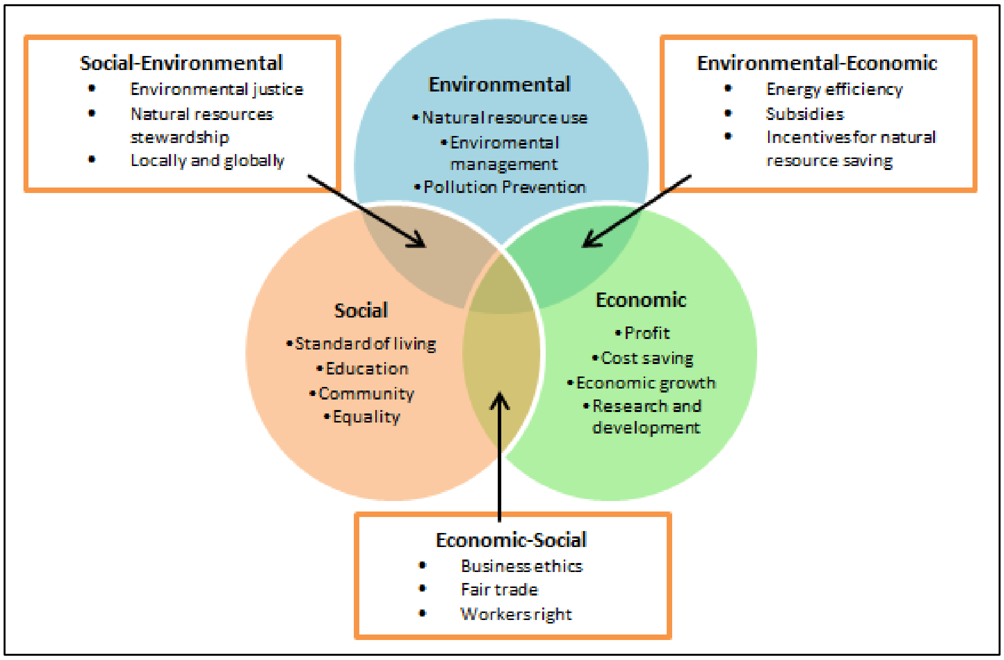

Figure 1.2. Sustainability Model 1

Note: Reprinted from Khalili (2011).

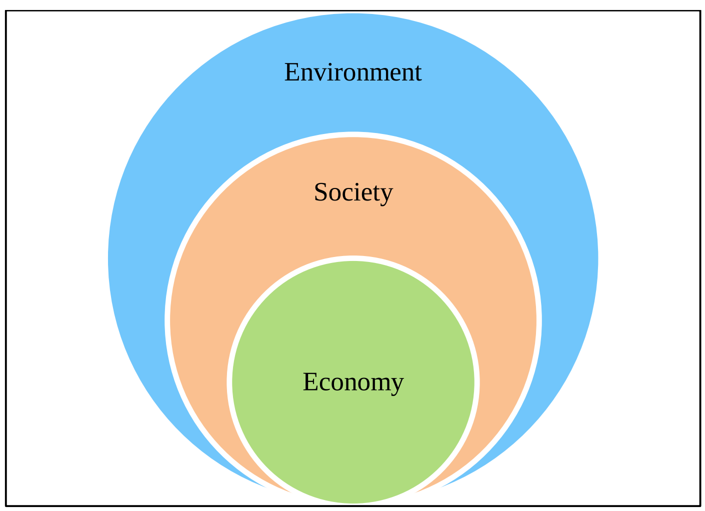

Figure 1.3. Sustainability Model 2

Note: Reprinted from NIST (2013).

From the manufacturing perspective, sustainable manufacturing is defined as "*the creation of manufacturing products that use materials and processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound*" (Dornfeld, Yuan, Diaz, Zhang, & Athulan, 2013; US Department of Commerce, 2007). The main objective of sustainable manufacturing is suggested as "*to produce better performing products using fewer resources, cause less waste and pollution and contribute to social progress worldwide*" (Nasr, Hilton & German, 2011).

Although the definition is self-explanatory, the mentioned definition and objective have unparalleled bias where the environmental element is explained in a more detailed manner. For example what is the thorough meaning of "*economically sound*" and in what form of "*contribution to social progress*" needs to be done? This description though true, might misguide our understanding regarding this concept. This issue exists because there is limited consensus regarding sustainability knowledge among various backgrounds (Helu & Dornfeld, 2013; Phillis, Kouikoglou, & Manousiouthakis, 2010). For example, environmentalist may perceive sustainable manufacturing as manufacturing that concerns on preserving the natural environment whereas economist may look it as manufacturing practice which promotes continuous economic growth.

As the formal concept is yet to be standardized, scholars are still working continuously to clarify this issue (Dornfield, 2013). Based on UN (2005), the sustainable manufacturing practice should not focus solely on the environment aspect but it also needs a balance with the economic and social sustainability aspects as well. For the usage of this thesis, sustainable manufacturing is defined as:

"The manufacturing practices which benefits towards environment, economic and society elements such that it meets present and future needs"

Based on this broader definition which is inspired by UN (1987), sustainable manufacturing should not only comply on the environment element, instead it should been emphasized equally between the three elements. In addition, it must also include the aspect that this practice can be implemented over time where it can meet the current and future needs as required.

1.2 Research Motivation

In this section, the main challenges of sustainable manufacturing as suggested by the literature are highlighted. It consists of the influence of sustainability in manufacturing system, the sustainable manufacturing issues from Malaysia's perspective, the importance of decision making in sustainability, the value of knowledge based manufacturing, the indicator necessities for sustainable manufacturing, the Knowledge Based Fuzzy Analytic Network Process approach and the application of Knowledge Based System and Fuzzy Analytic Network Process in Malaysia.

1.2.1 Influence of Sustainability in Manufacturing Systems

Global manufacturing community have recently recognized the importance of an efficient sustainable management for the production process (Onsrud & Simon, 2013). The manufacturing system function in sustainability depends on how sustainable manufacturing is actually conceptualized. Previously, a simple manufacturing system did not consider pollution prevention, end-of-pipe control and environmental restoration whereas the practice still prioritize their operations based on the traditional cost profit models, high end quality products, low cost, minimum resource usage and faster response time (Helu & Dornfeld, 2013).

This trend is unlikely to change until the future and nevertheless, the potential of sustainable element is worth to be included into the equation of current manufacturing system. The prospect of sustainable manufacturing should not be overseen and worth to be further investigated (Dornfeld, 2010; Dornfeld, 2013). The promising topics of interest which are highly inquired in the field of sustainable manufacturing are:

1. Development of metrics, indicators and any analytical technique for the performance assessment and the effect of manufacturing processes and systems.
2. Modeling and simulation of sustainable manufacturing processes and systems to examine the peculiarity of this kind of manufacturing compared with the previous practices.
3. Sustainable supply chain
4. Manufacturing tools or advancements with the objectives of minimizing the negative impact and maximizing sustainable energy sources.

Manufacturing background has changed rapidly and become more complicated due to the flexibility, adaptability and progressiveness of global manufacturing activities (Bi, Wang, & Lang, 2008). Most of the literature about sustainable manufacturing concerns on the requirements, characteristics and the needs, but they studied the sustainability components explicitly with other existing manufacturing paradigms (Jayal, Badurdeen, Dillon, & Jawahir, 2010). As the concept of sustainability has been considered as the new idea, there exist new challenges on the methodology to integrate the existing manufacturing paradigm together with the requirement of sustainable manufacturing.

In spite of plenteous researches on manufacturing system paradigms in previous years, current research regarding this matter has been halted which happens due to the uncertain research directions (Bi et al., 2008). The existing manufacturing paradigms has been implemented in current manufacturing setting and has been proven to produce good results, thus implies that it must not be simply neglected in the development of a ground model for sustainable manufacturing (Seliger, Kim, Kernbaum, & Zettl, 2008). Thusly, the current relevant issue raised here is the sustainability integration into the current manufacturing practices.

1.2.2 Sustainable Manufacturing Issues from Malaysia's Perspective

The inauguration of sustainable manufacturing in Malaysia in recent years was initiated by the launching of the Malaysian Green Technology Corporation which is also known as the GreenTech Malaysia in 2010. GreenTech Malaysia is a non-profit organization under the jurisdiction of the Ministry of Energy, Green Technology and Water Malaysia (KeTTHA). Since 2010, the organization has been held responsible to lead the implementation of projects and activities pertaining to the Green Technology Policy in Malaysia (GreenTech Malaysia, 2015).

The National Green Technology Policy was established on four main pillars which are (1) Energy, (2) Environment, (3) Economy and Social. Under this policy, green technology was aimed to be the key driver in accelerating the national economy and promoting the sustainable development in Malaysia. In spite of that, the sustainability thinking have not been nurtured appropriately in Malaysia due the strict usage of the term 'green'. During the Asia Green Conference 2013, it was not surprising that the notion of sustainability has been hailed to be more important than only preserving the natural environment (Haris, 2013).

In 2010, Malaysia was evaluated by the Environmental Performance Index (EPI) index value of 65.0 compared to the value of 53.0 for the previous year of 2009. The latest data indicated that Malaysia is ranked 25th from 163 countries and was categorized as a strong performer (YCELP, 2011). Albeit the report showed positive connotation of the Malaysia's performance towards sustainability, this data only specified the environmental sustainability performance, which did not include economic and social performance.

In general, there are three major challenges for Malaysia in moving towards sustainability, which are environmental awareness, renewable energy and cost effective green technology. From the perspective of the third challenge which is to develop a cost effective green technology, Malaysia still experiences a wide gap in understanding and implementing this technology into practice (Razak, 2009). Hence, the issue of sustainable manufacturing implementation in Malaysia is worth to be explored.

1.2.3 Importance of Decision Making in Sustainability

As the concept of general sustainability is still en route to be applied into various settings, the implementation guidelines are proposed by prominent organization of United Nations Educational, Scientific and Cultural Organization (UNESCO), United Nations Environment Programme (UNEP) and Organization for Economic Co-operation and Development (OECD). Most of these guidelines are being made available to global community in their attempt to promote sustainability practice across the globe. According to these guidelines, decision making process is fundamental during the sustainability transformation phase of an organization.

Decision making process involves the "*selection of a course of action from among two or more possible alternatives in order to arrive at a solution for a given problem*" (Trewartha & Newport, 1976). It can also be described in more detailed manner as "*a problem to be solved, a number of conflicting objectives to be reconciled, a number of possible alternative courses of action from which the best has to be chosen and some way of measuring the value of payoff of alternative courses of action*" (Clough, 1963). From Clough (1963) definition, it is essential if the decision making process strive for the best possible solution. In other words, optimal and perfection is the prime key. From the perspective of sustainability objective, it is desirable if the best courses of action can be chosen to solve the problem as addressed in this research.

In separate guidelines, UNESCO (2006) and UNEP (2009) established necessary decision making process flow for the development of sustainability policy. Both of these guidelines agreed that an effective method for policy and performance measurement is highly obligatory for sustainability transformation process. Prior to this, the selection of criteria used to evaluate the courses of action is indispensable to produce the best decision as shown in Figure 1.4. In addition, UNESCO (2006) also highlighted the importance of data, information and knowledge with regards to this process as shown in Figure 1.5.

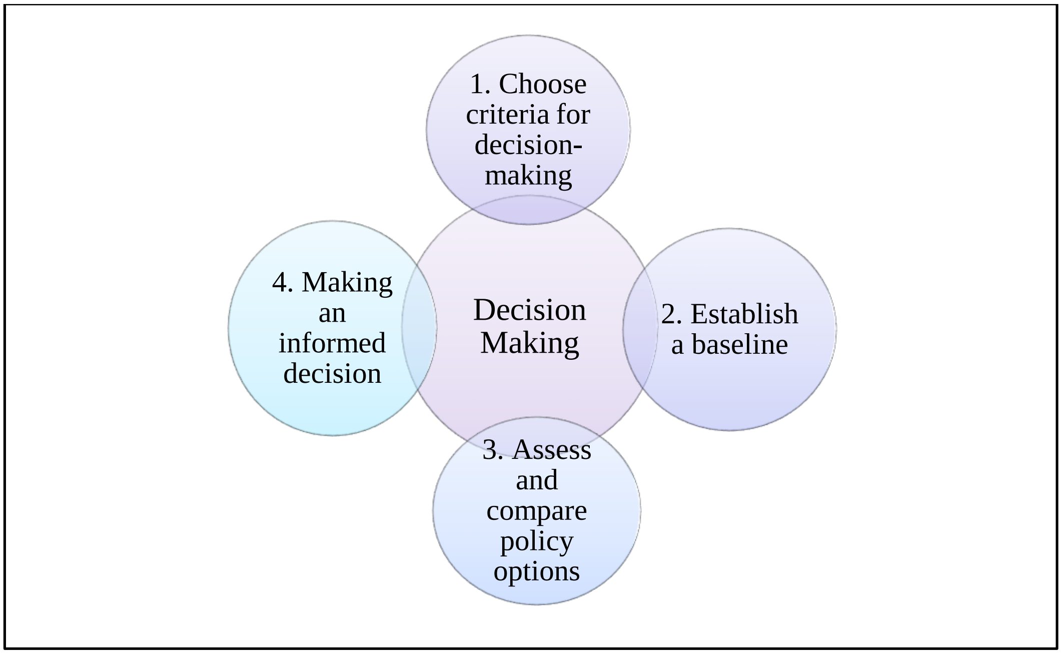

Figure 1.4. Decision Making Process of Sustainable Manufacturing

Note: Reprinted from UNEP (2009).

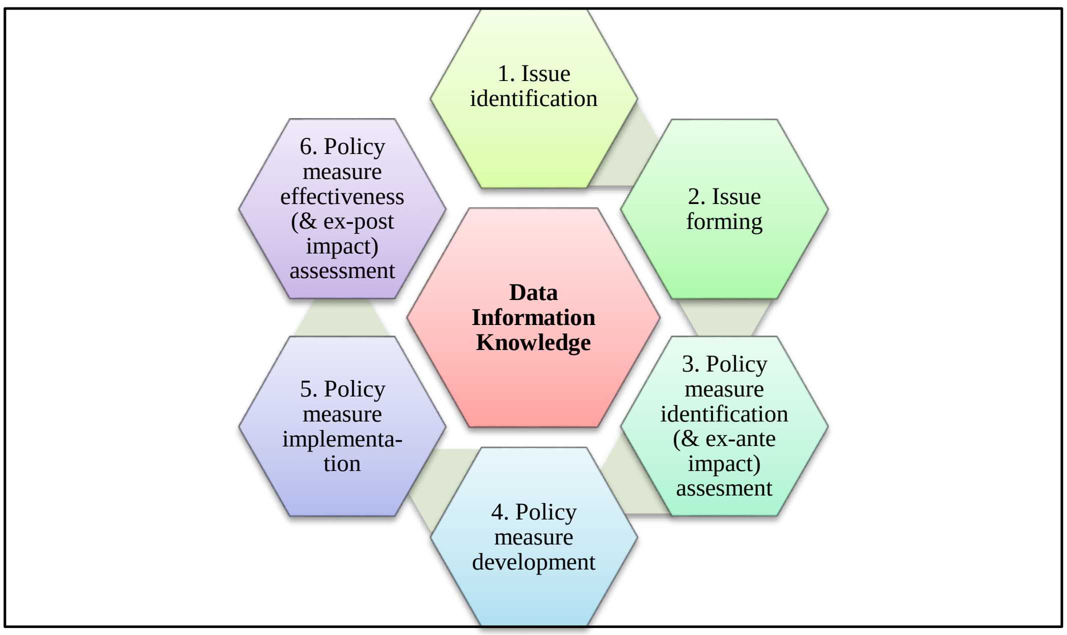

Figure 1.5. Decision Making Steps in Sustainable Manufacturing

Note: Reprinted from UNESCO (2006).

From the perspective of manufacturing application, OECD (2008) provided a thorough step by step guide for the sustainability decision making process. They suggested a seven step measure to achieve that purpose as shown in Figure 1.6.

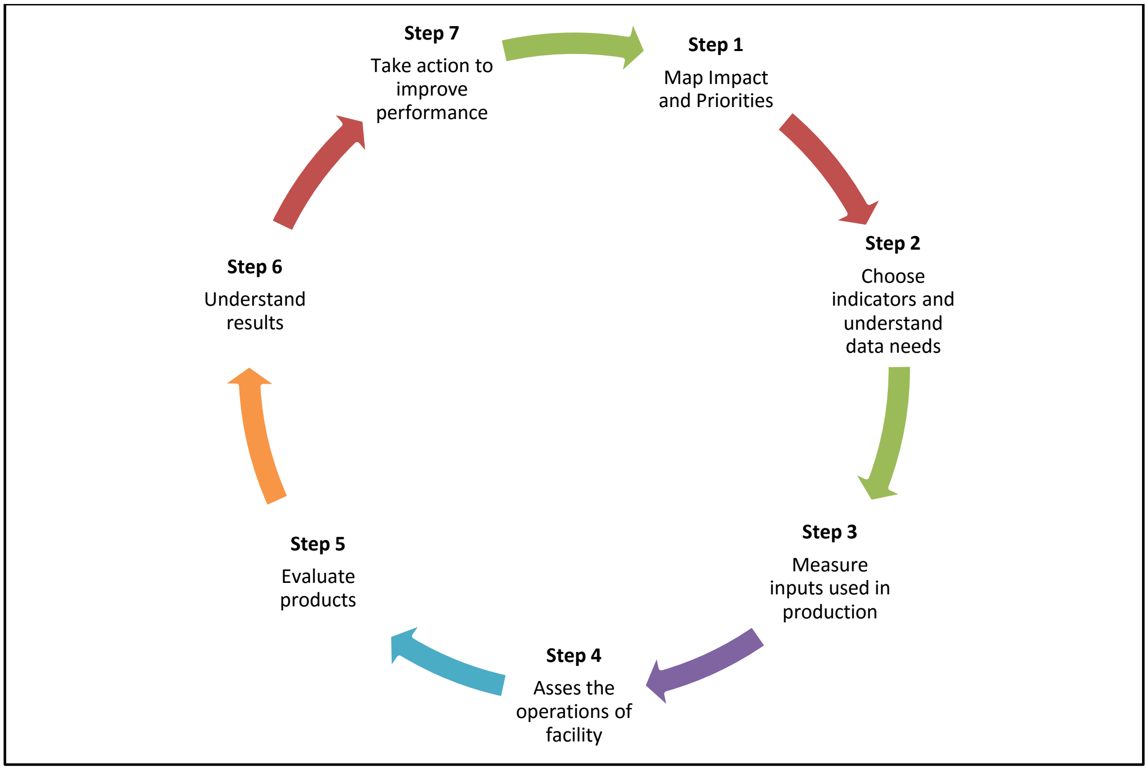

Figure 1.6. Seven Steps to Implement Sustainable Manufacturing

Note: Reprinted from OECD (2008).

Based on the decision making process flow given by UNESCO (2006), UNEP (2009) and OECD (2008), these guidelines can be made in accordance with Polya's methods of problem solving and Deming's PDSA cycle (Plan, Do, Study, Act) of continuous improvement (Deming, 1950; Polya, 1945). The planning stage inquires the organization to draft the overall mission and to set up a guideline for the implementation. The implementation process follows after that before a measurement mechanism is been done as a post mortem basis to check for the success and the failure elements which occurred during the implementation stage. The final stage involves the act stage which referred to the revision work done based on the correction on the check stage. These stages will be repeated again until the organization is able to achieve a flawless sustainability implementation.

Via these guidelines, there are two main aspects that need to be emphasized which are contained in the initial step of implementation. The aspects are the prioritization of criteria and the selection of indicators as a basis for continuous sustainable performance monitoring (OECD, 2008; Reich-Weiser, Simon, Fleschutz, Yuan, & Athulan, Vijayaraghavan, Hazel, 2013; UNEP, 2009; UNESCO, 2006). In addition, the initial step should be focused thoroughly as it is regarded as the most important step compared with other phases because if it is not being planned carefully, it may affect the overall decision making process.

1.2.4 Value of Knowledge Based Manufacturing

In describing, understanding and implementing the practice of sustainable manufacturing, it is essential to prioritize the element of knowledge. One of the earliest challenges ever suggested in the sustainable manufacturing movement are in fact focused on the issues of knowledge integration and organizational learning (Scapolo, Geyer, Boden, Dory, & Ducatel, 2003). This is unquestionably true because in order for the organization to be able to adapt to the rapid changes and complexity of the paradigm, the organization must go through learning process. Consequently, learning can be achieved through gaining and understanding the feedback of those changes (Sajja & Akerkar, 2010).

The latest manufacturing paradigm should composes of transforming the manufacturing industry from being only productivity based towards being more knowledge based (European Commission, 2003; Lanz, Jarvenpaa, Garcia, Luostarinen, & Tuokko, 2012; Paiva, Roth, & Fensterseifer, 2008). The key success in a complex manufacturing setting today depends on the performance of the information and knowledge management (Scapolo et al., 2003). The information and knowledge of the manufacturing management which includes internal knowledge, stakeholders' and customers' feedbacks, need to be integrated and processed in real time manner in order to support both daily operation and decision-making procedure.

1.2.5 The Indicator Necessities for Sustainability Decision Making

In a further step for current academician and industry practitioners to embark on the essence of sustainable manufacturing movement, the development of indicators is the most important thing which need to be prioritized compared with other efforts (OECD, 2008; UNEP, 2009; UNESCO, 2006). This fact is also has been highly advocated as the practical evidence has been substantial. In recent times, several organizations have begun to develop sustainability indicators in order for them to continuously monitor their real progress with respect to sustainability measure (Dornfeld et al., 2013; Emmet & Sood, 2010; Reich-Weiser et al., 2013).

Indicator is defined as "*a sign that shows the condition or existence of something*" or "*a device that shows a measurement*" (Merriam-Webster, 2013). From the context of sustainability, indicator is generally defined as a numerical assessment which delivers significant information in relation with the economic, environment and social sustainability aspects (Veleva & Ellenbecker, 2001). As a measurement instrument, indicator has three elementary objectives which are (1) to disseminate awareness, knowledge and understanding; (2) to guide and support the decision-making process; and (3) to appraise the development towards achieving the objective (Fan, Carrell & Zhang, 2010).

Based on researcher's exhaustive search, globally there are 12 general indicators to measure sustainability performance for an organization that may be applied to manufacturing environment (NIST, 2013). In term of specific sustainable manufacturing indicators from the academia, there are four applicable indicator which are: (1) (Veleva & Ellenbecker, 2001), (2) (OECD, 2008), (3) (Fan et al., 2010), and (4) (Amrina & Yusof, 2011). However, the challenges which exist in these indicators which are still not being resolved yet are:

1. No indicator is applicable to evaluate sustainable manufacturing as a whole.
2. There is a tendency to construct a single unified indicator which can be applied to any problem setting.
3. Social and economic sustainability indicators are not being developed thoroughly.
4. Most indicators with the exception to Global Reporting Initiative (GRI) only use quantitative approach to measure organizations' sustainability performance.
5. The indicator should being developed in a small manageable number between 10 and 20 criterions.
6. Lack of clear guidance and instructions on existing indicator for implementation purpose.
7. Wide diversity of existing indicators frameworks which made the indicator selection process becomes more complex and ambiguous.

As stated here, there are indeed many unresolved issues regarding the development of sustainable manufacturing indicators. Combining the issues of the sustainability influence towards manufacturing, the importance of decision making, the constructive value of knowledge based manufacturing and indicators prerequisite for sustainable manufacturing progression, a novel technique which can be used to resolve the aforementioned issues is advocated via this research, which is the Knowledge Based Fuzzy Analytic Network Process (KBFANP) system.

1.2.6 Knowledge Based Fuzzy Analytic Network Process Approach

Analytic Network Process (ANP) is recognized as one of the efficient tools for Multi Criteria Decision Making (MCDM) approach that has been extensively applied in various practical researches during this past decade (Saaty & Vargas, 2006; Saaty, 2010; Sipahi & Timor, 2010; Tzeng & Huang, 2011). ANP is a generalized and extension form of Analytic Hierarchy Process (AHP) where it relaxes the hierarchical assumption, thus enables a more complex interdependency and feedback formulation among the criteria considered as opposed to other MCDM methods. There are various researches which combined ANP with other techniques such as Fuzzy Sets and Fuzzy Logic, Quality Function Deployment (QFD) and Linear Programming (LP) which exhibits the flexibility of ANP compared with the other approaches in MCDM.

In general, MCDM method postulates that all of the considered criteria and its respective weight is represented in the form of crisp value. The crisp value in this manner refers to the value which is deterministic. Preferably, the most ideal condition to formulate MCDM problem is when the criteria rating and its relative importance scale is known accurately (Hwang & Yoon, 1981; Tzeng & Huang, 2011). In spite of that, most of the real-world decision making situation occurs in an environment where the goals, constraints, and actions taken are imprecise nor vague (Bellman & Zadeh, 1970; Kahraman, 2008a). In some practical cases, the attribute of the criteria can only be conveyed via verbal term which inquires the need for a combination between Fuzzy Sets Theory (FST) with MCDM approach.

In a research done by Etaati, Sadi-Nezhad and Moghadam-Abyaneh (2011), they revealed an increasing number of researches done using Fuzzy Analytic Network Process (FANP). This fact justifies the increasing trend of interest in this knowledge field in recent decades. From 2003 until 2011, there are 53 researches from various high impact journals which utilized FANP. From these 53 researches, 22 focused on the manufacturing problem and only two researches applied FANP on the sustainable manufacturing problem which are Tseng, Divinagracia and Divinagracia (2009) and Lin, Cheng, Tsen and Tsai (2010).

Tseng, Divinagracia, and Divinagracia (2009) scope is on the sustainable manufacturing indicator and Lin, Cheng, Tseng, and Tsai (2010) investigated on the environmental production requirements. Therefore, there is only one research which concerns on the development of sustainable manufacturing indicator with the application of FANP. However, using only FANP in this effort is not sufficient, because FANP only deals with the increased complexity manufacturing paradigm and the indicators issue whereas this does not make it a knowledge based manufacturing approach where it is considered to be essentially important in current manufacturing practice.

The decision making process is usually made by the top level managers as they are also regarded as the experts in their respective field. These top level managers usually cooperated and work together in the planning phase of strategic plan, goals and action to be implemented (Scapolo et al., 2003). As the concept of sustainable manufacturing is relatively new, its nurtured knowledge must be accurate as well as to be accepted comprehensively. Thus, it is strictly important such that the knowledge is been disseminated and understood among all the individuals in the company (Lanz et al., 2012; Onsrud & Simon, 2013). The initial problem in knowledge sharing is on the knowledge acquisition from the respective experts which can also be known as knowledge domain or knowledge source (Milton, 2007). There are many ways to represent the knowledge and one of the most effective ways to do this is by developing it into a Knowledge Based System (KBS)

A KBS is a computer system that comprises of the expertise knowledge required for solving a specific problem. KBS derives their effect from the knowledge in the form of knowledge base (Awad, 1996; Giarratano & Riley, 2005). The general advantages of KBS compared to other methods are that it can reduce knowledge dissemination time and minimize the burden of the experts which can promote an effective and efficient company's operation (Metaxiotis & Psarras, 2003). The main feature of KBS is that it can solve problem symbolically instead of numerically. Therefore, it can perform better in terms of both decision makers' preference and qualitative criteria which cannot be included on a basic mathematical model due to the increased degree of problem complexity (Kordon, 2010). The combination of KBS and other FMCDM approach can be a complement tool and may provide better solution to other practical problems. As El-Wahed (2008) pointed out, there exist limited amount of researches with regards to the mutual implementation of KBS with FMCDM, hence proving abundant opportunity for more future research in this knowledge field.

1.2.7 Application of Knowledge Based System and Fuzzy Analytic Network Process in Malaysia

At the present time, the integration of KBS and FMCDM in Malaysia's context is still limited especially in terms of sustainable manufacturing application. In spite of that, the application of KBS has been adopted in many of the Malaysia's problem background. Unfortunately, this situation is not the same towards FANP in which the method implementation was very scarce. In Malaysia, KBS has been extensively used in engineering, medical and disaster management field.

In engineering for example, Sapuan (2001) proposed a KBS framework for material selection in mechanical engineering. Similarly, Sapuan, Jacob, Mustapha and Ismail (2002) produced a prototype KBS for material selection of ceramic matrix composites for automotive engine components. In addition, Chandrasselan, Jehadeesan and Raajenthiren (2008) also developed a web-based KBS for selection of non-traditional machining processes. In other instances, Mustapha, Sapuan, Ismail and Mokhtar (2004) focused on a system for fault diagnosis of an aircraft engine and Arunagiri and Venkatesh (2004) engrossed on the simulation of voltage stability and alleviation. Shawal and Taib (2003) created a KBS based evaluation tool for photovoltaic power supply. Amelia, Wahab and Hassan (2009) managed to model the process of palm oil production using fuzzy KBS (FKBS). Moreover, Mustapha, Ismail, Sapuan, Noh, and Samsuri (2010) extended their work on fault diagnosis of aircraft engine with the Cessna Aircraft Company, which is an American aviation aircraft manufacturing corporation in Kansas, United States as their case study.

Interestingly, the development of KBS for medical purposes in Malaysia has been vigorous which revived the success of the first KBS ever made which is MYCIN (Awad, 1996). MYCIN was used to identify bacteria which cause severe infections and to recommend antibiotics. In contrast, Sharif, Daliman, Sha'ameri and Salleh (2001) produced a KBS for the classification diagnosis of heart sounds and murmurs whereas Ibrahim, Taib, Sulaiman and Abbas (2001) specialized on dengue fever (DF) and dengue haemorrhagic fever (DHF) symptoms analysis. Ibrahim, Ali, Jaais and Taib (2001) came out with a diagnosis system of eye diseases with specific interest on the Malaysian population. Finally, Javed, Venkatachalam, and Hani (2007) developed a KBS with embedded intelligent heart sound analyzer for diagnosing cardiovascular disorders.

Other honorable mentions of KBS applications in Malaysia includes Basri (2000) for landfill leachate management, Yousef, Adam, Daud, Omar, Ahmed and Musa (2004) for the performance of solar air collectors, Idrus, Nuruddin and Rohman (2011) for project cost contingency estimation model, Pauziah, Kamil, Latifah and Mohamed (2010) for river water quality management and Oshaksaraie, Basri, Bakar and Maulud (2012) for the storm water management plan in construction. Regardless, all of these researches did not focus on the indicator related problem along with the sustainable manufacturing problem field. The KBS developed by them was also case specific, and cannot be generalized or standardized for various case domain (Abdullah, Evans, Benest and Paige, 2004).

1.3 Problem Statement

In light of the environmental issue together with economic and society sustainability issues that becomes global attention at the moment, many approaches have been proposed and tested in order to solve this problem. From the manufacturing sector point of view, this movement can be branded as sustainable manufacturing. Therefore, the search for the best solution to solve the sustainability problem in this industry is still plausible and the search still continues (Dornfeld et al., 2013; Jayal et al., 2010; Nasr et al., 2011; Seliger, Kim, & Zettl, 2008; UN, 2005). It is no doubt, that this issue is definite importance to the manufacturing world today.

As the sustainable manufacturing is still a buzz word even for the industrial practitioner themselves, there are certain pertinent issues that need to be prioritized in order for the world to embrace the new wave of this relatively new concept. From the previous section, the sustainable paradigm has been regarded as the most complex manufacturing system to date. The fact is clarified as this paradigm covers three main issues holistically without compromising one element explicitly (Bi et al., 2008; Jayal et al., 2010).

The existing paradigms have been used by the manufacturing sector to give them insights on how to manage their factory operations and have been proven to be effective. Therefore, rather than building a novel concept of sustainable manufacturing from scratch, it is better to integrate the best existing paradigm, so that it can be used to achieve sustainability objective. This task is considered complex and the ongoing research to work on this issue is limited with few consensus exist among scholars on how can we actually define, describe and implement the aspects of sustainable manufacturing. Thus, the very first problem that needs to be addressed is the complex integration of existing manufacturing paradigm for the construction of sustainable manufacturing concept.

So then, how can we measure the level of sustainability progress related to manufacturing? The answer is fairly evident which is by the development of indicator in which some scholars refer to as metric. Unfortunately, the amount of indicator related to sustainable manufacturing is very inadequate. In addition to that, the existing indicators have several gaps that may that hamper an accurate explanation of the actual picture of the sustainability performance among the scholars and the industry practitioners. The problem in terms of indicators that being addressed in this research is there is no standardized indicator mechanism that can suit specific requirement of various manufacturing organizations as shown in Figure 1.7 (Amrina & Yusof, 2011; Fan et al., 2010; Reich-Weiser et al., 2013; Veleva & Ellenbecker, 2001).

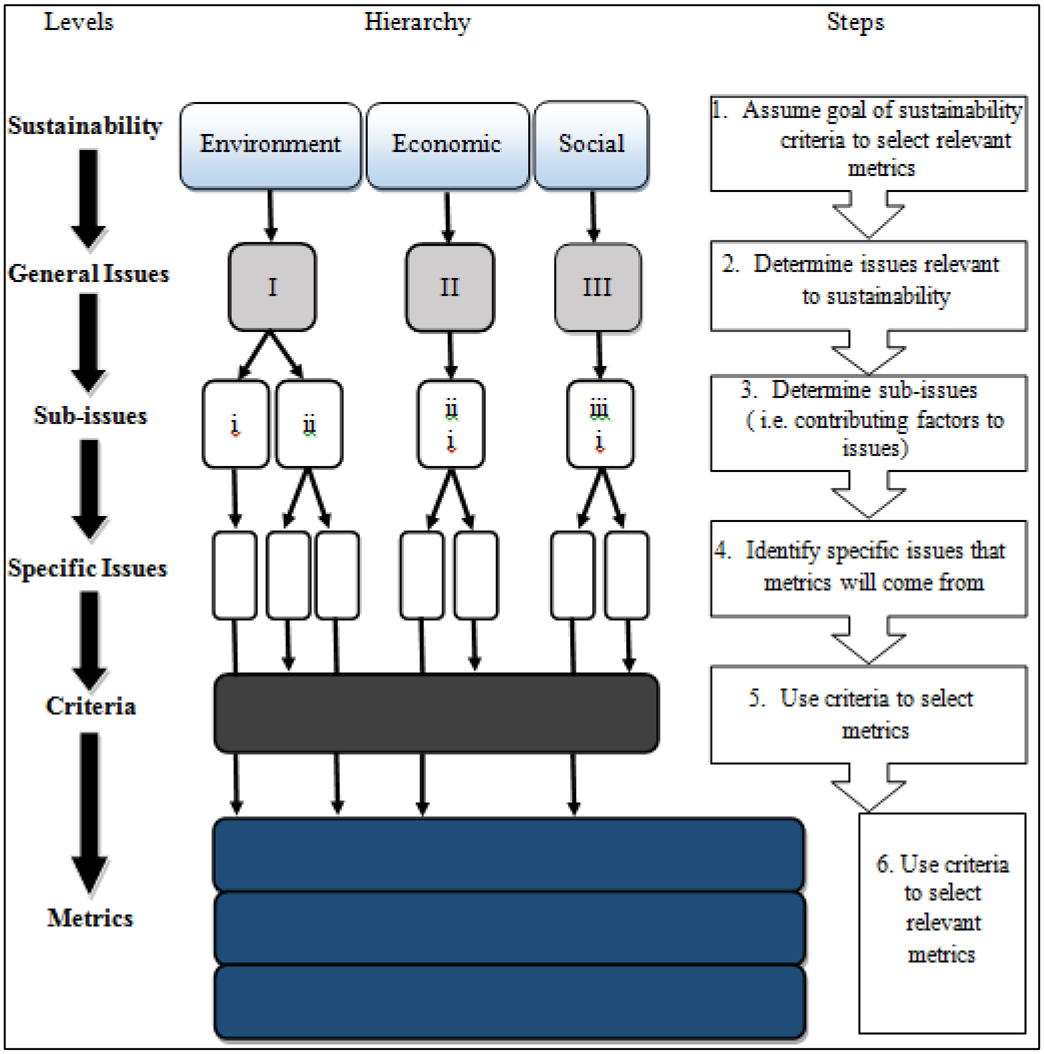

Figure 1.7. Future Trend of Standardized Indicator Mechanism

Note: Reprinted from Reich-Weiser et al. (2013).

In order to solve these problems, the Fuzzy Analytic Network Process (FANP) technique which has gained attention among the scholars in current period was explored (Etaati, Sadi-Nezhad, & Moghadam-Abyaneh, 2011). To the best of researcher's knowledge, to date there is only one research which used FANP technique in sustainability indicator problem field which is Tseng et al. (2009). However, the KBS or

Expert System (ES), the term used by Tseng et al. (2009), have no utilization of the KBS elements which are the knowledge itself. The system developed in their research lack the qualitative elements which includes knowledge base and reasoning. Thus, their system can be addressed more as a general Decision Support System (DSS) rather than KBS. In addition to that, there exists no effort in combining FANP with KBS tool in any kinds of problem domain. The researcher’s claim was justified by Kahraman (2008), El-Wahed (2008) and Etaati, Sadi-Nezhad, and Moghadam-Abyaneh (2011).

The utilization of knowledge is best represented in the form of Knowledge Based System (KBS) for practicability purpose. Fuzzy Sets Theory (FST) is needed in order to capture the sustainability knowledge where in the current time, is still not known precisely in all fields especially in the manufacturing sector. Analytic Network Process (ANP) together with normalization method are chosen as the sustainability indicator tool to measure the manufacturing sector implementation progress. ANP is chosen as it is the only Multi Criteria Decision Making (MCDM) method which allows complex interaction and interdependency among the criteria in the decision problem. In spite of that, ANP alone is not sufficient to solve the problem addressed. ANP must be incorporated with FST to deal with the ambiguous description of the problem. For a better representation of the problem statement, a summary is shown in Venn diagram form as in Figure 1.8.

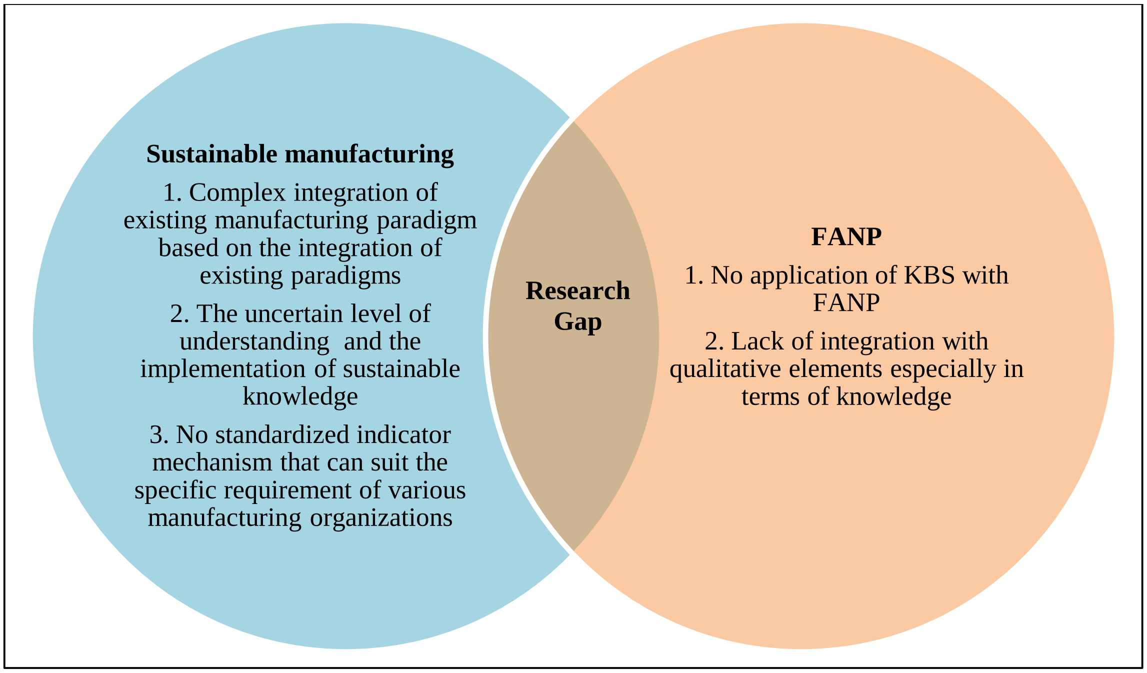

Figure 1.8. Summary of the Problem Statement

Based on FANP, an integration with KBS is being suggested in order to develop a standardized sustainability indicator mechanism that can suit specific requirement of the organization particularly in manufacturing. The approach also intended to support the decision making process, to enhance the productivity, the practicability and knowledge dissemination purpose. In a nutshell, the KBFANP system is highly proposed to solve the problem of this research.

1.4 Research Question

Based on the given problem statement, several disputes have arisen which was sum up as follows.

1. What are the best practices of sustainable manufacturing applied in the literature and the actual manufacturing industry?
2. What is the best sustainable manufacturing indicator model for sustainable manufacturing?
3. What is the suitable approach to implement a standardized sustainable manufacturing indicator which can solve the issues of
   a. The vagueness of sustainability dimensions and criteria?
   b. Inter-relationship among sustainability dimensions and criteria?
   c. A more accurate assessment of the sustainability performance of a particular organization?
4. How to develop the standardized sustainable manufacturing so that it can be implementable in real world manufacturing environment?
5. How to ensure that the approach used is effective and efficient?

1.5 Objective of the Research

Based on the research question, the overall aim of this research is to develop a Knowledge Based Fuzzy Analytic Network Process (KBFANP) system which can assist in the decision making process of sustainable manufacturing by the development of sustainable manufacturing indicators. Prior to this, the specific objectives of this research are:

1. To examine the best practices of sustainable manufacturing applied from the literature and the actual manufacturing industry
2. To suggest a sustainable manufacturing indicator model of sustainable manufacturing based on the chosen sustainable manufacturing practices.
3. To develop a Knowledge Based Fuzzy Analytic Network Process system for sustainable manufacturing indicator.
4. To implement and validate the Knowledge Based Fuzzy Analytic Network Process system for sustainable manufacturing indicator.

1.6 Scope of the Research

This research only concentrated on the indicators from the perspectives of general sustainable manufacturing without any specification towards different types of manufacturing such as automotive, chemical, petroleum and electronics. This research also did not investigate upon the context of general sustainability and other sustainability problem fields which includes sustainable transportation, sustainable energy or sustainable service. Thus, the indicator developed in this research may not be applicable to the aforementioned areas. This research was applied to manufacturing organization in Malaysia, which is coherent with the requirement to reduce the gap in sustainability practice implementation in Malaysia as discussed in Section 1.2.2. The method of KBFANP is anticipated to revitalize the application of KBS and to bring awareness of FANP method in Malaysia as mentioned in Section 1.2.7.

1.7 Originality of the Research

The main originality of this research is the notion of KBFABP system as a novel decision making tool to evaluate the overall progress towards achieving sustainable goals. As mentioned previously in the Section 1.3, to date there is only one research which used FANP method in sustainability indicators problem field which is Tseng et al. (2009). This research can be considered as a continuation of Tseng et al. (2009), Amrina and Yusof (2011) and Fan et al. (2010) combined with the suggestion for future work by El-Wahed (2008) and Reich-Weiser et al. (2013). The originality can be divided into two areas which are problem and method in Decision Science/Operations Research.

1.7.1 Problem

This research can be accounted for the development of a standardized sustainable manufacturing indicator which emphasize the balance between the environment, economic and society as insisted by Fan et al. (2010), Helu and Dornfeld (2013) and Reich-Weiser et al. (2013). Besides, this research also attempts to combine the existing manufacturing paradigm of lean and green manufacturing elements into the original setting of sustainable manufacturing indicator as advocated by Bergmiller, Mccright and Florida (2009), Carvalho, Duarte, and Machado (2011), Dues, Tan, and Lim (2013) and Miller, Pawloski, and Standridge (2010). Hence, this research is able to provide the reestablishment of sustainable manufacturing paradigm based on the integration of lean and green with the needs of sustainable manufacturing concept.

1.7.2 Method in Decision Science/Operations Research

The research of Tseng et al. (2009) managed to determine the ranking of the criteria in the indicator, whereas the researcher suited it with the requirements of specific manufacturing organization setting. It means that, although the criteria ranking is true for all application, it may or may not be necessary if the performance level is within the acceptable range. For example, if manufacturing company A managed to perform well in criteria 1, then it does not need to improve the area of indicator where the converse fact applies. This is proven to be a significant advantage to this research's approach as it can gives advice to the company by prioritizing which elements should be improved. This can be made with the combination of FANP capability to rank and the KBS capability to develop rules in the knowledge base and inference strategy. The approach also managed to include the reasoning strength of KBS which can be used to give explanation regarding the performance of sustainable manufacturing based on case company appropriateness.

In a nutshell, this research's strategy has both qualitative aspect from the usage of FST and KBS, and quantitative nature of ANP. It also has a systematic validation process of the qualitative input by utilizing FST and provides inter-dependency competency among elements via ANP. The KBFANP can be made as a decision support system (DSS) which provides decision making guide by promoting the value of knowledge, knowledge sharing and organizational learning via KBS application. All of these components which are unified under a single approach in this research can be claimed as a novel one, as all of these essences did not exist in the previous research.

1.8 Significance of the Research

Based on the approach proposed via this research, it is expected that this research will give contributions from the perspectives of the areas of Decision Science/Operations Research, manufacturing industry and society.

1.8.1 Decision Science/Operations Research

The contribution of this research towards Decision Science/Operations Research field is by the KBFANP system as a novel decision making support tool which is applicable as a benchmarking tool to evaluate any defined problem setting. The approach's contributions can be divided into three folds. The KBS part is used to acquire the knowledge needed, to provide practical mechanism for knowledge implementation and to refine the indicators to suit specific requirement of various organizations. The vague nature of sustainability knowledge constraint can be relaxed by FST during the knowledge acquisition process which is needed in the ANP formulation. The integration of these three separate techniques can be used as a unified strategy of qualitative and quantitative scheme as well as beneficial to both theory and application side. This profound novel method is essential as it represents the gist of Decision Science/Operations Research itself which is the application of mathematical or analytical tool to unravel the real world problem in the society (Decision Sciences Institute, 2014).

1.8.2 Manufacturing Industry

The inauguration of sustainable manufacturing which is still relatively new to the current global manufacturing industry via this research is extremely beneficial to the industry. This research will create awareness to this new paradigm which has started to revolutionize the manufacturing world through its positive potential that it provides. In addition, this research involves existing paradigms of lean and green, which are currently being implemented in most of the manufacturing companies today especially the lean paradigm. The ideas of integration with the sustainable elements will give an insight on the transition together with the KBFANP system which is hopefully can accommodate the process.

The solution provided by this research also will help them in measuring their overall progress in achieving the sustainable objective and to compare the difference in results after the implementation. The intention of this KBFANP system is to support the manufacturing company to be able to suit their own problem requirement. Therefore, instead of just knowing which criteria is the best, they will also are able to know which criteria is related to them and which area that needs to be improved accordingly. The enhanced version indicator that is produced could give a more detailed result along with the explanation on why they need to improve those area.

1.8.3 Society

As Malaysia is moving towards environmental sustainability, there is a need to emphasize on the usage of green technology (Razak, 2009). The application of green technology in the field of manufacturing can be employed by the concept of sustainable manufacturing. The knowledge of sustainable manufacturing to be suggested by this research hopefully may help the decision makers in related organizations to have a clear understanding regarding sustainable manufacturing and to assist them in decision making situation. Additionally, this research also has been funded by the Ministry of Higher Education (MOHE) under MyBrain15 MyPhD program and Fundamental Research Grant Scheme (FRGS) which demonstrates its significance to the Malaysian society due to the possible potential it possesses.

1.9 Outline of Thesis

This thesis composes of six chapters. Chapter One is the Introduction which briefly describes the general concepts of sustainability and sustainable manufacturing. It includes the main matter related to sustainable manufacturing as discussed in the research motivation section. The justifications of the needs to focus on those problems are also summarized into a problem statement which yielded several research questions. Prior to these needs, a novel technique of Knowledge Based Fuzzy Analytic Network Process system is proposed. The scope, the originality as well as the significance of the research are also clarified in this chapter.

Chapter Two is the Review of Sustainable Manufacturing Indicator which comprises of the review of sustainable manufacturing and the existing manufacturing paradigm which contributes to the formation of a sustainable manufacturing framework. In this chapter, two manufacturing paradigms are discussed which are lean and green manufacturing. These two paradigms are perceived to be the best combination out there to date in order to build up a potent sustainable manufacturing framework. In addition, a review regarding the sustainable manufacturing indicators which is used in previous researches to measure the performance of sustainable manufacturing is shown and discussed.

Chapter Three is the Review of Fuzzy Analytic Network Process Knowledge Based System which targeted to the novel strategy of this research which is the Knowledge Based Fuzzy Analytic Network Process (KBFANP) System. In this part, a review of Knowledge Based System, Fuzzy Sets Theory and Analytic Network Process is briefly described. Next, review of past researches which utilized Fuzzy Analytic Process and Knowledge Based system issues are surveyed. This chapter ends with the justification of combining these three separate techniques and the advantages of this combination.

Chapter Four is the Methodology which embarks the journey of this research. The research process flow is shown according to the phases of research design, system development and implementation. At each phase, the steps required to be done is described. This chapter ends with the proposed approach of this research which is the Knowledge Based Fuzzy Analytic Process (KBFANP) system.

Chapter Five is the Results and Discussions which describe the implementation of the KBFANP system in manufacturing organization. The progress of the steps mentioned in the Methodology is explained explicitly before the development of the KBFANP system which encompasses of Initialization, Selection, Evaluation and Prioritization phases which is described in detailed manner. The implementation of two case companies and three experimental data was then revealed and analyzed. The performance of the KBFANP system is also verified and validated in this chapter.

Chapter Six is the Conclusion which recaps the research in a nutshell. It includes the summary of the research which includes the achievement of research objectives in sync with the breakthrough of this research. This chapter proceeds with the implication of the research towards Decision Science/Operations Research and manufacturing industry. This chapter ends with the limitation of the research together with fruitful future work recommendations.

CHAPTER TWO

REVIEW OF SUSTAINABLE MANUFACTURING INDICATOR

The understanding of the current manufacturing's knowledge experiences rapidly changing paradigms, which becomes more complicated due to the flexibility, adaptability and progressiveness of the global manufacturing activities. This chapter begins with a brief description of the concept of sustainable manufacturing. Next, the past manufacturing paradigms which contribute to the conceptualization of sustainable ideology in manufacturing are compared and examined. This structure flow is relevant because it shows the precedent manufacturing philosophies changes and improvisation which leads to the ideas of sustainable manufacturing subject to their value and significance.

Then, a review of the past indicators used to measure the sustainable practice in manufacturing is examined as it is shown to enhance the decision making process specifically to this particular problem. These indicators are examined before a suitable indicator which is used in this research is selected to be integrated to be used as a ground model. By exploring the discussed areas of literature, a significant indicator model is made via this research. At the end of this chapter, it is hoped that critical understanding of key issues of sustainable manufacturing indicator is exhibited, in such a way that the reader will be well informed in this areas of research.

2.1 Sustainable Manufacturing Ideology

The first time the concept of sustainability was introduced to the manufacturing community, it was being initially established to solve the problem of environmental calamity. A number of new terminologies have been proposed to support this notion from the viewpoint of manufacturing such as Green Manufacturing, Environmentally Conscious Manufacturing, Reverse Manufacturing, Energy Efficient Manufacturing, Renewable Energy Source Manufacturing, Economically Advantageous Manufacturing and also the latest one which is Sustainable Manufacturing (Dornfeld et al., 2013; Jayal, Badurdeen, Dillon, & Jawahir, 2010).

Even though various jargons manifested, they are all contemplating on the same matter which is the preservation of the natural environment which is contained under the context of environmental sustainability. In exception to all of these, only Sustainable Manufacturing was formerly intended to include the economic and society dimensions as well. Nevertheless, the term sustainable manufacturing is more appropriate to current global situation as it addresses all of the sustainability elements holistically (Dornfeld et al., 2013; OECD, 2008; Seliger et al., 2008).

As discussed previously in Section 1.2.1, in order to progress for the notion of sustainable manufacturing, it is preferable if the sustainability element is being integrated with other existing manufacturing paradigms rather than to create a whole basic idea from square one. The integration with those paradigms is crucial due to the proven effectiveness shown by the previous manufacturing paradigms. Notably, there exist several researches that attempted to do so by linking the best elements from multiple paradigms and intersect it with the sustainability elements preferred to develop a new ground model for sustainable manufacturing. At some point, some of the researches even showed that some of the previous paradigms are already progressing towards sustainable manufacturing inadvertently. Ergo, the attempt to promote sustainable ideas has actually already existed even during the earliest onset of manufacturing practice.

2.2 Evolution of Manufacturing Paradigms towards Sustainable Manufacturing

A manufacturing paradigm is defined as "*a symbolic representation of a manufacturing system which represents the architecture used to determine the components and their relationships in the system*" (Bi et al., 2008). The design parameter of manufacturing system paradigm depends on the customers' requirements and the overall company's aim and objective which include cost minimization, productivity maximization and product quality optimization (Mehrabi, Ulsoy, & Koren, 2000). For illustration, manufacturing paradigms include craft production, agile manufacturing, flexible manufacturing, lean manufacturing, mass customization, mass production, rapid manufacturing, reconfigurable manufacturing and holonic manufacturing. In spite of that, the global manufacturing requirement has always becomes more demanding and more complex compared to previous manufacturing paradigms due to the ever changing global necessities.

It is exhibited by previous researches that existing manufacturing system paradigms are developed to meet some criteria for example quality, cost, delivery, flexibility and supply chain effectiveness, but none of them contains the requirement of which contributes to general sustainability holistically (Dornfeld et al., 2013). The restrictions of existing manufacturing system paradigms which needs to be inclusive with the sustainability requirements should be included in the current trend of research (OECD, 2008; US Department of Commerce, 2007). On that account, it is considered a new worthy challenge to explore a brand new system paradigm which includes the criteria of sustainability in systematic order.

As for the latest trend of the research in regard to manufacturing paradigms, Bi et al. (2008) projected the requirements of sustainable manufacturing systems into a wider scope before they reviewed back upon the most used existing paradigms to clarify the limitations of each of them and their relationship with the components of sustainability. The manufacturing system has evolved into six main phases as shown in Figure 2.1. The manufacturing system paradigms at each transition were (1) mass production, (2) lean manufacturing, (3) mass customization, (4) reconfigurable manufacturing, and (5) sustainable manufacturing respectively.

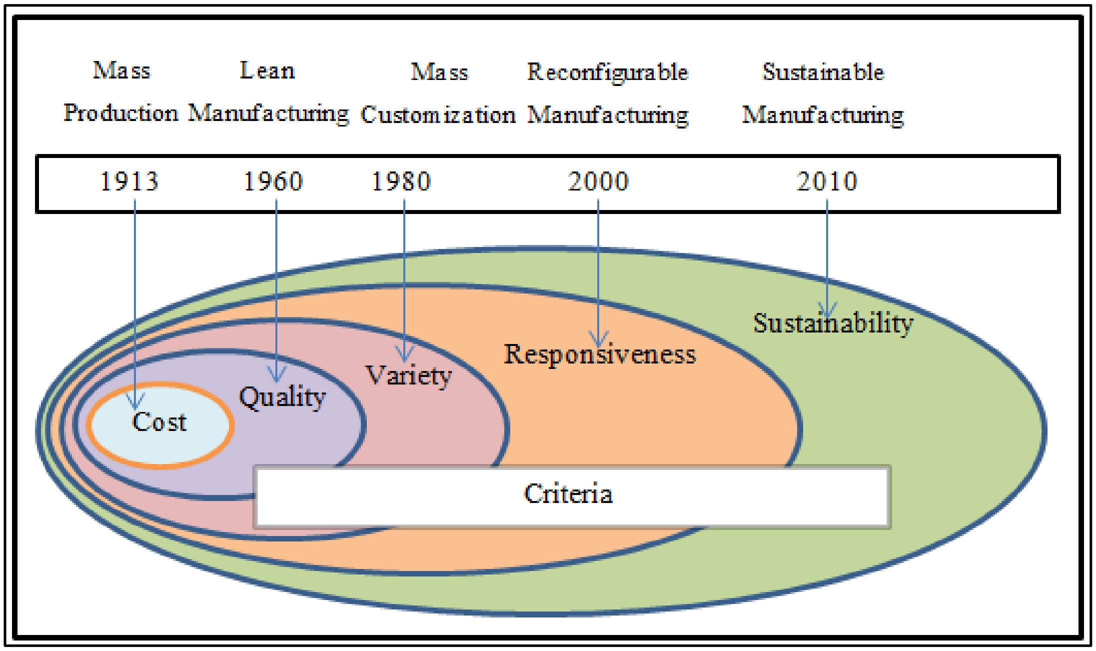

Figure 2.1. Evolution of Manufacturing Complexity

Note: Reprinted from Bi et al. (2008).

By referring to Figure 2.1, the range of manufacturing's requirements has been progressively expanded starting from a simple lower cost need in the early 1900s. As times goes by, the customer look upon the products which has higher quality, more variety range of choices and faster responsiveness of production time and services. In the current era, the customers became more aware of the damaging results of environment pollution which make them to be more environmentally conscious, which then made them to opt for a more environmental friendly product. The growing obligation to this matter has forced the global manufacturing to catch up with the momentum of environment conservation, which forces them to become more competitive from this sense.

Jayal et al. (2010) recommended a different perspective regarding the evolution of manufacturing system paradigms towards sustainable manufacturing as shown in Figure 2.2. They divided the evolution into four phases which started from (1) traditional production, which may be referred to the mass production, followed by (2) lean manufacturing, (3) green manufacturing and (4) sustainable manufacturing. This perspective was supported by Dornfield (2013) because it only highlighted the main revolution of the manufacturing system compared to Bi et al. (2008). Based on this scheme, it was deduced that all manufacturing system practice have already contributed directly or indirectly towards the requirement of sustainability. Recall that sustainability does not only involves environment, but also the economic or society standpoint of a company, which were already embedded as the customary foundation in the earlier paradigms.

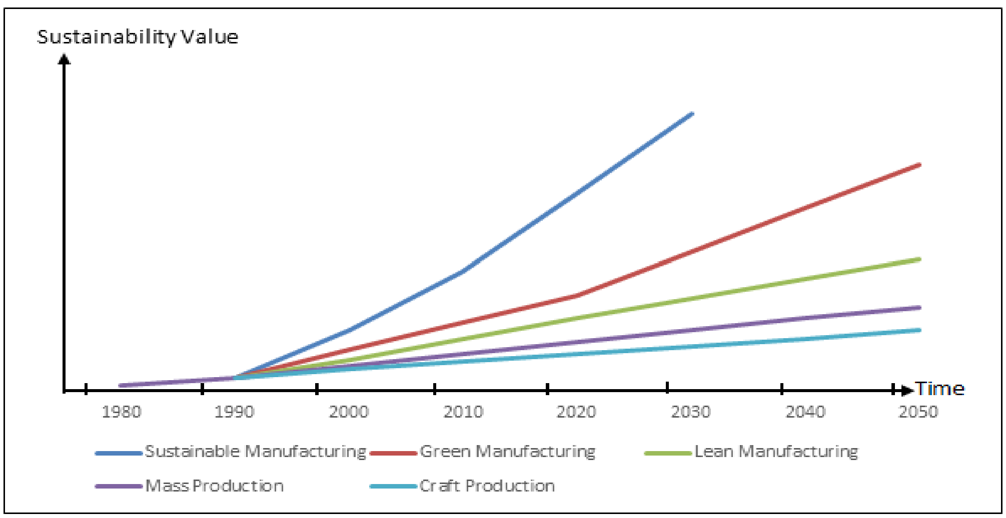

Figure 2.2. Evolution of Manufacturing Paradigm towards Sustainable Values

Note: Reprinted from Jayal et al. (2010).

In reference to Bi et al. (2008), Jayal et al. (2010) and Dornfeld (2013), handful evidences of literature were discovered that supported the notion from Jayal et al. (2010) sustainable manufacturing evolution perspective. In fact, there is a research movement that focuses ultimately only on providing supporting proof of two paradigms of lean and green manufacturing which is claimed to be vital to the development of sustainable manufacturing. These ample literatures perceived to be consistent with each other's finding which entitled the lean and green manufacturing paradigms to be emphasized. In the following section, the concept of lean and green manufacturing are briefly described before integrating them forward to the concept of sustainable manufacturing.

2.2.1 Lean Manufacturing

Lean manufacturing concept which is originally known as Toyota Production System (TPS) was inspired by the Toyota Motor Corporation, a Japanese automaker company. The term '*lean*' was coined by Womack, Jones and Ross for the evolution of lean manufacturing practices in the automotive manufacturing industry (Womack, Jones, & Roos, 2007). The core idea of lean manufacturing is to "*create more value for the customer with less work*". Particularly, it means to deliver highest quality of products and services to customers by utilizing waste minimization approach.

Toyota was a key player in the development of lean manufacturing and has influenced global manufacturing company of chemical, construction, electronics, engineering, energy, food, and beverage. In addition, the practices of lean principles of *kaizen* (continuous improvement) and "*Respect for People*" have been applied to service industries including call center services, health care, higher education, software development, public sector and professional services (OEE, 2013). All in all, lean is best conceptualized as a philosophy rather than a technical implementation of organizations operations.

In light with the concern regarding to improve overall manufacturing performance, majority of companies today has started to consider lean manufacturing approach in contrast to the conventional style of mass production approach (Holweg, 2007). Whereas mass production is based on the prediction of demand, the lean is based on Just in Time (JIT) concept, in which the production is made when the order or actual demand comes in. However, when the orders do came, the production must be done in a quick but efficient manner (Reeb & Leavengood, 2010). Lean practice greatly reduced cost in many aspects and the main framework for the lean manufacturing is shown in Figure 2.3.

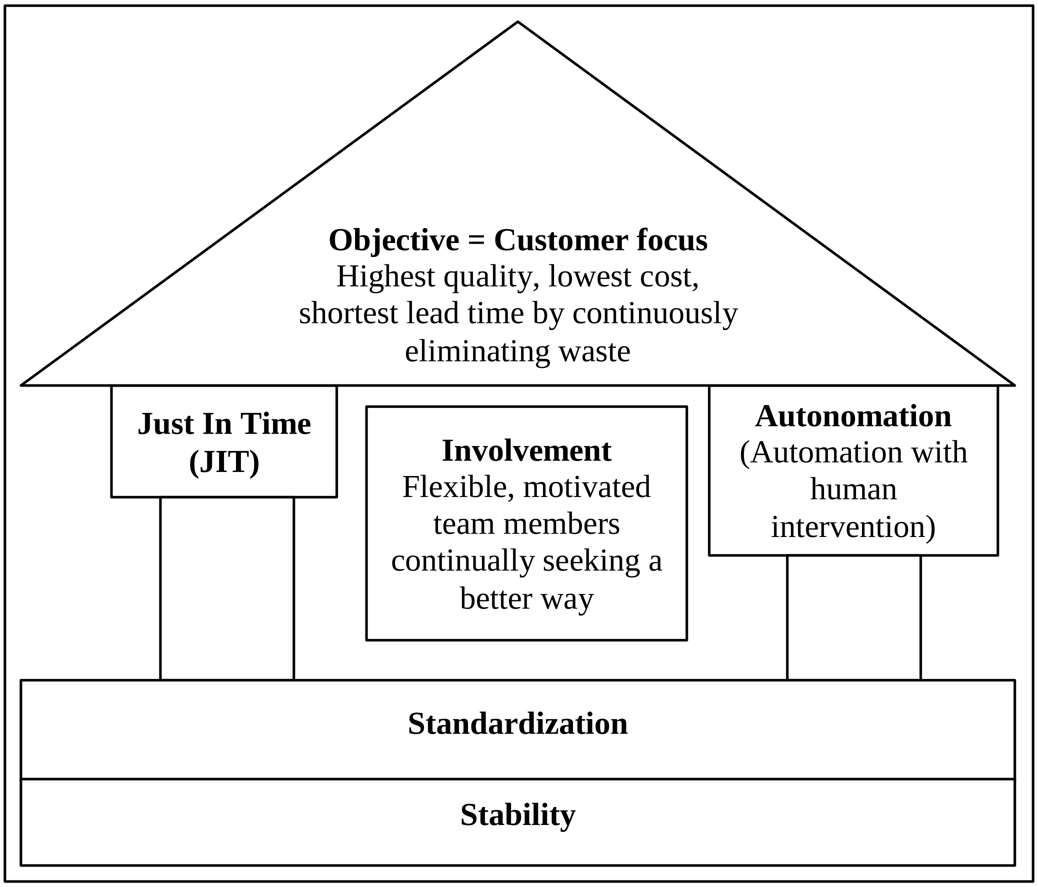

Figure 2.3. The Framework of Lean Production

Note: Reprinted from Shingo. (1989).

2.2.2 Green Manufacturing

Frankly speaking, it is not well established who initiated the idea of green manufacturing and when it started (Dornfeld, 2013). The term "*green*" in this context referred to as (1) "*relating to or being an environmentalist political movement*", (2) *"concerned with or supporting environmentalism"* and (2) "*tending to preserve environmental quality* (*as by being recyclable, biodegradable, or nonpolluting*)" (Merriam-Webster, 2013). The basic description of green manufacturing is a manufacturing system which mainly has a minimal, nonexistent, or negative impact on the natural environment (Dornfeld et al., 2013).

The term itself is also extended to the terms such as green remanufacturing, green operations, green design, and green supply chain (Srivastava, 2007). The main objective of this paradigm is to prevent pollution and save energy through the discovery and development of new knowledge that reduces and/or eliminates the use or generation of hazardous substances in the design, manufacture, and application of chemical products or processes (Center for Green Manufacturing, 2013). The concept of green manufacturing is not similar with sustainable manufacturing although there exists correlation among them. The premise used in this research is that green manufacturing is a progress towards sustainable manufacturing rather than a separate singular component.

2.2.3 Lean and Green Manufacturing

It is stated previously, that both of lean and green manufacturing paradigms should be embedded in the context of sustainability objective. In this section, past researches which exhibited the relationship between lean manufacturing and green manufacturing and why both of them are sustainable at some point are reviewed.

Florida (1996) investigated the connection between advanced manufacturing practices which includes lean manufacturing and environmental performance. He concluded that company which applied advanced management techniques (e.g. the use of teams, technology investment, process improvement, involvement of suppliers and customers, pursuit of zero waste, involvement of all types of employees) is heading towards minimizing environmental waste. This research indicated that these techniques are associated with both lean manufacturing and green manufacturing.

Rothenberg, Pil, and Maxwell (2001) focused on the case of the automotive industry where the research illustrated that lean manufacturers are proven to be more energy efficient than non-lean manufacturers thus making them ‘greener’. King and Lenox (2003) demonstrated that ISO 9000 (International certification for Total Quality Management Systems (TQM)) certified manufacturers with low inventories of hazardous materials have lower emissions of toxic chemicals. However, this research assumed that ISO 9000 standards are equivalent with lean manufacturing concepts where this assumption is not accurate. In addition, Environmental Protection Agency, EPA (2003) showed that the Boeing’s lean manufacturing program reduced environmental waste as a byproduct of process efficiency and quality improvements.

More recently, Bergmiller, Mccright, and Florida (2009) concerned on the relationship between lean and green where they believed that lean manufacturers transcend to green manufacturing. They proposed a comprehensive Lean and Green framework which fills the gap of all previous lean manufacturing model and green manufacturing model. The research developed an improved framework of lean manufacturing namely, Advance Lean System Model and Advance Green System Model before combining it into their novel Lean and Green framework. These three frameworks were developed and classified under three main elements which are Management Systems, Waste Reducing Techniques, and Business Results.

In spite of the efforts, the current unresolved debate in the body of knowledge is the true nature of association between lean manufacturing and green manufacturing. The major question still exist whether Lean and Green should be addressed as parallel, complementary, transcendence or synergy elements as shown in Figure 2.6 (Bergmiller & McCright, 2009; Bergmiller, 2006). To date, this issue is still being discussed as the relationship between this two may hold the key for the foundation of the sustainable manufacturing (Dues et al., 2013).

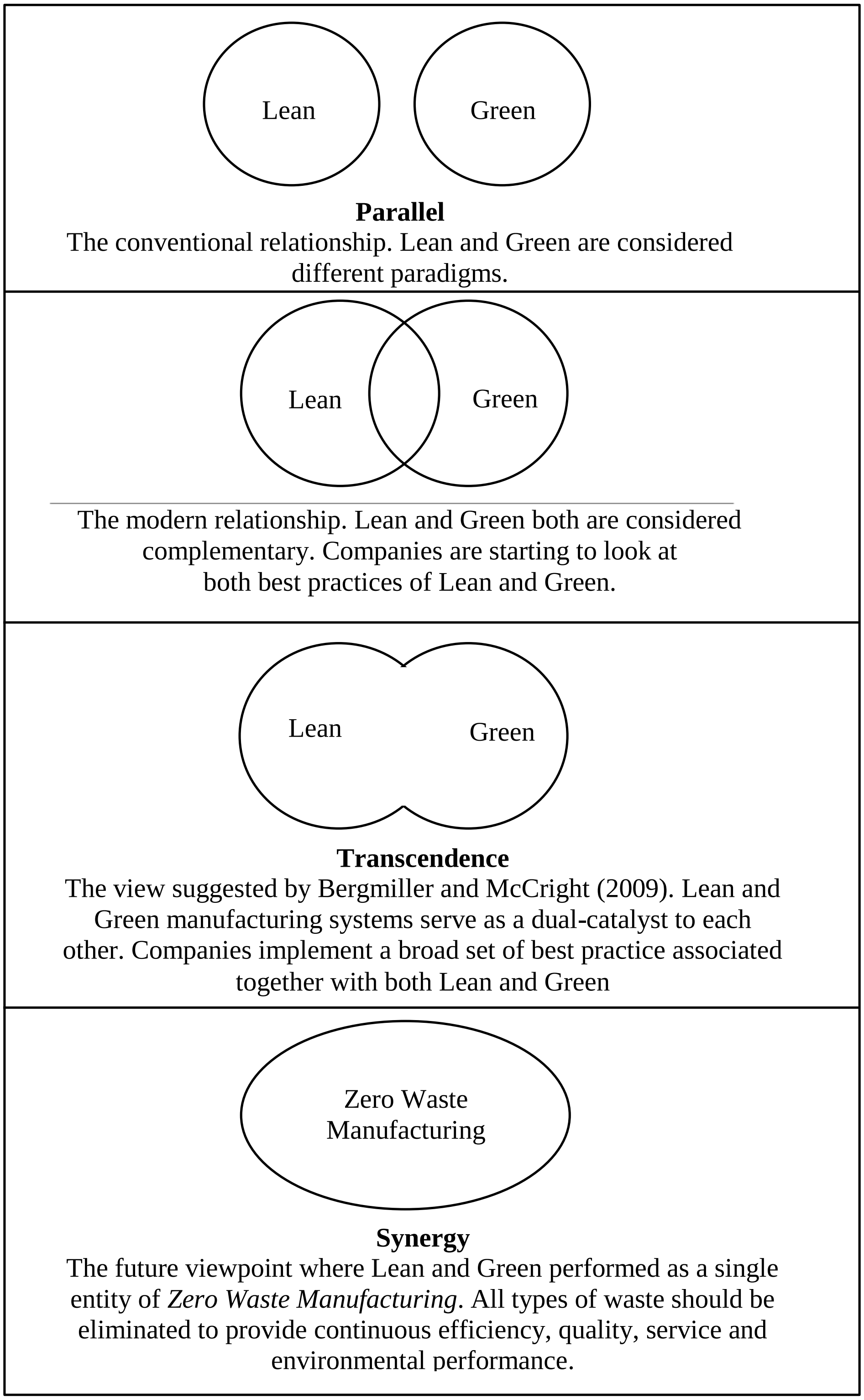

Figure 2.4. Relationship among Lean and Green.

Note: Reprinted from Bergmiller (2006).

The most common methodology of linking green manufacturing and lean manufacturing together is by considering waste minimization approach by these two systems (Bergmiller et al., 2009; Dornfeld et al., 2013; Miller et al., 2010). Lean manufacturing stressed on the importance of waste elimination thinking which includes seven traditional waste or ‘mura’ which is shown in Table 2.1 (Reeb & Leavengood, 2010; Shingo, 1989).

In contrast to lean manufacturing, the waste of green manufacturing is pertaining more to environmental waste as shown in Table 2.2. The waste of lean manufacturing gives negative impacts in terms of activities that diminished the value for the customers whereas the waste of green manufacturing gives harmful impacts in terms of natural environmental health (EPA, 2003; Miller et al., 2010).

Table 2.1.

Wastes of Lean Manufacturing

Types of waste	**Description**
Overproduction	Producing more than is required which leads to excess inventory
Transportation	Moving tools or materials to another location than is needed
Waiting	Delays of time for people, process, information etc.
Motions	People moved or worked unnecessarily
Defects	Defect products force reworks which can leads to delays
Inventory	Excess inventory of the raw materials, work-in-progress (WIP), or finished goods, represents a capital that has bring any income yet either by the producer or for the consumer
Over-processing	Doing extra work which is not needed

Note: Adapted from Shingo (1989).

Table 2.2.

Wastes of Green Manufacturing

Types of wastes	**Description**
Permit Compliance	Compliance with applicable permits
Toxic Release Inventory (TRI)	Over 300 chemicals subject to release
33/50 Chemicals	A subset of TRI chemicals identified by the EPA as priority candidates for voluntary reductions by industry
Clean Air Act Toxics	189 chemicals listed in the Clean Air Act as air toxics
Risk-Weighted Releases	Toxic chemicals weighted by their relative toxicity
Waste Per Unit of Production	Percentage of production lost as waste, generally measured by weight
Energy Use	Total energy use by all aspects of corporate operations; also expressed as carbon dioxide
Solid Waste Generations	Total solid waste going to landfills or other disposal facilities
Product Life Cycle	The total impact of a product on the environment from raw materials sourcing to ultimate disposal

Note: Reprinted from EPA. (2003).

Based on Bergmiller et al.(2009), Dues et al. (2013) extended lean and green beyond the waste reduction objective. They suggested that lean practices can be used as catalyst to greening the supply chain. Their finding supported the transcendence relationship of lean and green as in Figure 2.6. Based on Womack, Jones and Roos (2007), Jayal et al. (2009) and Dues et al. (2012), the difference and the similarities of lean and green manufacturing are summarized and compiled in Table 2.3. Other conspicuous researches in this area were Aminuddin (2013), Carvalho, Duarte, and Machado (2011), Franchetti, Bedal, Ulloa, & Grodek (2009), Parveen, Kumar, and Rao (2011), Ross (2003), Simons, Mason, and Cardiff (2003) and Venkat and Wakeland (2006).

Table 2.3.

Comparison of Lean and Green Manufacturing Paradigms

Lean	**Criteria**	**Green**
Cost minimization and flexibility	Focus	Sustainable development and ecological impact
Driven by cost, quality and time efficiency	Customer	Driven by environmental friendly conscious
Seven waste of lean	Definition of Waste	Inefficient use of resource, non-product output (scrap and polluted emissions)
Performance maximization and cost minimization	Product design	Life-cycle assessment
Increase replenishment frequency	Practice	Reduce replenishment frequency
High utilization, Just in Time (JIT)	Manufacturing	Remanufacturing
No concern for impact of product use or end-of-life recovery	End-of-life	Consideration of impact of product use and end-of-life recovery in form of re-use or recycling
Cost	Key Performance Index (KPI)	Greenhouse gas (GhG) emission
Physical cost (Monetary and resource)	Dominant cost	Cost for future generation (Quality of life)
Lean Value Stream Mapping (VSM)	Principal tool	Life-Cycle-Assessment (LCA)

Table 2.3 continued

Lean and Green
Objective of waste reduction
Waste reduction technique
People and organization
Lead time reduction
Supply chain relationship
KPI: Quality of service
Tools/Practice

Note: Adapted from Dues et al. (2013).

2.3 Lean and Green towards Sustainable Manufacturing

In addition to various researches which focused on the integration of the lean and manufacturing paradigm, this research is keen to look forward to integrate these two paradigms with the new paradigm of sustainable manufacturing. As Lu et al., (2010) and Shuaib, Metta, Lu, Badurdeen, and Jawahir (2011) clarified, the sustainable manufacturing generalize the requirements of the current manufacturing to accommodate with the needs of environment, economic and social sustainability as a whole.

In this section, a review is shown on how we can adopt the concepts of lean and green and bring it together with the sustainable manufacturing movement. As mentioned in Section 1.1, sustainable manufacturing is defined as "*the manufacturing practices which benefits towards environment, economic and society elements such that it meets present and future needs*". The main objective of sustainable manufacturing is "*to produce better performing products using fewer resources, cause less waste and pollution and contribute to social progress worldwide*" (Nasr et al., 2011).

Majority of the current global manufacturing companies who applied lean manufacturing are still unaware with the benefits if lean is being used together with green (Emmet & Sood, 2010). As it is has been proven that these two manufacturing paradigms can be integrated, it is unnecessary for a manufacturing company to shift their whole operations towards a new paradigm totally. Then, the ideas of sustainable manufacturing emerged and instead of try to develop a whole new concept, it is best to integrate the best existing paradigms which can suit the need of sustainable manufacturing. Bergmiller and McRight (2009) even suggested that in the future, the lean and green paradigm can be developed as a single paradigm of zero waste manufacturing which means any types of waste, be it the lean's seven waste and environmental waste, should be minimized or better yet eliminated. This notion is suitable and may be applied into the concept of sustainable manufacturing.

In spite of that, there are still some main conflicts where these two cannot be unified especially in terms of replenishment frequency (Dues et al., 2013). These conflicts may hamper the synergy relationship towards zero waste manufacturing notion. Thus, more research should be done to determine an optimal tradeoff mechanism in regard to the conflict elements in lean and green. There is also difference in terms of the implications of each of the paradigms.

It is well known that lean manufacturing general purpose is to maximize value to customers by utilizing waste minimization approach as well as to maximize profit via cost reduction (Reeb & Leavengood, 2010; Shingo, 1989). From the perspective of lean, it is all for the sake of business and customer satisfaction where the production process is being made efficient without compromising the high quality of the end-product. In addition, the lean practice of "*Respect for People*" towards better organizational culture and empowering people also contribute to overall continuous improvement in the organization (Sayer & Williams, 2012). Therefore, lean paradigm only concern heavily on the economic and society side of sustainability although the waste of environment may coincide with the waste as defined in lean.

In contrast with lean, the green manufacturing main purpose is to reduce the environmental risks and impacts while improving the ecological efficiency of the organizations (Carvalho et al., 2011; Miller et al., 2010). From the perspective of green, it only concern heavily on the environmental and society side of sustainability, where the production is being made to be not harmful to the environment and the end-product can be made to be re-used and recycled to inhibit the extraction of natural resources which in the end can be beneficial to the society.

Dornfeld et al., (2013) and Helu and Dornfeld (2013) investigated the influence of both paradigms into the sustainability model 1 of Figure 1.2 as shown in Figure 2.5. From their findings, it can be concluded that none of the existing manufacturing paradigms actually consider social sustainability as their main priority. Although lean and green have significant impact to the society, it cannot be said that their practices are built based on society measure. Hence, "*socially conscious manufacturing*" is highly advocated to force any manufacturing paradigms to develop more upon the social aspect (Dornfeld et al., 2013; Helu & Dornfeld, 2013).

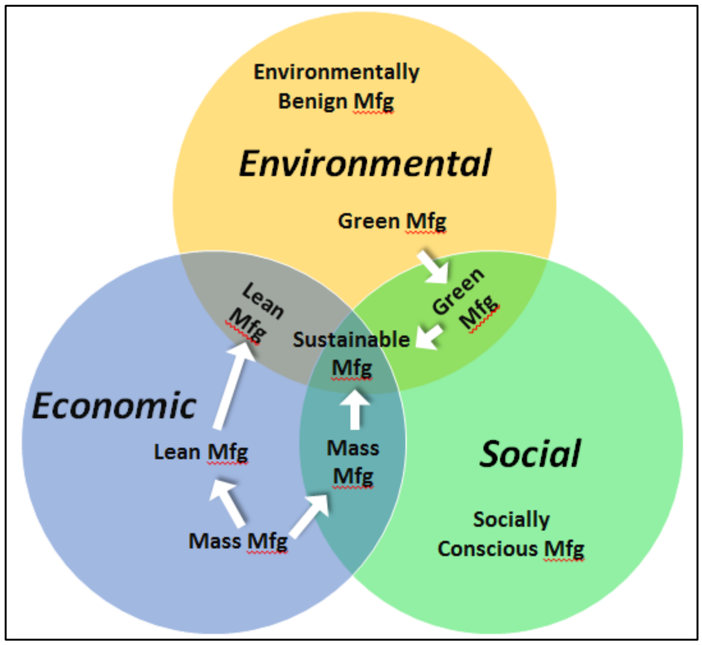

Figure 2.5. The Influence of Lean and Green towards Sustainability.

Note: Reprinted from Dornfeld et al. (2013).

By reviewing both Bergmiller and McCright (2009) and Dornfeld et al. (2013), it is preferable if the relationship between lean and green paradigm to include socially conscious thinking as well. As it is being established that synergy relationship towards zero waste manufacturing by Bergmiller and McCright (2009), is considered plausible due to several components of lean and green which cannot be integrated, the lean and green paradigm is suggested to being made compulsory into the development of sustainable manufacturing. However, the question remains on what extent the improvement can be made improve in order to raise the issue of social aspect significantly.

Correspondingly, the lean manufacturing original principle does not include environmental sustainability aspect. Although environmental waste may coincide with the waste of lean, it is not sufficient to justify the lean influence towards environment. Likewise, the green manufacturing original goal does not involve the economic sustainability aspect. As the bidirectional influence of these paradigms is still fuzzy and seemed to be complex with the inclusion of social factor, it is necessary to examine upon the relative importance of lean and green manufacturing with respect to sustainable components.

2.4 Indicators of Sustainability

The need for indicators in measuring the progress and the success of the sustainable practice especially in manufacturing cannot be simply ignored. The indicators selection is the initial step in guiding the organizations to adopt sustainable practice in their business and operations. Indicator may also serve as the technology enabler during the initial process of manufacturing planning (Dornfeld, 2010). In addition, the indicators can be made as a basis for continuous improvement measure during the decision making process. Thus, it does not only serve as the initial guide element, but also as the necessary element that comes along throughout the whole duration of the organizations' operations (OECD, 2008; UNEP, 2009; UNESCO, 2006). In this review, the general indicators of sustainability with the one that applied specifically to manufacturing environment are discussed in separate manner.

2.4.1 General Sustainability Indicators

Universally, there are 12 general sustainability indicators which are developed on the premise that it can be applied to all types of organizations as shown in Table 2.4. The pioneer and the leader in the sustainability assessment in this field is Global Reporting Initiative (GRI) even though the concept of sustainability is suggested by UN (Parris & Kates, 2003). These indicators are intended to measure the overall performance of an organization with respect to sustainability conformance. However, 2005 and 2006 Environmental Performance Indicator, ISO 1403 Environmental Management, Environmental Performance Evaluation, Environmental Indicators for European Union, and Eco-Indicators 1999 are in fact only represented the environment dimension of sustainability which does not sufficient to address the sustainability concept in a holistic manner.

Table 2.4.

List of General Sustainability Indicators

No	Indicator Set	Source	Components
1.	Global Reporting Initiative (GRI)	(GRI, 2013a)	One criteria with 70 indicators
2	Dow Jones Sustainability Index (DJSI)	(DJSI, 2013)	12 criteria based single indicator
3.	2005 Environmental Sustainability Indicators	(University of Yale, 2005)	76 building blocks of indicator
4.	2006 Environment Performance Indicators	(University of Columbia, 2006)	19 indicators
5.	United Nations Committee on Sustainable Development Indicators	(UN, 2005)	50 indicators
6.	OECD Core indicators	(OECD,2013)	46 indicators
7.	Indicator database	(NIST, 2013)	409 indicators
8.	ISO 14031 Environmental Management - Environmental Performance Evaluation	(ISO, 2013)	155 indicators
9.	Walmart Sustainability Product Index	(Walmart, 2013)	15 questions
10	Environmental Indicators for European Union	(EU, 2013)	60 indicators
11.	Eco-Indicators 1999	(Eco-Indicator, 2013)	Three criteria based single indicator
12	Interbrand	(Interbrand, 2014)	83 individual sub-metrics across six pillars

Note: Adapted from NIST (2013).

As shown in Table 2.4, there is no consensus or a unified approach yet in sustainability performance assessment. The justification is based on various numbers of indicators predicated and different styles in the methodology of indicator measurement. Thus, all of these indicators are made in accordance to the respective organizations that made it. To date, there is no research which compares the effectiveness and validity of each of these indicators and there is no unified standardized mechanism for sustainable manufacturing indicator (Fan et al., 2010; Reich-Weiser et al., 2013). Regardless, the organizations may still choose the indicators of their choice although the most preferred indicator in practice is the GRI (Isaksson & Steimle, 2009; Parris & Kates, 2003, Sherman, 2011).

2.4.2 Sustainable Manufacturing Indicators

Veleva and Ellenbecker (2001) suggested a novel method for the evaluation of the manufacturing sustainability performance based on a set of core and supplemental Indicators of Sustainable Production (ISP). Their method is the improvised version of the indicator developed by the Lowell Center for Sustainable Production (LCSP) with some adjustments made in accordance to previous version of GRI indicator. Veleva and Ellenbecker (2001) argued that sustainable manufacturing should consist of six main aspects, which are (1) Energy and material use (resources), (2) Natural environment (sinks), (3) Social justice and community development, (4) Economic performance, (5) Workers and (6) Products. Based on these aspects, they proposed an indicator model as shown in Table 2.5

Table 2.5.

Indicators for Sustainable Manufacturing by Veleva and Ellenbecker (2001)

Aspects of Sustainable Manufacturing	**Indicators**
Energy and material use	Fresh water consumption Materials used Energy use Percent energy from renewables
Natural environment	Kilograms of waste generated before recycling Global warming potential (GWP) Acidification potential Kg of PBT chemical used
Economic performance	Cost associated with EHS compliance Rate of customer complaints and returns Organization openness to stakeholder review and participation in decision making process
Community development and social justice	Community spending and charitable contributions as percent of revenues Number of employees per unit of product or dollar sales Number of community-company partnership
Workers	Lost workdays injury and illnesses case rate Rate of employees' suggested improvement in quality, social and EHS performance Turnover rate or average length of service employees Average number of hours of employee training per year Percent of workers who report complete job satisfaction
Products	Percent of products designed for disassembly, reuse or recycling Percent of biodegradable packaging Percent of products with take-back policies in place

Veleva and Ellenbecker (2001) indicators are exhaustive as they cover each aspects of sustainable manufacturing specifically. There is some dispute in their suggestion though where they put out six elements of sustainable manufacturing rather than the original three elements of sustainability. They differentiated energy and material use explicitly with environment and economic elements rather than a simple environment, economic and society, which imply that their classification is redundant itself. Maybe they tend to classify it to suit the manufacturing requirement uniquely than other background field though it is being perceived as unnecessary (Dornfeld, 2013; Reich-Weiser et al., 2013; Reich-Weiser, Vijayaraghavan, & Dornfeld, 2008).

OECD Sustainable Manufacturing Toolkit suggested 18 criteria of indicators for environmental performance as shown in Table 2.6 (OECD, 2008). According to them, the indicator was able to support the decision making process and can be applied to all classes of manufacturing line.

Table 2.6.

The OECD Sustainable Manufacturing Indicators

Input	**Operations**	**Products**
I1: Non-renewable material intensity	O1: Water intensity	P1: Recycled/reused content
I2: Restricted substance intensity	O2: Energy intensity	P2: Recyclability
I3: Recycled/reused content	O3: Renewable proportions of energy	P3: Renewable materials content
	O4: Greenhouse gas (GhG) intensity	P4: Non-renewable materials intensity
	O5: Residual intensity	P5: Restricted substance content
	O6: Air releases intensity	P6: Energy consumption intensity
	O7: Water release intensity	P7: Greenhouse gas emission (GhG) intensity
	O8: Proportions of natural land	

The indicators provided by OECD prove to be insufficient as it only concerns of the environmental aspect of sustainability. Hence, this does not represent a whole structure of sustainable manufacturing itself. Until today, OECD does not yet provide indicators in terms of the economic and social sustainability. Nevertheless, these environmental indicators can be made as a part of a full set of indicator.

Fan et al. (2010) refined a new list comprises of 32 indicators which is built upon GRI's indicators and Veleva and Ellenbecker (2001), This refined version of indicator is divided into three dimensions of sustainability as well which are environmental, economic, and social. Each dimension is distributed into six aspects of (1) Energy and Material Usage, (2) Emissions to Natural Environment, (3) Economic Performance, (4) Products, (5) Workers, and (6) Community Development and Social Justice as shown in Table 2.7.

Table 2.7.

Indicators for Sustainable Manufacturing by Fan et al. (*2010*).

Environmental	
Energy and Material (EM)	Emissions to Natural Environment (EN)
EM1: Material usage (total and per unit of product)	NE1: Total greenhouse emissions by weight
EM2: Percent of material used that are recycled input material	NE2: NO and SO percentage and air emissions by weight
EM3: Energy consumption (total and per unit of product)	NE3: Total water and discharge volume
EM4: Percent of renewable energy	NE4: Total solid waste weight
EM5: Energy save due to conservation and efficiency improvements	NE5: Total hazardous waste weight
EM6: Total water consumption	
EM7: Percent of recycled/reused water	
Economic	
Economic Performance (EP)	Products (P)
EP1: Percent of supplier without EHS violations	P1: Percent of products design for disassembly, reuse and recycling
EP2: Investments in Environmental Protection	P2: Percent of products with an environmental label
EP3: Investments in local suppliers	P3: Percent of products with take-back policies in place
EP4: Costs associated with EHS compliance	P4: Customer satisfaction
EP5: Organization's openness to stakeholder review and participation	P5: Adherence to General Guideline for Warning and Safety Labels
Social	
Workers (W)	Community and Social Justice (CS)
W1: Lost of workers due to illness and injury	CS1: Community spending and charitable contributions
W2: Average hours of employee training per year	CS2: Number of community-company partnerships
W3: Employee job satisfaction rate	CS3: Percent of product consumed locally
W4: Employee turnover rate	CS4: Ratio of company wage compared to local minmum wage
W5: Gender ratio	CS5: Percent of investment in human rights clauses

Fan et al. (2010) also recommended that indicators should be simple and the less the better as it is more manageable, easier to manipulate, compared and understand. Thus, it can be used as strategic indicator for sustainability assessment for the manufacturing application. This research supports this idea and seem that a simple yet comprehensive indicator can be understood much better especially for the stakeholders of the manufacturing company.

Amrina and Yusof (2011) improvised the research of Fan et al. (2010) via the integration of manufacturing performance indicators and the sustainable manufacturing indicators. Their initial indicator still adopted the triple bottom line of sustainability consisting of environmental, economic, and social performance factors. Four manufacturing performance indicators of quality, cost, delivery, and flexibility are assimilated as the economic sustainability dimensions whereas the other dimension of environmental and social are derived from other literatures. The three factors of environmental, economic, and social performance are further divided into nine dimensions. A total of 41 sub-dimensions was then adopted and modified from relevant literature as shown in Table 2.8.

Table 2.8.

Indicators for Sustainable Manufacturing by Amrina and Yusof (*2011*)

Environmental	
Emission	1. Air emission
	2. Water pollution
	3. Land contamination
Resource utilization	4. Energy utilization
	5. Water utilization
	6. Fuel utilization
	7. Land used
Waste	8. Solid waste
	9. Hazardous waste
	10. Waste water
Economic	
Quality	11. Product reliability
	12. Product durability
	13. Conformance to specification
	14. Customer complain
	15. Scrap and rework
	16. Reject rate
Cost	17. Material cost
	18. Setup cost
	19. Overhead cost
	20. Inventory cost
	21. Unit cost
	22. Labour cost
Delivery	23. On time delivery
	24. Delivery lead time
	25. Delivery speed
	26. Cycle time
	27. Due date adherence
	28. Schedule attainment
Social	
Employee	1. Training and development
	2. Occupational health and safety
	3. Turnover rate
	4. Job satisfaction
	5. Community satisfaction
Supplier	6. Supplier certification
	7. Supplier commitment
	8. Supplier initiative

In spite of that, the integration is being done with the assumption that quality, cost, delivery, and flexibility are embedded only in the economic sustainability aspect. In contrast to indicator simplification notion by Fan et al. (2010), Amrina and Yusof (2011) further categorized the three factors of environmental, economic, and social performance into nine dimensions with a total of 41 sub-dimensions.

Other related researches in this area can also be found in Feng and Joung, (2011) and Joung, Carrell, Sarkar, and Feng (2013). These researches asserted that a large number of conflicting indicator sets has caused negative complications in terms of the understanding of the sustainable manufacturing terminology. They reviewed a set of publicly available indicator sets and suggested a categorization methodology of indicators that are quantifiable and clearly related to manufacturing. The categorization is being made based on mutual similarity in terms of five dimensions of sustainability which are (1) environmental stewardship (2) economic growth (3) social well-being, (4) technological advancement, and (5) performance management.

2.5 Discussion of the Review of Sustainable Manufacturing Indicator

In order to promote sustainability into the application of manufacturing principles, it is necessary to integrate this concept with the earlier existing manufacturing paradigms. From all of these, two paradigms are hailed to be the most significant to the development of a sustainable manufacturing model, which are the lean and green paradigms. Nonetheless, these two paradigms still does not endorsed profoundly in term of the social sustainability aspect. Furthermore, the connection between these paradigms with the economic and environment sustainability aspect is considered ambiguous in several components (Dornfeld, 2013). Regardless, the combination lean and green paradigm is complex and is not yet comprehensive for the implementation of sustainable movement in manufacturing. Thus, there is a need to investigate upon the relative importance of lean and green manufacturing with respect to sustainability components.

From the perspective of the decision making process for sustainability, an effective method for policy and performance measurement is compulsory in the process of organizations sustainability transformation. Prior to this, criteria and its respective indicators used to evaluate the courses of action with assistance of the data, information and knowledge is necessary to come out with the best decision for any organization. Based on existing sustainability decision making guidelines, there are two main issues that need to be emphasized in the initial steps of sustainability implementation which are (1) the prioritization of criteria and (2) the selection of indicators as a basis for sustainable performance measurement. Unfortunately, the effort in the prioritization of indicators is always being simply overlooked by the organizations, as this process is normally being done only by the top managerial raw decision (Searcy, 2009). On the other hand, a systemic decision making approach should be utilized in order to assist organizations to make the best informed decision for sustainability revolution.

In the matter of sustainable manufacturing indicators, both of the latest researches from Fan et al. (2010) and Amrina and Yusof (2011) utilized Multi Criteria Decision Making (MCDM) method of the Analytic Hierarchy Process (AHP) into their indicator model. This suggests that MCDM maybe a significant method in solving this matter. The drawback in their research according to them is that the indicator for economic and social aspect is not adequate and this is also proven to be true from other previous researches of Helu and Dornfeld (2013), Isaksson and Steimle (2009) and Parris and Kates (2003). Next, the judgment from the respondents may not be generalized to the population of the organization, due to the inadequate amount of respondents, insufficient resources and limited time. Another shortcoming in their researches is they could not find a method to verify the effectiveness of their indicators and the outcome may vary among the organizations. Due to the inconsistent results, they suggested that the indicator needs to be case specific to represents particular characteristics at each of organizations' setting. The needs to overcome this limitation is further emphasized by Reich-Weiser et al. (2008) which stated that an indicator of sustainable manufacturing must being made to comply all types of organizations setting or comprehensive, yet specific enough to cater each organizations explicitly.

The major drawback that was found via this research, in Fan et al. (2010) and Amrina and Yusof (2011) is that their research did not consider the inter-relationship which exist among environment, economic and social whereas these category have some dependency or overlapping among them (UN, 1987). By default, AHP as well as other MCDM methods is not suitable that can be used to address the subject of sustainability indicator as it must assume the relationship among the criteria to be independent (Saaty, 1980; Saaty, 2010). In addition, the complex nature of sustainability problem should involves fuzzy approach to capture the gist of this problem more accurately (Phillis et al., 2010).

Feng and Joung (2011) and Joung et al. (2013) also stated that various number of conflicting indicator sets constitute misunderstanding in terms of the sustainable terminology and sustainability of the manufacturing organizations. Combined with suggestion provided by Fan et al. (2010) and Reich-Weiser et al. (2008), it is indispensable if the indicator is developed in such a way that it is comprehensive and consistent to cater all types of organizations yet can be made to be case specific to the requisite for applied organizations.

CHAPTER THREE
REVIEW OF KNOWLEDGE BASED FUZZY ANALYTIC NETWORK PROCESS SYSTEM

As mentioned previously in Section 1.3 and Section 2.5, this research investigates on the problem area of the sustainable manufacturing indicators selection and prioritization processes. Prior to the selection process, there are several sustainability criteria which are pertinent to each decision makers of the manufacturing organization. This problem involves decision making with the considerations of multiple numbers of criteria which requested a review on the Multi Criteria Decision Making (MCDM). This chapter begins with a brief description of MCDM before the chosen integrated method used, which is the Fuzzy Analytic Network Process (FANP), is reviewed together with the foundation of Analytic Network Process (ANP) and Fuzzy Set Theory (FST).

This chapter proceeds with the importance of the integration between Knowledge Based System (KBS) with FMCDM followed with a basic description and major issues of KBS. At the end of this chapter, a discussion is being done regarding this research novel method which is the Knowledge Based Fuzzy Analytic Network Process (KBFANP) system. It is anticipated that critical understanding of the key methods and theory used in the creation of KBFANP system is exhibited, in such a way that the reader will be well informed of the justification used in this research’s approach

3.1 Multi Criteria Decision Making

Multi Criteria Decision Making (MCDM) is one of the major branches in Decision Science or Operations Research, which focuses on the decision problem under the presence of multiple numbers of decision criteria. The MCDM approach combines the information from the decision's problem with the information acquired from the decision maker in order to determine the best decision (Hwang & Yoon, 1981). In today's world problem, various decisions needs to be made with the existence of numerous criteria thus making it very hard to come out with a best possible decision. The importance of MCDM should not be neglected due to its practical advantages that utilizes both of decision problems structure and considers the decision makers needs and expectations as well (Martin, Lakshmi, & Venkatesan, 2013; Umm-E-habiba & Asghar, 2009).

There are two primary disciplines in MCDM, which are Multi Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). MADM involves ranking, screening or selection process among predetermined, finite number of decision criteria and alternatives. In contrast, MODM involves infinite or non-existent cases of potential decision criteria and alternatives. Although MADM methods is more pragmatic in a sense that the real world problem usually involves finite set of criteria and alternatives, MODM are able to offer a mathematical structure for constructing a set of decision alternatives, which is evaluated based on the proximity with the decision problem's objective (Chen & Hwang, 1992; Hwang & Yoon, 1981; Kahraman, 2008b; Tzeng & Huang, 2011).

The problem addressed in this research involves ranking and selection process of sustainability indicator which is based on available finite set of attributes. Prior to selection, the indicators are ranked and screened based on fixed number of attributes enlisted from the GRI G4 Sustainability Report under three dimensions of economic, environmental and society which a total of 20 attributes (GRI, 2013c). MADM method is suited to this problem compared to MODM, as the number of decision alternatives is predefined. Based on Kahraman (2008), Tzeng and Huang (2011) and Martin et al. (2013), general methods of MADM which has been routinely practiced to date were compiled into Table 3.1 and briefly described.

Table 3.1.

List of General MADM Methods

No	MADM Methods	Description
1.	Dominance	An alternative is dominated if another alternative outperforms it with respect to at least one attribute and performs equally with respect to the remainder of attributes.
2.	Maximin	A method which gives each alternative a score equal to the strength of its weakest attributes.
3.	Maximax	A method which gives each alternative a score equal to the strength of its strongest attributes.
4.	Conjunctive (Satisficing)	A screening method in which the selected alternative must exceed the given performance thresholds for all attributes.
5.	Disjunctive	A screening method in complementary with conjunctive method in which the selected alternative must exceed the given performance thresholds for all attributes
6.	Lexicographic	The attributes are rank-ordered in terms of importance. The alternative with the best performance by the order of the most important attribute is selected.
7.	Lexicographic Semi-Order	A variant of the lexicographic method, where the same attribute performance value are allowed to count as ties without any penalty given to the alternative.
8.	Elimination by Aspects	An elimination method of alternative with respect to attributes
9.	Linear Assignment Method	A method which utilizes cardinal importance weights for each attribute and rankings of the alternatives with respect to each attribute.
10.	Additive Weighting	A method which requires the sum of cardinal importance weights for each attribute and rankings of the alternatives with respect to each attribute.

Table 3.1 continued

11.	Weighted Product	A method which requires the product of cardinal importance weights for each attribute and rankings of the alternatives with respect to each attribute.
12	Distance from Target	The selected alternative is the one with the shortest distance using Euclidean distance principle to the target attribute point
13.	Multiple Attribute Utility Models	Utility theory defines the selection of a preferred solution as the maximization of satisfaction derived from its selection. The selected alternative is the one that maximizes utility for the decision makers.
14.	Non-traditional Capital Investment Criteria	A method which utilizes pairwise comparisons of the performance gains (in monetary unit) among attributes, for a given alternative.
15.	Grey relational analysis	A method which deal with incomplete data which represented as grey, hazy or fuzzy. Information quantity and quality is formed as a continuum from a total lack of information to complete information from black through grey to white
16.	Goal Programming	Introduced by Charnes and Cooper (1957). A method which involves the division of more than one objective which conflicts with each other. The objective is achieved by the minimization process of information which is inappropriate.
17	Outranking Methods - ELECTRE, PROMETHEE and ORESTE	ELECTRE (ELimination Et Choix Traduisant la REalité - ELimination and Choice Expressing REality) was introduced by Roy (1968). The outranking relationship is determined using pairwise comparisons among alternatives with respect to each criterion separately. An alternative is dominated if another alternative outranks it based on given attributes.
18.	Data Envelopment Analysis (DEA)	Introduced by Charnes, Cooper, and Rhodes (1978). A non-parametric method of measuring the efficiency of a decision making unit by calculation of weights using the input/output ratio of the assessed production units.

Table 3.1 continued

19.	Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)	Introduced by Hwang and Yoon (1981). The selected alternative should be as similar to ideal solution as possible and not similar to non-ideal solution as possible. The ideal solution is determined by the best performance value based on attribute and non-ideal solution is determined in opposite manner. Similarity to ideal solution is evaluated using Euclidean distance principle.
20.	Analytic Hierarchy Process (AHP)	Introduced by (Saaty, 1980). A type of additive weighting method which converts the attribute weighting into a matrix form of relative pairwise comparisons among competing attributes.
21.	Analytic Network Process (ANP)	Introduced by Saaty (1996). An improved version of AHP to accommodate some real world decision problems, where the local weights of criteria are different for each alternative (in the form of network and multi directional relationship). In contrast, AHP only use the same local weights of criteria for each alternative (in the form of hierarchical and unidirectional relationship)

From all of these MCDM methods, ANP is the most suitable method that can be used to address the subject of sustainability indicator as it can handle the inter-relationship which occurs among the criteria of sustainability (Bottero & Ferretti, 2010; Bottero & Mondini, 2008; Garcia-Melon, Gomez-Navarro, & Acuna-Dutra, 2010; Hsu, Hu, Chiou, & Chen, 2011). Previous researches of the application of MCDM in sustainable manufacturing indicator such as Fan et al. (2010) and Amrina and Yusof (2011) did not consider the inter-relationship elements in their approaches thus this research looked upon to test ANP capabilities into the research problem.

3.2 Analytic Network Process

In 1980, Saaty (1980) developed the Analytic Hierarchy Process (AHP) technique, which constructs a decision-making problem into hierarchy which consists of goal, criteria, sub-criteria, and decision alternatives. The AHP technique performs pairwise comparisons to measure relative importance among attributes at each level of the hierarchy, and evaluates alternatives in order to construct the best decision. AHP provides decision makers with a way to transform intangible judgments into quantitative value of measurement (Saaty, 2010). Due to its mathematical simplicity and flexibility, AHP has been a popular decision tool in many fields which includes engineering, food, business, ecology, health, and government (Saaty, 2010; Vaidya & Kumar, 2006).

In spite of that, in most of the real world decision problem setting, there exists situation where the local weights of criteria are different for each alternative. AHP has limitation in treating such cases since AHP uses the same local weights of criteria. This happens due to singular direction of influence among attributes considered in a form of hierarchy. The hierarchy structure assumes that all attributes to be interdependent where an attribute only influence other attribute in a single direction as shown in Figure 3.1. To overcome this limitation, Saaty (1996) proposed the Analytic Network Process (ANP) method that allows for more complex, interdependent, relationships, and feedback among the elements in decision problem as shown in Figure 3.2

ANP is represented by a network which is represented by cycles which connects its components of elements by source and sink nodes as shown in Figure 3.3. A source node is the origin of influence or importance path and never a destination of such paths whereas sink node is a destination of paths of influence and never an origin of such paths. A real world decision problem always involves feedback relation which can be formed into networks. The implementation of ANP can further justify the validity of the ranking outcome compared to AHP as well as other MCDM methods (Saaty, 1996, Saaty, 2010; Sipahi & Timor, 2010).

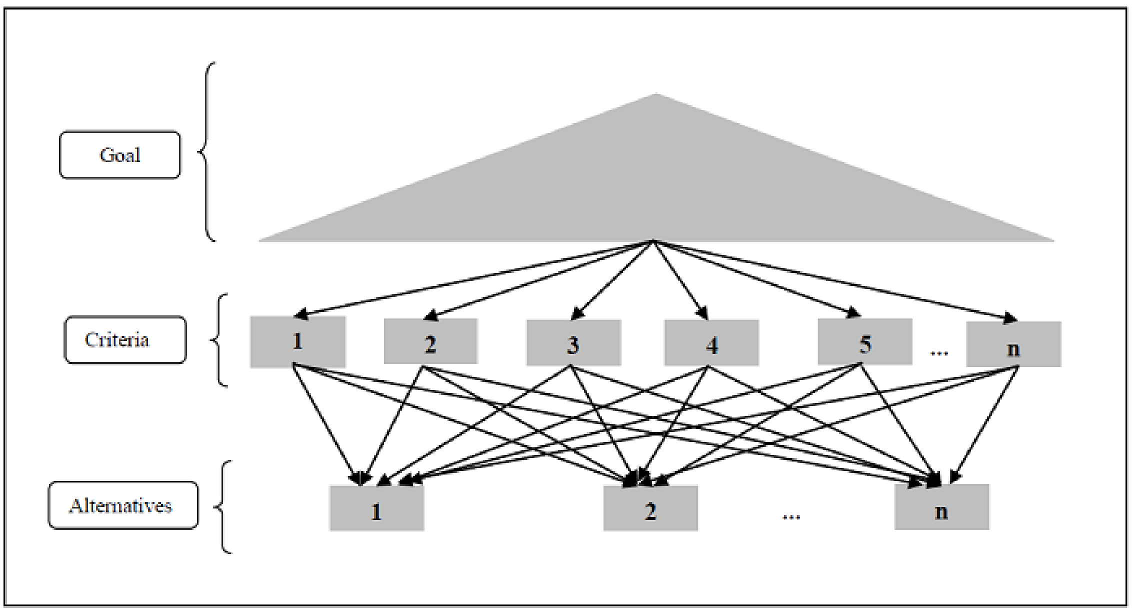

Figure 3.1. Analytic Hierarchy Process (AHP) Structure

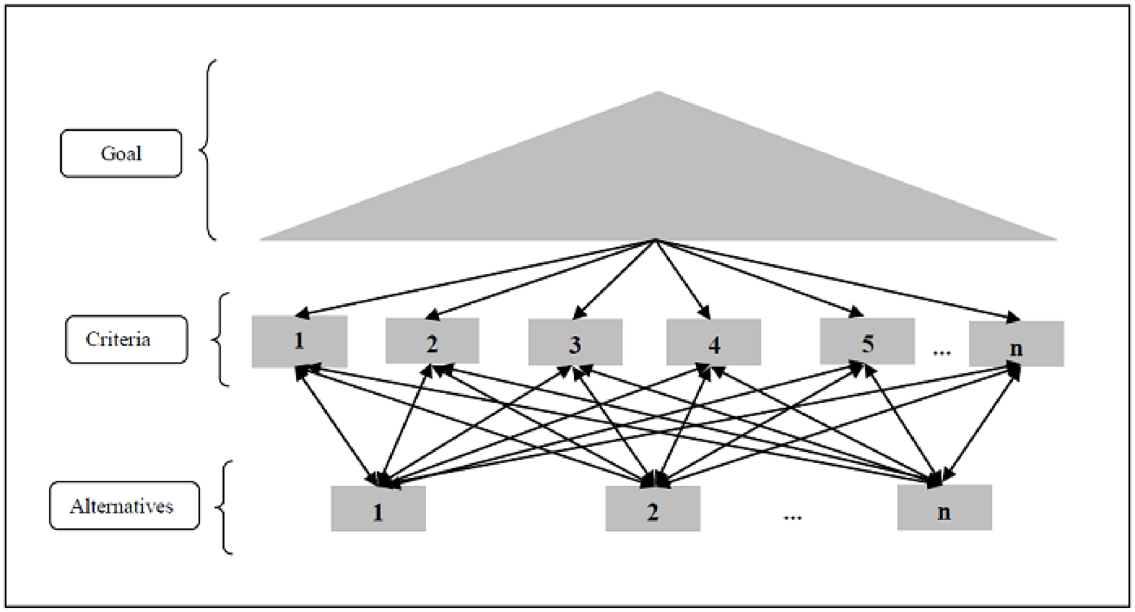

Figure 3.2. Analytic Network Process (ANP) Structure

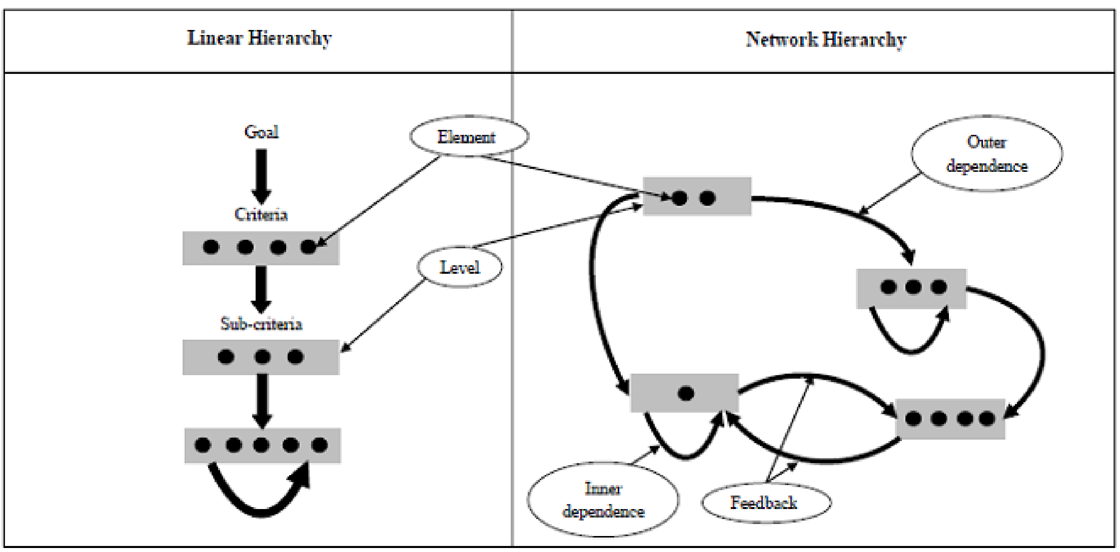

Figure 3.3. Structural Difference of Linear and Network Hierarchy

Predominantly in a real-world decision situation, the application of MCDM method most probably faces severe practical constraint from the criteria which may consists of imprecise or vague information (Bellman & Zadeh, 1970). This implication is exceptionally relevant to sustainability problem as the concept is considered to be complex and fuzzy (Dornfeld, 2013; Helu & Dornfeld, 2013; Shiau & Liu, 2013; Tseng et al., 2009). In addition, Phillis and Kouikoglou (2009) claimed that it is compulsory to research the sustainability problem from the Fuzzy Sets Theory (FST) point of view as it is almost impossible to gather a solid consensus concerning information on this matter especially the decision makers' judgment. Therefore, the integration of Fuzzy Sets Theory (FST) with MCDM is considered which opens for a review of Fuzzy Multi Criteria Decision Making (FMCDM).

3.3 Fuzzy Multi Criteria Decision Making

The elementary MCDM methods normally assume that all criteria and their respective weights are expressed in absolute numbers or crisp values which may simplify the rating and the ranking of the decision alternatives. The most ideal state for a MCDM problem is when all ratings of the criteria and their degree of importance are known precisely which makes it feasible to arrange them in the form crisp ranking. Regrettably in many practical cases, the performance of the criteria may only be expressed qualitatively in words and sentences which appeal for a more proper method (Zimmerman & Zysno, 1985).

In addition, decision makers always find it more convincing to provide interval judgments rather than a fixed value of judgments. This happens as the decision makers are unable to explicit their preferences due to the fuzzy characteristics of the pair wise comparison process (Li, Liu, Wang, & Li, 2010). Hence, the diffusion of Fuzzy Sets Theory (FST) into MCDM is introduced by Bellman and Zadeh (1970) and highly advocated by Zimmermann (1978). The concept of Fuzzy Multi Criteria Decision Making (FMCDM) is believed to be a better strategy to inquire the fuzziness nature which always occurs in the real world decision making situation.

3.3.1 Fuzzy Sets Theory

Most decisions which need to be made in the practical problem happens in unstructured, incomplete and complex situations. The complexity in this sense refers to the problem representation which is almost impossible to be known precisely and cannot be implied in the form of absolute numbers. In response to deal with these kinds of vague and imprecise problem characteristics, Zadeh (1965) suggested the concept of Fuzzy Set Theory (FST).

FST is introduced as an expansion of the conventional notion of set where it can be generalized to enhance the flexibility on how we form a set. In the conventional set theory, the membership of elements in a set is measured in binary term, which means whether an element is either belongs or does not belong to the set. In contrast, FST allows the gradual measurement of the membership of elements in a set which is described with the presentation of a membership function consists of real number with interval range of [0, 1].

FST is generally known as a mathematical modeling tool for complex problems which is hard to define in neither exact nor precise manner. A system which is developed via FST can be generally known a mathematical modeling mechanism system which uses natural language and non-crisp fuzzy value. Based on FST, three main related fields emerged which are (1) Fuzzy sets (2) Fuzzy logic and (3) Fuzzy systems (Ganesh, 2006).

Fuzzy sets concerns from the notion of sets, fuzzy logic deals with the reasoning process of the fuzzy concepts. On the other hand, a fuzzy system is the knowledge based system which is built upon the fuzzy representation (fuzzy inference rule) of knowledge domain (Klir, 2006; Kordon, 2010). FST has been abundantly applied in diverse fields of decision making, knowledge based system, artificial intelligence (AI), computer science, control theory, medical diagnostics, neural network, pattern recognition, and even social science.

3.3.2 Definition of Fuzzy Sets

In this section, a brief concept of fuzzy sets is described which is the building block for the understanding of the FANP method.

3.3.2.1 Definition 1: Crisp sets

Crisp set is also known as the classical notion of sets. A set is a collection of elements. The empty set $\emptyset$ has no elements. $x \in X$ when we say that element x belongs to the set X.

3.3.2.2 Definition 2: Fuzzy sets

Let X be a set and let x be an element in X. A fuzzy set A in X is a collection of ordered pairs $[x, \mu\_A\ (X)]$ for $x \in X$. X is called the universe of discourse of A and $\mu A\ (X)$ is a number in [0,1] which represents the membership grade of x to A (degree to which x belongs to A

$$A = \{x, \mu\_A\ (X)], x \in X\} \tag{3.1}$$

For example, let human height and a fuzzy set A= "tall height". Let X= {1.60, 1.65, 1.70, 1.75, 1.80, 1.85, 1.90} be a set of heights in meters. An example of fuzzy set A

$$A = 0/1.60 + 0/1.65 + 0/1.70 + 0.2/1.75 + 0.8/1.80 + 1/1.85 + 1/1.90 \tag{3.2}$$

A defined as follows: 1.60 is tall with 0 degree of membership, 1.65 is tall with 0 degree of membership and so on up to 1.90 is tall with degree of membership 1. The notation above fractions of membership grades and particular values connected by summation signs is quite standard and does not imply division or summation.

3.3.2.3 Definition 3: Linguistic Variable

Linguistic variable is a variable of natural language which its values is in the form of words or sentences. For example, age is a linguistic variable if its values is defined in linguistic form rather than numerical, i.e., young, not young, very young, quite young, old, not very old and not very young, etc., rather than 20, 21, 22, 23.

3.3.2.4 Definition 4: Membership function

The membership function μA(X) describes the membership of the elements x of the base set X in the fuzzy set A. Membership functions are often in the form of piecewise linear functions, where the most commonly used are triangular or trapezoidal functions.

3.3.2.5 Definition 7: Defuzzification

Defuzzification is the process of conversion of the fuzzy value to crisp value. Defuzification converts the fuzzy value into crisp value for further processing. There are seven basic methods which are used to defuzzify the fuzzy output functions which are.

1. Max-membership principle,
2. Centroid method,
3. Weighted average method,
4. Mean–max membership,
5. Centre of sums,
6. Centre of largest area, and
7. First of maxima or last of maxima

3.4 Fuzzy Analytic Network Process

As FMCDM is regarded to be the necessary foundation for the sustainability problem, the combination of FST with ANP method known as Fuzzy Analytic Network Process (FANP) is revised. A total of 32 researches which utilized FANP based on best exhaustive search is reviewed. ANP together with its predecessor, AHP has been widely used in various types of applications, and their benefits are well extended to FANP (Sipahi & Timor, 2010; Vaidya & Kumar, 2006)

Vaidya and Kumar (2006) suggested 10 themes in the field of AHP application which are selection, evaluation, benefit–cost analysis, allocations, planning and development, priority and ranking, decision-making, forecasting, medicine and related fields and AHP applied with Quality Function Deployment (QFD) (Vaidya & Kumar, 2006). As both ANP have the almost the same architecture with AHP and has been used in almost identical field of applications, it can be assumed that this classification can be used on the review of ANP (Etaati et al., 2011). In this research, 32 researches with FANP based applications is classified into four themes from ten themes suggested by Vaidya and Kumar (2006) which are (1) selection, (2) evaluation, (3) location selection, and (4) decision making as shown in Table 3.2.

Table 3.2.

FANP Applications by Themes

Theme	Application	Research
Selection	Supplier	(Lin, 2009) (Pang, 2009) (Razmi, Rafiei, & Hashemi, 2009) (Wei & Sun, 2009) (Önüt, Kara, & Işik, 2009) (Boran & Goztepe, 2010) (Vinodh, Anesh Ramiya, & Gautham, 2011)
	Container port	(Onut, Tuzkaya, & Torun, 2011)
	Production line	(Bi & Wei, 2008)
	Transportation-mode	(Tuzkaya & Onut, 2008)
	Flexible manufacturing system scheduling	(Sadi-nezhad, Didehkhani, & Seyedhosseini, 2008)
	Project management	(Ahmadvand, Bashiri, & Alighadr, 2010)
	Strategic management	(Lin, Lee, & Wu, 2009)
	Personnel	(Ayub, Md, & Md, 2009)
	Concept	(Ayağ & Özdemir, 2009)
	3PL Service Support	(Chunhao, Sun & Yuanwe, 2008)

Table 3.2 continued

Evaluation	Sustainable production indicators	(Tseng, Divinagracia, & Divinagracia, 2009)
	Knowledge management	(Sun & Bi, 2008)
	Project management performance	(Gao, 2010)
	Support plan	(Qu, Kang, & Long, 2009)
	Supply chain management	(Li, 2009) (Zhou & Xu, 2006)
	Agile service development	(Lin & Hsu, 2007)
	Contaminated site remedial countermeasures	(Promentilla, 2008)
	ERP readiness	(Razmi, Sangari, & Ghodsi, 2009)
	E-learning	(Sadi-Nezhad, Etaati, & Makui, 2010)
Location Selection	Shipyard location	(Guneri, Cengiz, & Seker, 2009)
	Distribution center location	(Wei & Wang, 2009)
	Location selection based on environmental assessment	(Wu, Lin, & Chen, 2009)
Decision Making	Decision support system	(Mikhailov, 2003)
	Supply chain	(Wong, 2010)
	Organization design	(Nuhodzic, 2010)

3.4.1 FANP Fuzzy Linguistic Scale

Based on these researches, the first step in FANP implementation is the determination of the fuzzy linguistic scale. Some of the common fuzzy linguistic scales which are used in these researches were classified into three prominent scales which are Saaty's Scale, Cheng's Scale and Kahraman's Scale as summarized in Table 3.4.

3.4.1.1 Saaty's Scale

In reality, Saaty's scale is not proposed by Saaty (1980). This scale is derived from the original fundamental scale of absolute numbers used in crisp ANP. A lot of researches related to FANP used Saaty's linguistics scale as a potential reliable source because it is based on the original ANP nine point fundamental scale of pairwise comparison as shown in Table 3.3. Table 3.5 presents the researches which used this scale.

Table 3.3.

Crisp Pairwise Comparison Scale

Intensity of importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocal of above non-zero number	If activity *i* has one of the above non-zero numbers assigned to it compared with activity *j*, then *j* has the reciprocal value when compared with *i*.	

3.4.1.2 Cheng's Scale

Cheng and Yang (1999) asserted that in any evaluation process, attributes describe by language or ambiguous expressions and some quantitative requirements are represented by quality. Hence, they utilized the hierarchy structure diagram to structure complicated problems and combined fuzzy theory to deal with some vague or not well defined language variables and qualitative requirements (Cheng & Yang, 1999). Table 3.5 presents the researches which used this scale.

3.4.1.3 Kahraman's Scale

Kahraman, Ertay, and Büyüközkan (2006) proposed a linguistic scale for deriving relative importance and they implemented this scale in Chang's FAHP model. In addition, they proposed an integrated framework based on fuzzy-QFD and fuzzy optimization model for determining the product technical requirements (PTRs) in designing a product. Table 3.5 presents the researches which used this scale.

Table 3.4.

The Prominent Fuzzy Linguistic Scale

Authors	**No of terms**	**Fuzzy linguistic scale**
Saaty (1980)	5	{(1,1,1),(2,3,4),(4,5,6),(6,7,8),(8,9,10)}
Cheng & Yang (1999)	5	{(0,0,0.25),(0,0.25,0.5),(0.25,0.5,0.75),(0.5,0.75,1),(0.75,1,1)}
Kahraman et al. (2003)	7	{(1,1,1),(0.5,1,1.5),(1,1.5,2),(1.5,2,1.5),(2,2.5,3),(2.5,3,3.5)}

Table 3.5.

The Researches which Used Prominent Linguistic Scale

Fuzzy linguistic scale	Research
Saaty (1980)	(Razmi, Sangari, et al., 2009)
	(Önüt et al., 2009)
	(Vinodh et al., 2011)
	(Tuzkaya & Onut, 2008)
	(Ahmadvand et al., 2010)
	(Ayağ & Özdemir, 2009)
	(Wong, 2010)
	(Nuhodzic, 2010)
Cheng & Yang (1999)	(Pang, 2009)
	(Tseng et al., 2009)
Kahraman et al. (2003)	(Wei & Sun, 2009)
	(Bi & Wei, 2008)
	(Tuzkaya & Onut, 2008)
	(Sadi-nezhad et al., 2008)
	(Gao, 2010)
	(Li, 2009)
	(Lin & Hsu, 2007)
	(Sadi-Nezhad et al., 2010))
	(Wei & Wang, 2009)

3.4.1.4 Self-Define Scale

In spite of Saaty's Scale, Cheng's Scale and Kahraman's Scale, some researches defined their own fuzzy linguistic scale. According to these researches, their scales are deemed to be more suitable with the requirement of their own applications. These self-defined scales are shown in Table 3.6.

Table 3.6.

Self-Defined Fuzzy Linguistic Scale

Fuzzy linguistic scale	No of terms	Research
{(0.5,1,1.5),(1,1.5,2),(1.5,2,2.5),(2,2.5,3)}	4	(Razmi, Rafiei, et al., 2009)
{(2/3,1,3/2),(1,3/2,2),(3/2,2,5/2),(2,5/2,3), (5/2,3,7/2), (3,7/2,4);(7/2,4,9/2)}	7	(Boran & Goztepe, 2010)
{(1,1,1),(1,2,3),(2,3,4),(3,4,5),(4,5,6),(5,6,7), (6,7,8),(7,8,9),(9,9,9)}	9	(Lin et al., 2009)
{(0.5,1,1.5),(1.5,2,2.5),(2.5,3,3.5),(3.5,4,4.5), (4.5,5,5.5),(5.5,6,6.5),(6.5,7,7.5),(7.5,8,8.5),(8. 5,9,9.5)}	9	(Qu et al., 2009)
{(1,1,1),(1,2,3),(2,3,4),(3,4,5),(4,5,6),(5,6,7), (6,7,8), (7,8,9);(8,9,10)}	9	(Zhou & Xu, 2006)
{(1,1,1),(1,1,3),(1,2,3),(1,3,5),(2,4,6),(3,5,7), (4,6,8), (5,7,9);(6,8,10);(7,9,11)}	10	(Ayub et al., 2009)

In spite of that, there are no research yet which determines which linguistic scale is more preferable. At the root, it always comes to the number of judgment answers on which decision makers can comply to. Moreover, all of the mentioned linguistic scale utilizes triangular function of fuzzy number (TFN) where each individual scale set has three points except Buckley (1985) which used four points trapezoidal function. Other types of linear membership function or non-linear form has not been attempted yet in FANP.

3.4.2 FANP Defuzzification Methods

A number of defuzzification methods have been proposed to handle fuzzy pair-wise comparison matrices in the case of FANP. The first attempt to develop the procedure in the defuzzification procedure to derive crisp value from the fuzzy pair-wise comparison matrices is from Van Laarhoven and Pedryz (1983). They suggested a fuzzy logarithmic least squares (FLLS) method to obtain triangular fuzzy weights from a triangular fuzzy comparison matrix. Buckley (1985) utilized the geometric mean method to calculate fuzzy weights. Chang (1996) proposed an extent analysis method, which derives crisp weights for fuzzy comparison matrices.

Meanwhile, Xu (2000) brought forward a fuzzy least squares priority (FLSP) method. Csutora and Buckley (2001) came up with λ-Max method, which is a direct defuzzification of the *k*-max method. Mikhailov (2003) developed a fuzzy preference programming (FPP) method, which is inspired from the linear programming (LP) method. Lately, Wang, Elhag, and Hua (2006) presented a modified FFLS method which is the improved method based on Van Laarhoven and Pedryz (1983). To date, various novel defuzzification for fuzzy pairwise comparison is still being suggested as an alternative to derive crisp values for ANP basis. These methods are historically listed in Table 3.7. In addition, there are also researches which use alternate defuzzification method as shown in Table 3.8.

Table 3.7.

General Methods of FANP Defuzzification

FANP Defuzzification Methods	Description
Van Laarhoven & Pedryz (1983)	Fuzzy logarithmic least squares method (LLSM)
Buckley (1985)	Geometric mean method
Chen & Hwang (1992)	Lootsma's logarithmic least square method
Chang (1996)	Extent analysis method
Xu (2000)	Fuzzy least squares priority method
Csutora & Buckley (2001)	λ- max method
Cheng & Yin (2002)	Fuzzy group decision-making method
Mikhailov (2003)	Fuzzy preference programming method
Wang, Elhag & Hua (2006)	Modified logarithmic least squares method

Table 3.8.

Other Methods of FANP Defuzzification

Other FANP Defuzzication Methods	Research
α- cut concept	(Ayağ & Özdemir, 2009) (Vinodh et al., 2011) (Nuhodzic, 2010) (Lin & Hsu, 2007)
Geometric mean	(Ayub et al., 2009)
Defuzzification method of (Liou & Wang, 1992)	(Wu et al., 2009)
Defuzzification method of (Opricovic & Tzeng, 2004)	(Tseng et al., 2009)

These methods are systematic approaches to the alternative selection and justification problem by using the concepts of fuzzy set theory. From the 32 researches, four defuzzification methods that have been used more often compared to other methods are being highlighted, namely (1) Chang's, (2) Mikhailov, (3) Chen and (4) Cheng.

3.4.2.1 Chang's Extent Analysis

Chang (1996) claimed that their method's algorithm had less time complexity than logarithmic least squares approach of Van Laarhoven and Pedryz (1983). They used triangle fuzzy number to derive pair wise comparison judgments and extent analysis method before they applied the comparison principle of the fuzzy number. Most of researches asserted that they used Chang's algorithm because it is the easiest and fastest method among existing defuzzification method. Table 3.9 and 3.10 presents the researches which used this defuzzification method.

3.4.2.2 Mikhailov's Fuzzy Preference Programming

Mikhailov (2003) criticized Chang (1996) approach due to the utilization of arithmetic mean which produces inconsistent fuzzy pairwise comparison matrix. He proposed an approach for deriving priorities from fuzzy pair wise comparison judgments based on α-cuts decomposition of the fuzzy judgments into a series of interval comparisons. He also claimed that the proposed approach is independent to the specific form of the fuzzy sets used to represent the judgments, and can be used when some of the judgments are represented as intervals or crisp values. In addition, this method used the concept of Linear Programming (LP) for deriving crisp priorities from the fuzzy interval judgments namely, Fuzzy Preference Programming (FPP). Table 3.9 and 3.10 presents the researches which used this defuzzification method.

3.4.2.3 Chen and Hwang's Lootsma's Logarithmic Least Squares

Inspired by Laarhoven and Pedrycz (1983), Chen and Hwang (1992) proposed Lootsma's Logarithmic Least Squares for the assessment of weights which is based on Saaty's AHP methods (Saaty, 1980). This method is considered to be ancient as better method can be used. Table 3.9 and 3.10 presents the researches which used this defuzzification method.

3.4.2.4 Cheng's Fuzzy Group Decision Making

Cheng suggested a method for the fuzzy group decision-making method. Via this method, experts' opinions may be defined by linguistic terms of trapezoidal or triangular fuzzy numbers. In order to reach a consistency among the judgments, Delphi method is used for the fuzzy rating to achieve consensus. By constructing fuzzy decision matrices, the whole fuzzy numbers were obtained by multiplying the fuzzy decision matrix with the corresponding fuzzy attribute weight. Table 3.9 and 3.10 presents the researches which used this defuzzification method.

Table 3.9.

FANP Themes with Respect to Defuzzification Methods

FANP Theme	Defuzzification Method				
	Chang	**Mikhailov**	**Chen**	**Cheng**	**Others**
Selection	(Wei & Sun, 2009) (Boran & Goztepe, 2010) (Bi & Wei, 2008) (Lin et al., 2009)	(Pang, 2009) (Sadi-nezhad et al., 2008) (Lin, 2009)	(Önüt et al., 2009) (Onut et al., 2011) (Tuzkaya & Onut, 2008) (Ahmadvand et al., 2010)	(Chunhao, Sun & Yuanwe, 2008)	(Ayağ & Özdemir, 2009) (Vinodh et al., 2011) (Ayub et al., 2009) (Razmi, Rafiei, et al., 2009)
Evaluation	(Sun & Bi, 2008) (Gao, 2010) (Qu et al., 2009) (Li, 2009) Lin & Hsu, 2007) (Razmi, Sangari, et al., 2009)	(Sadi-Nezhad et al., 2010)		(Tseng et al., 2009) (Zhou & Xu, 2006) (Promentilla, 2008)	
Location selection	(Guneri et al., 2009) (Wei & Wang, 2009)				(Wu et al., 2009)
Decision making		(Mikhailov & Mdan G, 2003) (Wong, 2010)			(Nuhodzic, 2010)

Table 3.10.
Fuzzy Linguistic Scale with Respect to Defuzzification Methods

Fuzzy linguistic scale	Defuzzification Method				
	Chang	**Mikhailov**	**Chen**	**Cheng**	**Others**
Cheng		(Pang, 2009)		(Lin, Cheng, Tseng, & Tsai, 2010)	(Tseng et al., 2009)
Kahraman	(Tuzkaya & Onut, 2008) (Wei & Sun, 2009) (Wei & Wang, 2009) (Bi & Wei, 2008) (Gao, 2010) (Li, 2009)	(Sadi-nezhad et al., 2008)			(Lin & Hsu, 2007)
Saaty		(Wong, 2010)	(Önüt et al., 2009) (Vinodh et al., 2011) (Tuzkaya & Onut, 2008) (Ahmadvand et al., 2010)		(Ayağ & Özdemir, 2009) (Razmi, Sangari, et al., 2009) (Nuhodzic, 2010)
Self-defined	(Razmi, Rafiei, et al., 2009) (Boran & Goztepe, 2010) (Lin et al., 2009) (Qu et al., 2009)			(Zhou & Xu, 2006)	(Ayub et al., 2009)

Table 3.9 illustrates relationships between researches which used various methods of fuzzy weighing and prioritization with their themes. For instance, it can be inferred that most of the researches which used Chang's and Mikhailov's were in selection area, Also it is observed that researches with Chang's method were applied in evaluation process. In contrast, there is no research in the field of forecasting and location selection which used Mikhailov's, Chen's and Cheng's methods. Table 3.10 shows existing relationship between fuzzy scale and defuzzification methods. Most of the researches which used Kahraman's scale applied Chang's method, whilst Saaty's scale implementation applied Chen's method. In brief, fair amount of researches which implemented Mikhailov's and Chang's methods can be found in all types of fuzzy scales.

The presence of fuzziness features in a MCDM problem however increases the problem's complexity (Tzeng & Huang, 2011). The fuzzy values together with the qualitative data are more problematic to process than crisp data in which certainly increases the computational requirements especially during the process of ranking, sorting and the selection of the preferred alternatives (Kahraman, 2008; Martin et al., 2013; Umm-E-habiba & Asghar, 2009). Because of these drawbacks, FMCDM appeals the attention to improvise the available method and the latest ideas suggested into this field is known as the Intelligent FMCDM (El-Wahed, 2008).

3.5 Integration of Knowledge Based System with Fuzzy Multi Criteria Decision Making

Intelligent FMCDM is the integration method between artificial intelligence (AI) and FMCDM. The summary of the integration is shown in Figure. Based on El-Wahed (2008), Artificial Intelligence (AI) techniques can be classified into three groups namely, symbolic processing, search methods and learning process as shown in Table 3.11 and Figure 3.4.

Table 3.11.

AI Groups by Functionality.

AI groups by functionality	**Description**	**Example of techniques**
Symbolic processing	The knowledge is implemented in symbolic manner not numerically. The process is not algorithmic.	Knowledge based system, fuzzy knowledge based system and decision support system
Search methods/ Heuristics	Search the global solution space of optimization problem. They look for the local optima solution under the pretense that it is acceptable faster.	Genetic Algorithm (GA), Simulated Annealing (SA), Ant Colony Optimization (ACO), DNA computing, and hybrid search methods.
Learning process	Forecast, classify and estimate the solution based on the historical data.	Artificial Neural Network (ANN) and neuro-fuzzy systems.

Note: Adapted from El-Wahed (2008).

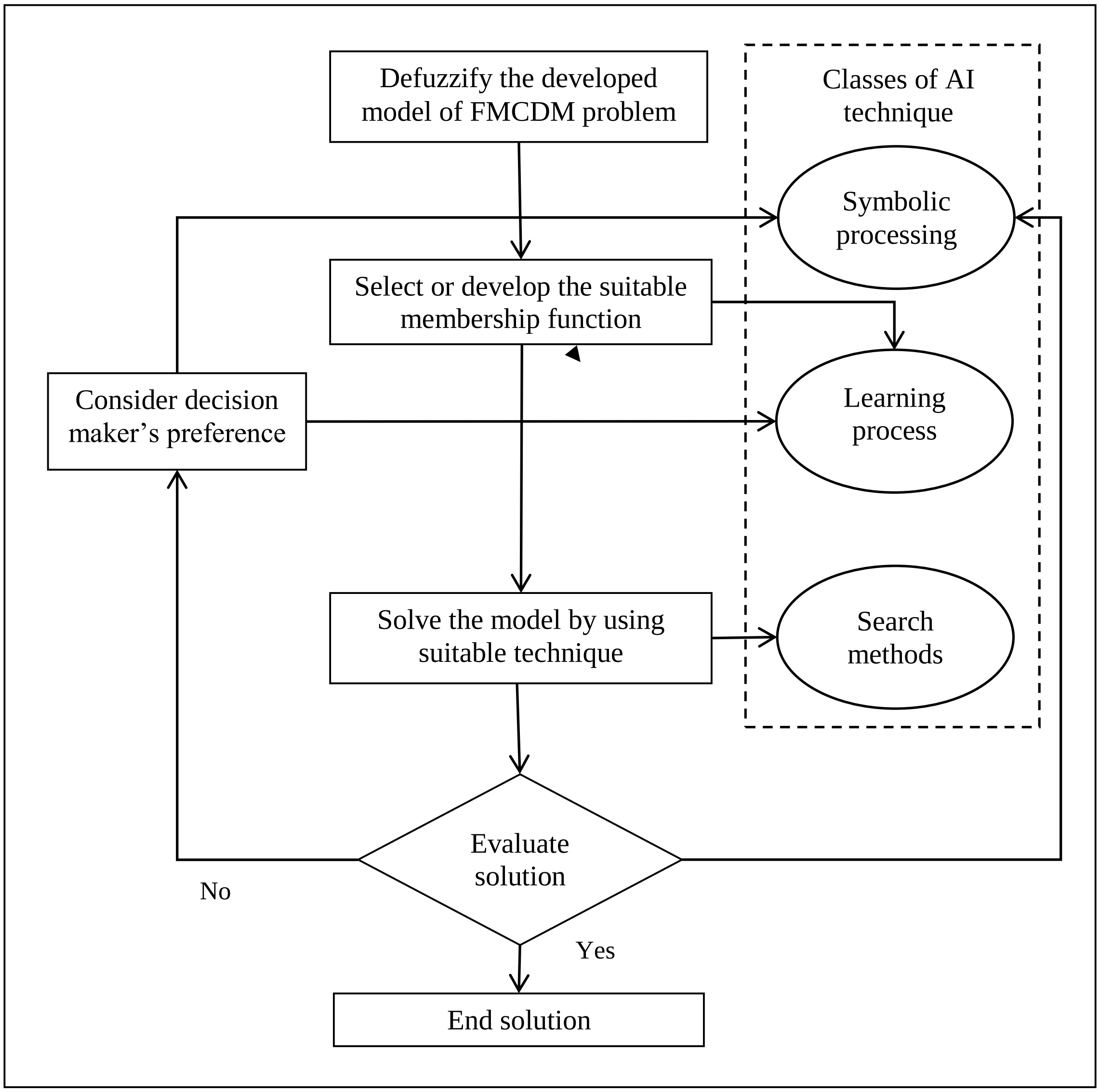

Figure 3.4. The Integration of FMCDM and AI Flowchart.

Note: Reprinted from El-Wahed, (2008).

This research attempted to utilize the symbolic or qualitative processing capability of KBS with FANP, as Tseng et al. (2009) did not involve qualitative elements of knowledge into their method.

3.6 Knowledge Based System

Knowledge Based System (KBS) is generally understood as the representation tool of any types of knowledge element in a form of computer system to solve specific tasks and is one of the major techniques in the field of Artificial Intelligence. From a formal viewpoint, KBS is defined as "*a computer program for extending and/or querying a knowledge base which is a collection of knowledge expressed using some formal knowledge representation language. A knowledge base forms part of a knowledge based system*" (FOLDOC, 2000) or "*A computer system that is programmed to imitate human problem-solving by means of artificial intelligence and reference to a database of knowledge on a particular subject*" (Computer & Tech Dictionary). The best definition of KBS due to its thorough explanations of the system's elements together with its potential functionality is suggested by the Elsevier Knowledge Based Systems Journal which entitles as:

"*Knowledge Based Systems focuses on systems that use knowledge based techniques to support human decision making, learning and action. Such systems are capable of cooperating with human users and so the quality of support given and the manner of its presentation are important issue*" (Knowledge Based System, 2005).

KBS is also been extensively renowned as Expert System (ES) though Davenport and Prusak (1998) and Stelzer (2003) argued that case-based reasoning (CBR) and Neural Network (NN) are also KBS. However, Davenport and Prusak (1998) Stelzer (2003) claims are not supported by the other researchers in the field of AI, which most of them claim that KBS can only be proclaimed as ES. A counter argument fact that KBS is indeed ES is given by the International Journal of Knowledge Based and Intelligent Engineering Systems where they classified KBS separately from ES ("International Journal of Knowledge Based and Intelligent Engineering Systems (IJ KBIES)," 2004).

However, based on further investigation to search for conclusiveness regarding this matter, Awad (1996) and Cornelius (2000) defined ES as a KBS where users gains the knowledge from the experts of a particular problem field. Thus, proving that ES is a subset of KBS thus ES is indeed a KBS. Based on the definition by Knowledge Based Systems (2005), there are four key aspects in defining a KBS which are (1) knowledge, (2) decision making support (3) learning and (4) action/implementation. In this research, the term KBS is being used rather than ES although ES is being widely used in the literature.

The term KBS is opted because the knowledge should not only be restricted to the so-called experts. The knowledge can be classified into more types of explicit, tacit, common sense, heuristic, and meta domain as shown in Table 3.12 and the description of knowledge can best be shown in the form of DIKW components as in Table 3.13 (Sajja & Akerkar, 2010). In addition, the usage of the term 'expert' always promotes the problem in terms of the expertise knowledge validation (Gackowski, 2012a, 2012b). In other words, it is difficult to claim the system is expert enough to a certain extent where all of the users will all agree that the system built is an expert. The knowledge validation still being a major problem of the formation of the KBS and is discussed later.

Table 3.12.

Types of Knowledge

Types of Knowledge	**Description**
Explicit	Shown on the form of words or numbers in the form of data. Instructions, guidelines etc. It is can be easily understood because it is more structured, systematic and organized.
Tacit	Knowledge in the form of unstructured, informal and non-systematic in the mind of an individual. It is highly unique and it is hard to understand.
Common sense	Knowledge which is generally known and present in most normal people.
Heuristic	A specific rule-of-thumb which utilize unsupported/incomplete evidence of rule which is usually derived from experiences.
Meta	Knowledge which provide descriptions of the other knowledge
Domain	Valid and trusted source of knowledge which gained from the experts/specialist on certain matter/problem setting.

Table 3.13.

DIKW Components

Major Elements	Description	Example	Volume	Complexity
Data	Symbols that represent objects, events, and their properties	Percentage of carbon dioxide (CO_2)	Highest	Lowest
Information	Refined processed data which has been made useful	20% of CO_2 is considered high	High	Low
Knowledge	Synthetized and analyzed information such that it can provide meaningful function and outcome which consists of instructions and explanations	How to measure the percentage level of CO_2	Low	High
Wisdom	Knowledge which comes from experience, judgment, values and laws and it is usually developed in a period of certain times	The level of CO_2 should be constantly monitored to maintain the safety level for the staff in the manufacturing facility	Lowest	Highest

With regards to the availability of advanced computing technologies, KBS is being pushed to response to more demanding tasks in which at some point may require higher level of intelligence (El-Wahed, 2008; Kordon, 2010). In that sense, KBS can also be classified under the field of Computational Intelligence (CI) or Intelligent System (IS). Those two fields is the extension of AI field with the addition of human involvement of in the decision making process for a more responsive, faster and more efficient implementation techniques (Kordon, 2010).

3.6.1 Types of Knowledge Based System

KBS has wide application in many areas and can function as knowledge dissemination, decision support, knowledge management, diagnostics, selection, planning and advisory systems (Speel, Van Jooligen & Beijer, 2001). There are three main types of KBS which are rule-based KBS, frame-based KBS and fuzzy KBS (Kordon, 2010). A rule-based KBS is made up by a set rule. A rule is consists of two parts of antecedent which is the fact's hypotheses and the consequent which specifies the actions if the facts' hypotheses value is true or false. For example:

If the manufacturing company recycle their products;

Then the manufacturing company is environmentally sustainable.

A frame-based KBS consists of frames in which a frame represents the value of the subjects in the form of attributes. A frame-based KBS is capable to portray highly abstract type of knowledge by defining a hierarchy of classes. For example, the class hierarchy of a sustainable manufacturing monitoring system may include basic classes of systems unit, forms of hazardous material and types of equipment.

Fuzzy KBS incorporates Fuzzy Sets Theory (FST) into the reasoning and/or knowledge representation process. The integration of FST into KBS was introduced to overcome one of the biggest drawbacks of a KBS which are the uncertainty, imprecision and vague knowledge that is gathered during the knowledge acquisition phase. Compared to the rule-based KBS, the rule is stated in the form of fuzzy linguistic terms which holds a certain degree of membership function. Fuzzy KBS also relaxes the hard assumption applied for a certain specific rules. For example:

If the manufacturing company recycle most of their products;

Then the manufacturing company is environmentally sustainable (0.85).

This statement can also been interpreted as "*If the manufacturing company recycles most of their products, then the manufacturing company is 85 percent more likely to be environmentally sustainable*".

3.6.2 Components of KBS

KBS is consolidated with separate elements that work together as a unit to entitle it to be a KBS. The component of KBS includes knowledge domain, knowledge engineer, knowledge acquisition, knowledge base, inference engine, database, interface and user. The connection between these components is shown in Figure 3.5.

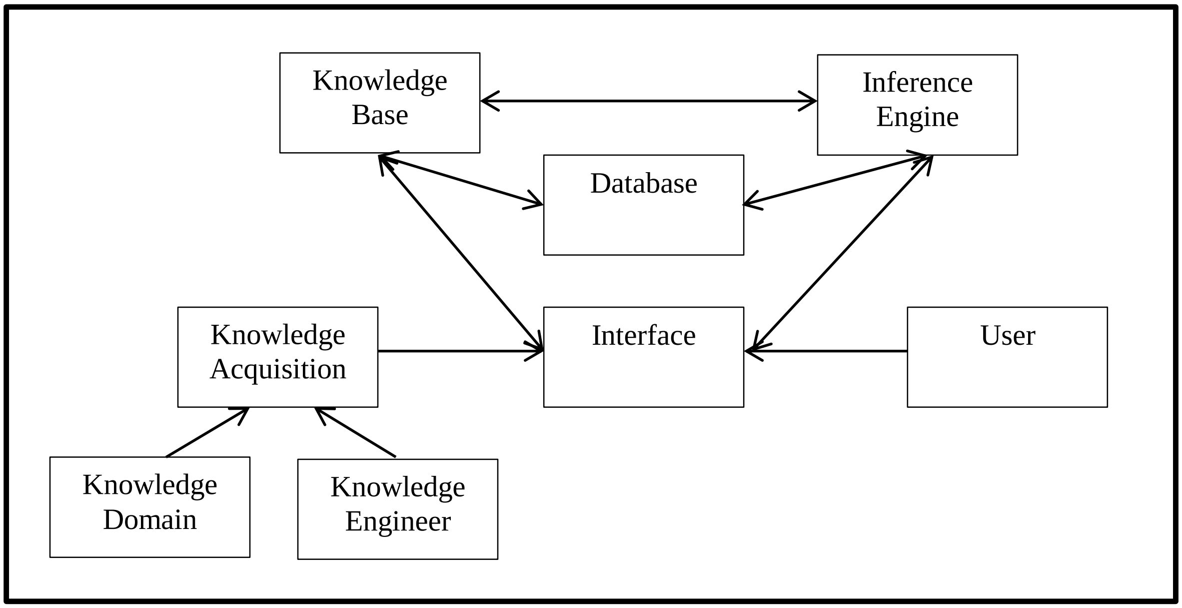

Figure 3.5. The Architecture of Knowledge Based System.

Note: Reprinted from Kordon (2010).

By referring to Figure 3.5, the knowledge engineer is the person who develops the KBS. The knowledge engineer collaborates together with the knowledge domain thorough a process known as the knowledge acquisition. During this process, the knowledge is collected and organized which usually requires series of interviews with the knowledge experts, observations, and also literature review (Milton, 2007).

The gathered knowledge is simplified and process into a codified structure in the forms of rule-based, frame-based or fuzzy. The inference engine acts as a ‘brain’ which controls and processes the knowledge content to provide the answers or solutions for the case problem. There are two main techniques in developing the inference which are forward chaining and backward chaining.

Forward chaining is data driven. It starts by the collection of knowledge base which is then being used as an inference. Forward chaining is usually used in planning type of KBS. Backward chaining is goal-driven. It starts by seeking the sets of knowledge base towards goal until it matches the requirement of the goal. If an appropriate knowledge based is found and its antecedent statement fits the available data, then it is assumed that the goal achieved.

Backward chaining is usually used in diagnostic type of KBS. After the relationship between the knowledge base and the inference engine managed to achiever the considerable objective, it is shown in the form of the user interface which is a user-friendly communication structure with the end user who benefits from the knowledge of the KBS (Awad, 1996; Cornelius, 2002; Kordon, 2010).

3.6.3 Issues of Knowledge Based System

The major advantage of KBS is indeed in terms of its reasoning capability. The reasoning process is built up upon the formation of knowledge base which consists of rules via the inference engine. The arrangement of rules can be made to a point of decision, answer or even a simple explanation. This advantage is being taken into consideration as it highlights the significance of this research which distinguished it from other researches in the FANP field.

The next benefit which can be gained from KBS is the knowledge distribution competency. The knowledge acquired which from the knowledge domain which is usually the experts in the problem field can be made accessible to other target users at any region and anytime. In spite of the dissemination prowess, the more advanced KBS can be made as decision support and making, planning, diagnostic, and advisory system which can be used together with people in order to achieve the desired objective as well to solve specific problem.

The biggest weakness of KBS that is still not been resolved to date is the verification and the validation process of KBS The knowledge is generally not well understood in the knowledge acquisition process and the system is incapable to provide a substantial reasoning to the systems user. Next, the knowledge acquired by the knowledge domain is usually inconsistent and this also may hamper the content validity of the outcome of KBS. In addition, most of the knowledge engineers do not have an automated mechanism of these tasks and it is always being done manually, which may increase the likelihood of errors (Laudon, Laudon, & Fimbel, 2010). Abdullah, Evans, Benest and Paige (2004) also asserted that there is no standardized approach to model KBS as it tend to be used in an ad hoc way and is highly dependent on the experience of the knowledge engineers. Furthermore, they claimed that the role of KBS has been under-utilized in recent years due to the problems of coordination, incomprehension of KBS task, legal implication and user expectation which became a hindrance in rejuvenating the significance of KBS.

KBS is classified under the symbolic processing in which its role is more on providing the description, explanation and reasoning for the problem of concern. In the recent years, KBS has been underestimated due to its lack of numerical proofing which provide more logical and rational decision. This happens due to the qualitative nature of the technique, which requires knowledge acquisition from people. In addition, from the KBS research done until today, it still does not solve the main drawback of the KBS which is the verification and the validation process of KBS (Gackowski, 2012a, 2012b; Laudon et al., 2010).

As being stressed out by Kordon (2010), the human thinking and reasoning process is highly complex and unstructured. The human's knowledge is mostly in the tacit category and even involves high level of wisdom (Sajja & Akerkar, 2010). Thus, it is almost impossible for the highest power computer to emulate the whole thinking process of a human. This proves to be an ongoing challenge for the field of AI in spite of its numerous advancements in recent years.

The results of El-Wahed (2008) emphasized that the research which combine both KBS and FMCDM needs further attention to explore the benefits that can be gained from the integration of these techniques. Moreover, KBS can be one of the main alternatives which can be used to solve the weakness of FMCDM. Hence, the conjoint combination of KBS and MCDM or FMCDM is a potential unification that can be used to solve the real world problem.

3.7 Discussion of Knowledge Based Fuzzy Analytic Network Process

In the previous section, a fundamental description of three distinct techniques of Knowledge Based System, Fuzzy Sets Theory and Analytic Network Process has been introduced. In the following section, the justification of the integration of these three separate techniques that are used in this research is explained.

Analytic Network Process (ANP) was chosen as the sustainability indicator technique for the selection of the best alternatives. The justification for choosing ANP lies on two facts. The first one is the analysis of the sustainability as well as sustainable manufacturing is a MCDM problem. Next, the factors and criterion which are involved in three dimensions of sustainable manufacturing of economic, environment and society may interdependent among each other, whether within the dimensions or across the dimensions. The model developed via ANP must account for three major components of general sustainability before linking the elements which are necessary to the manufacturing side. Pertaining to this, it is essential to assume all possible indicators of sustainability are significant to the manufacturing model. Thus, it is better to make assumption that all the indicator elements are related among each other, where each of the elements may affect the outcome of the other elements. This assumption cannot be done using AHP, where the AHP and other MCDM methods should assume that the elements priorities are hierarchical and not dependent among each other.

ANP is not sufficient to solve the problem and should be integrated with FST to deal with the uncertain description and judgment of the problem, thus FANP should be utilized as the strategy in this research. The justification regarding the selection of FANP is because the problem nature of sustainability itself is fuzzy. As the consensus on the definition and description of sustainable manufacturing indicator is still uncertain among the academia and industry practitioners, the FST concept is suitable to be used to tackle this matter. In this research, the utilization of FANP which is an enhanced version from the original ANP is suggested. The main advantage of this measure is to increase the validity of the judgment made during the pair-wise comparison phase of ANP. Besides, it can be used to improve the consistency of the collected judgment weights and can develop a unified consensus of the knowledge domain.

Finally, the implementation of the knowledge can best be represented in the form of Knowledge Based System (KBS). Based on FANP, the KBS is being integrated as a method to enhance the productivity, the practicability and knowledge dissemination resolution. The KBS in this research is not just only a medium to process, organize and display the result of FANP as the system made by Tseng et al. (2009). The knowledge base component can be made to accommodate the need for a standardized indicator mechanism that can suit the specific requirement of various manufacturing organizations as advocated by Fan et al. (2010) and Reich-Weiser, Simon, Fleschutz, Yuan, and Athulan, Vijayaraghavan, Hazel (2013). In this research, the KBS was being integrated with the technique of Fuzzy Analytic Network Process (FANP) as a strategy to exploit the benefits from both knowledge fields.

The reasoning capability of KBS by the inference component can provide a huge advantage by the added value for the sustainability indicators. Thus, it can be made as an advisory mechanism by providing the explanation and suggestions, which at the end should enhance the users' experience of the system. The integration of these three separate techniques should enhance the possibility to evaluate the sustainability performance in manufacturing effectively. KBFANP is perceived to be the best combination of strategy yet to solve the problem addressed in this research.

CHAPTER FOUR
METHODOLOGY

In Chapter 2, the importance to include sustainability elements into the manufacturing setting is emphasized. The third objective of the research is to demonstrate the novel utilization of the Knowledge Based Fuzzy Analytic Network Process (KBFANP) system method in incorporating the major variable used in measuring the performance of the sustainable manufacturing. The strategy of the integration of these three techniques into KBFANP has also been justified accordingly in Chapter 3 specifically in Section 3.7 and it is believed to be the best mechanism to solve the problem addressed. In this chapter the methodology used to implement the KBFANP system is described. It includes the research process and the research design before the development mechanism of the system. Finally, the process of verification and validation of the system are described. At the end of this chapter, it is hoped that the journey process of this research is well exhibited, in such a way that the reader will be well informed.

4.1 Research Process

This research was divided into three main phases which includes research design, KBFANP system development and implementation. The flow of these phases is shown in Figure 4.1 and followed with the description of each phases in their respective sections.

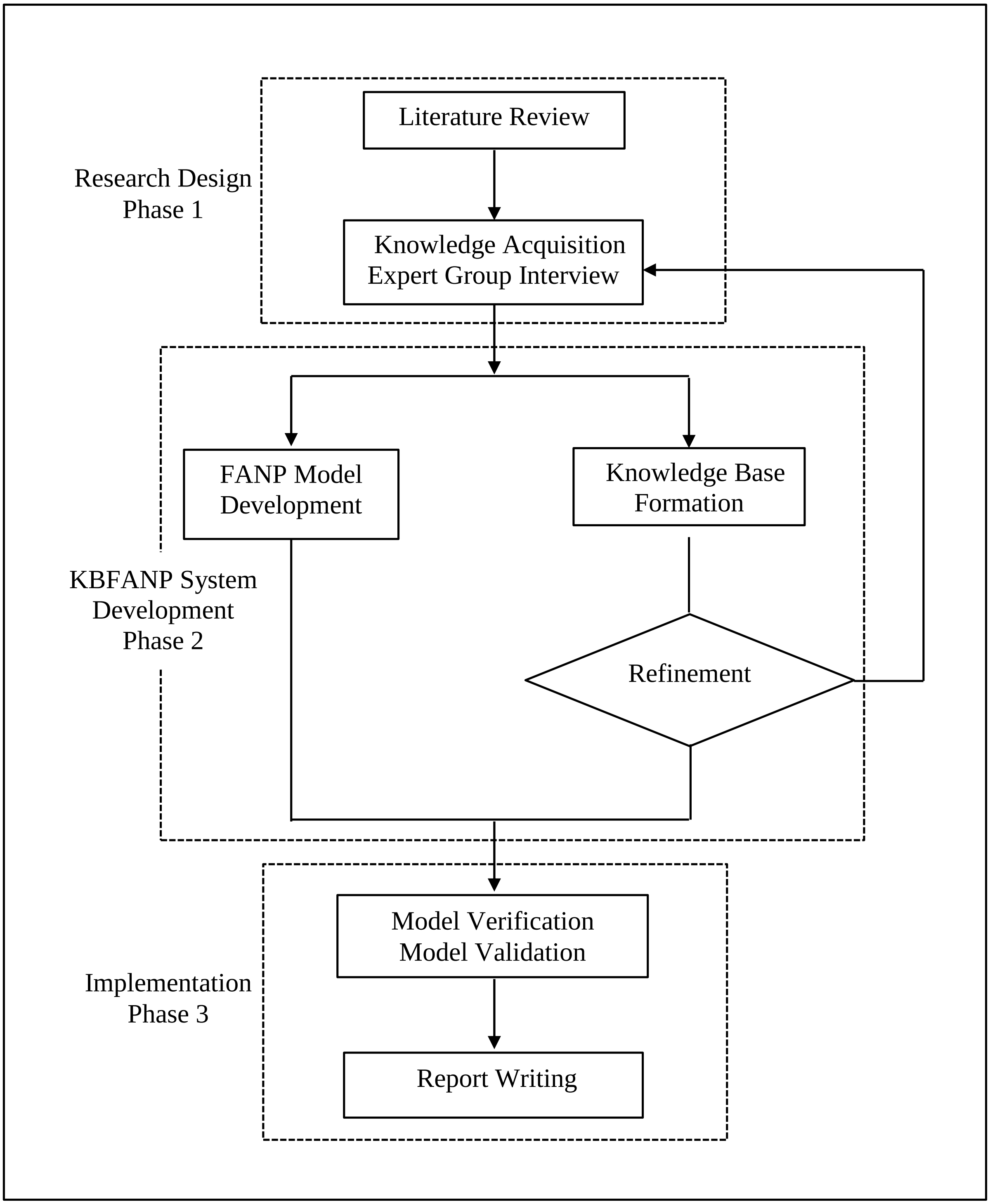

Figure 4.1. Research Process Flow

4.2 Research Design

This research started off with an extensive literature review regarding the recent philosophy and best practices of sustainable manufacturing. Based on the literature review, the sustainable manufacturing is suggested to consist of lean and green manufacturing. The lean and green paradigm complements each other in several aspects towards pursuing sustainability objective although the relationship between the aspects is still indefinite. Hypothetically, the practice of the lean philosophy may suit more on the economic and the society sustainability whereas the green philosophy fit more on the requirements from the aspect of environment sustainability. Thus, the relative importance between lean and green with each of the sustainability elements should be further investigated.

The knowledge was being further gathered by visiting a real world manufacturing company which has the initiative efforts or at least interests in implementing the concept of sustainable manufacturing. As an added value, the company which has already applied the lean manufacturing practice or showing interest in green or sustainable practice has be taken into account. Prior to this, a visit to the manufacturing company was done which comprised of series of observation and interview with the experts' group from the company to further discuss the matter.

4.2.1 Observation Phase

A direct observation was also done in a targeted manufacturing company. The objective of the observation is to learn on the operations and implementation of lean and green manufacturing practices within the company. In addition, a validation is done to align with the literature whether the lean and green practice are indeed advantageous compared with the other manufacturing paradigm as claimed in literature. The observation was needed as an added value especially to support the data obtained from the interview phase (Creswell, 2003). The implementation was being held in the company's location and certain non-confidential information was recorded using camera and note- taking measures.

4.2.2 Interview Phase

The series of industry interview contents includes the discussion on the topics of:

1. The current manufacturing paradigm implemented in the company
2. The concepts of sustainable manufacturing from the theoretical point and the practical viewpoint.
3. The overall company's own strategy and initiatives to embrace sustainable manufacturing.
4. The necessary criteria from each of economic, environment and society dimensions that should be considered in measuring the manufacturing sustainability performance from the practical point of view.
5. The relationship among the criteria of sustainable manufacturing.

The investigation made on the real world manufacturing process was intended to align and to validate the knowledge gained from the literature. The collaborative measure that is taken should enhance the outcome of this research. The most suggested paradigms, ideas from the literature and real practice are suggested later and combined in the form of a new indicator model.

4.3 KBFANP System Development

This phase is the most important in this research because the KBFANP system distinguished itself from previous researches which focus on the development of sustainable manufacturing indicator. The intention of the KBFANP system is to let the user, preferably from the manufacturing company planners to be able to suit their own problem requirement and setting. Therefore, instead of just knowing which criteria is the best, they are also able to know which criteria are related to them and which criteria that needs to be improved accordingly. In addition, this system let the user to choose indicator which is applicable to them, which made the assessment of sustainable performance to be more accurate. The KBFANP system proposed comprises of four major phase as shown in Figure 4.2 which are (1) Initialization, (2) Selection, (3) Evaluation and (4) Prioritization. These phases were encapsulated into the KBFANP model which is inspired by the DIKW model of Sajja and Akerkar (2010) and the standardized sustainable manufacturing indicator model by Reich-Weiser et al. (2013).

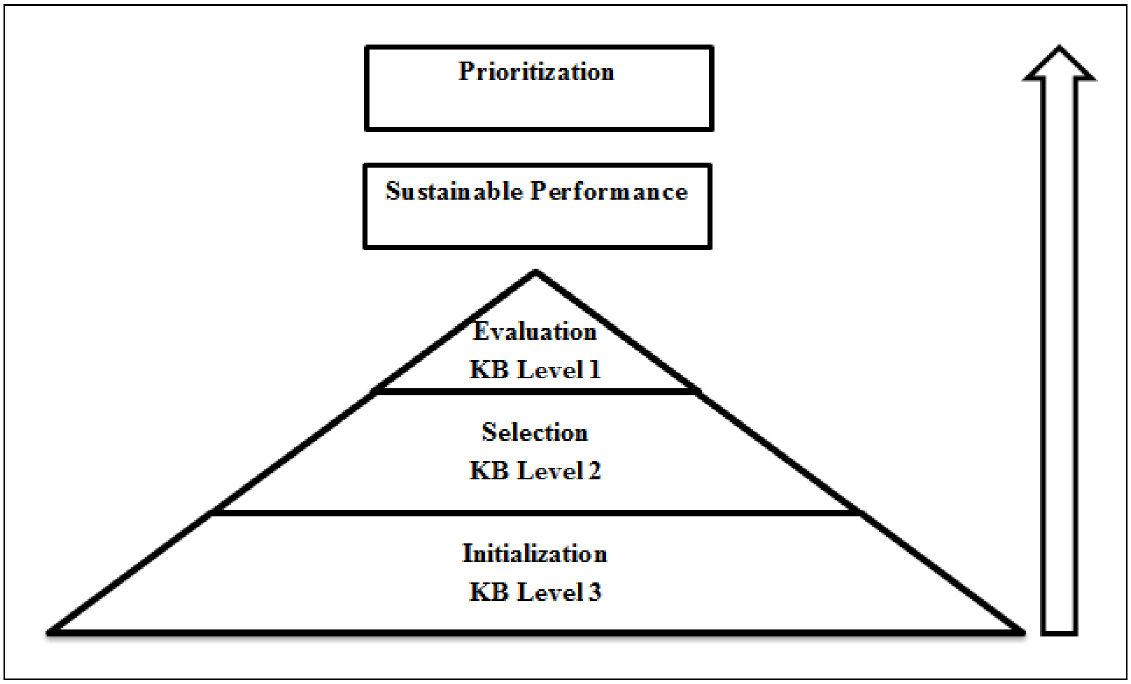

Figure 4.2. KBFANP System Model

4.3.1 Initialization Phase

In the initialization phase, the criteria associated with sustainability indicators are established. As foundation basis, the relative importance for each of the criteria is determined to distinguished which criteria is more significant towards sustainability goals compared with other criteria. In order to determine the relative importance, FMCDM approach of FANP is used because (1) it can consider the inter relationship among the sustainability criteria and (2) reduce the uncertainties due to the fuzzy nature of sustainability problem. The input obtained from experts regarding the relative importance of sustainability criteria is processed using FANP to obtain the final weightage for each criterion.

4.3.1.1 FANP Model

The FANP model developed is based on the GRI latest sustainability criteria which are embedded in G4 Sustainability Reporting Guidelines (GRI, 2013a, 2013b, 2013c).

4.3.1.1.1 Overview of GRI G4 Sustainability Reporting

The Global Reporting Initiative (GRI) is a pioneer and leading global non-profit organization in the sustainability reporting area. GRI's core mission is to make sustainability reporting standard practice for all companies as well as organizations. Its reporting system framework that includes Reporting Guidelines, Sector Guidance and other resources contains indicators and methods for measuring and reporting sustainability-related impacts and performance. Thousands of organizations, of all sizes and sectors, currently use GRI’s framework as a mechanism to measure their sustainability performance.

GRI's headquarter is located in Amsterdam, Netherlands, and their regional offices are located in Australia, Brazil, China, India, South Africa, and the USA. GRI also has strategic partnerships with global prominent organizations of the United Nations Environment Program (UNEP), the UN Global Compact, the Organization for Economic Co-operation and Development (OECD), and the International Organization for Standardization (ISO) . The GRI Framework is being developed collaboratively with the assistance of experts from these organizations and international company stakeholders’ which entitled it to be the most credible sustainability assessment standards for all types of organization (GRI, 2013a; Isaksson & Steimle, 2009).

4.3.1.1.2 FANP Methodology

The methodology of FANP is inspired by Mikhailov (2003), Saaty (1996) and Zhou (2012) which comprises of six major steps. The FANP model development was implemented using SuperDecisions software. The calculation of the fuzzy pairwise comparison input's defuzzification was calculated using MATLAB software before it was utilized back into SuperDecisions for a better sense of reporting.

4.3.1.1.2.1 Overview of MATLAB

MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. Using MATLAB, data can be analyzed, algorithms can be developed and models and applications can be created. The language, tools, and built-in math functions enable multiple approaches to be explored and solution can be found faster compared with spreadsheets or other types of programming languages for example C/C++ or Java.

4.3.1.1.2.2 Overview of SuperDecisions

The SuperDecisions is a software which is developed specifically for the implementation of ANP. The program was written by the ANP Team, working for the Creative Decisions Foundation. The Creative Decisions Foundation was established by the creator of ANP, Thomas Saaty and Rozann Saaty to promote more rational decision-making via ANP.

The FANP methodology consists of six steps which are:

Step 1. Problem identification

Establish a problem framework and define the evaluative criteria and sub-criteria. This involves identification of the decision problem and to structure it in the form of ANP model with goals, control criteria, clusters, elements and alternatives. In this research's model, the main goal is to analyze the sustainable manufacturing performance indicators. The ranking of the indicators are determined to improve the overall sustainable performance of the case company. The selection of the best manufacturing system is based on the competitive priorities in which the ANP terminology labeled to as control criteria. The control criteria involved are:

1. Environment
2. Economic
3. Society

The criteria considered is shown in Table 4.1

Table 4.1.

Criteria of Sustainable Manufacturing System

Category	Criteria
Economic	1. Economic Performance 2. Market Presence 3. Indirect Economic Impacts 4. Procurement Practices
Environment	5. Materials 6. Energy 7. Water 8. Biodiversity 9. Emissions 10. Effluents and Waste 11. Product and Services 12. Compliance 13. Transport 14. Overall 15. Supplier Environmental Assessment 16. Environmental Grievance Mechanism
Society	17. Labour Practices and Decent Works 18. Human Rights 19. Society 20. Product Responsibility

The alternatives considered are:

1. Lean Manufacturing System

2. Green Manufacturing System

Step 2. FANP model development

The FANP model can be represented as a network model or in the form of the original FAHP hierarchical structure (Agarwal, Shankar, & Tiwari, 2006; Bayazıt, 2006; Saaty, 2010). The hierarchical structure of the FANP model is similar to FAHP where the top element is the goal, and the lower elements are the criteria and sub-criteria and the bottom element being the alternatives. The only difference relies on the inclusion of the multi way, interdependencies relationship's indication among the criteria and sub-criteria. Figure 4.3 and 4.4 shows 2 FANP models which are suggested in this research.

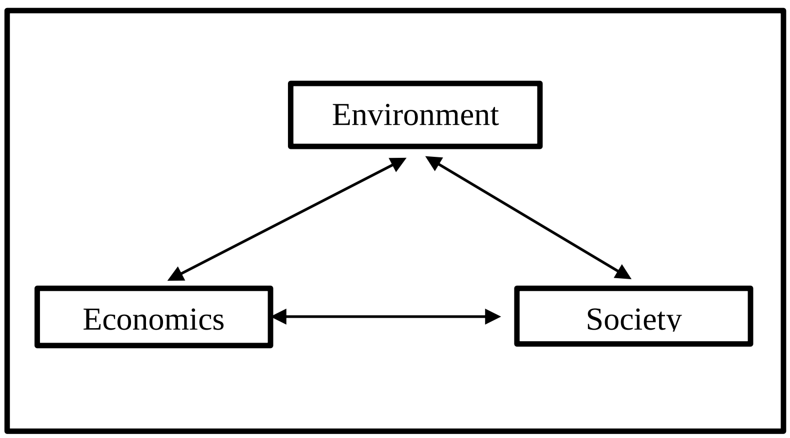

Figure 4.3. FANP model 1 without Alternatives

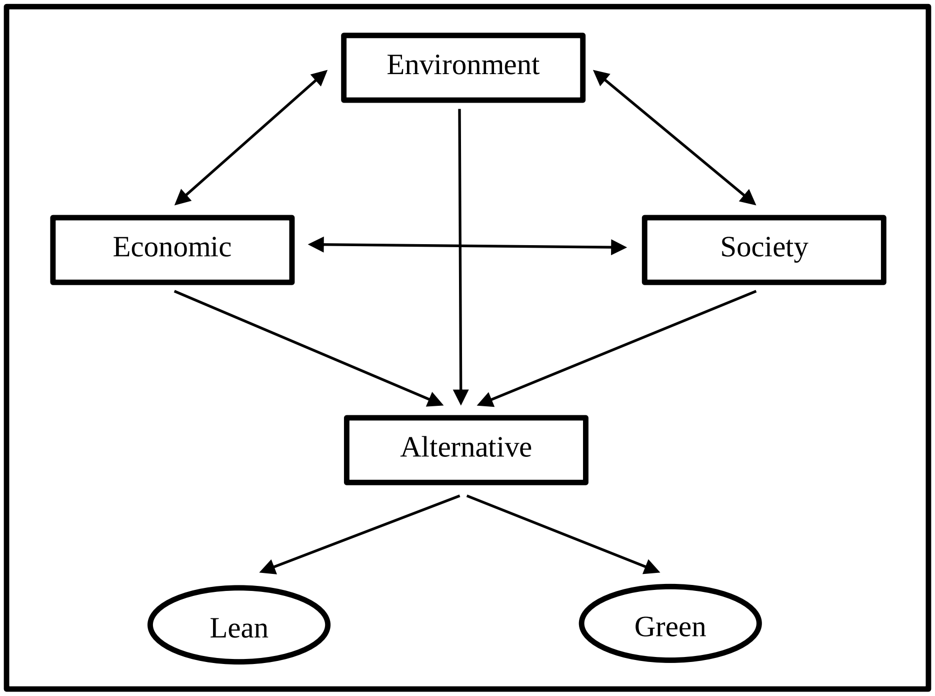

Figure 4.4. FANP Model 2 with Alternatives

Step 3. Fuzzy linguistic scale construction

Fuzzy linguistics scale for fuzzy pairwise comparison matrix which is built upon most of the FANP researches is based on the triangular function known as triangular fuzzy number (TFN) although trapezoidal function is also acceptable (Buckley, 1985**.** TFN is denoted simply as (*l*, *m*, *u*) where (1) *l* represents the smallest possible value, (2) *m* as the most promising value and (3) *u* as the largest possible value that define the fuzzy occurrence function. Each TFN has linear representations on its left and right side with the membership function shape as shown in equation (4.1) and Figure 4.5

$$U_M(x) = \begin{cases} (x-l)/(m-l) & l \leq x \leq m \\ (u-x)/(u-m) & m \leq x \leq u \\ 0 & otherwise \end{cases} \tag{4.1}$$

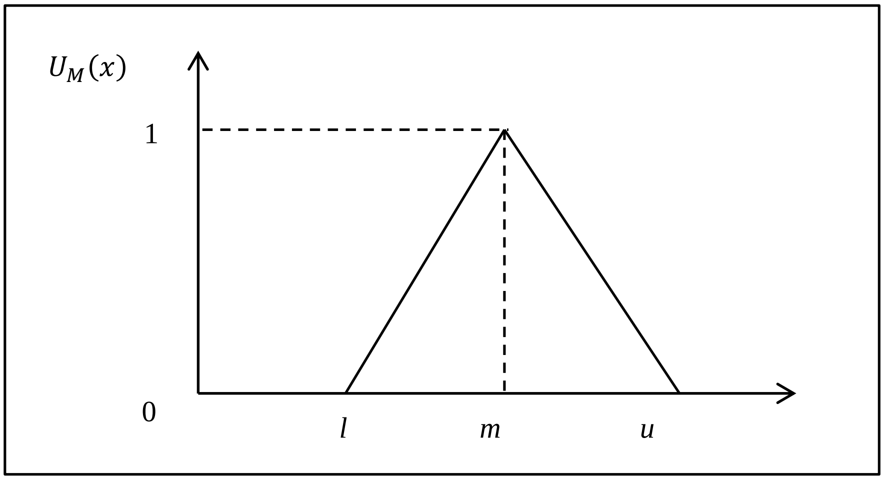

Figure 4.5. Triangular Fuzzy Number M

Based on Section 3.4.1, there are three prominent fuzzy linguistic scales which were used in FANP researches, which are the Cheng' scale, Kahraman' scale and Saaty's scale. These three scales applied TFN concept although these scales difference relies on the number of terms used and the values of the *l*, *m* and *u.*

Table 4.2.

The Prominent Fuzzy Linguistic Scales

Authors	**No of terms**	**Fuzzy linguistic scale**
Cheng & Yang (1999)	5	{(0,0,0.25);(0,0.25,0.5);(0.25,0.5,0.75);(0.5,0.75,1);(0.75,1,1)}
Kahraman et al. (2003)	7	{(1,1,1);(0.5,1,1.5);(1,1.5,2);(1.5,2,1.5);(2,2.5,3);(2.5,3,3.5)}
Saaty (1980)	5	{(1,1,1);(2,3,4);(4,5,6);(6,7,8);(8,9,10)}

This research applied Saaty (1980) nine-point fundamental scale of absolute numbers with five linguistic terms which are (1) EI (Equal Importance), (2) MI (Moderate Importance), (3) SI (Strong Importance), (4) VSI (Very Strong Importance) and (5) ESI (Extreme Strong Importance). A lot of researches which used Saaty's fuzzy linguistic scales justified it to be reliable as the scale is derived from the original fundamental scale of ANP (Etaati et al., 2011). The fuzzy scale used only differs in terms of the intensity of importance. Instead of absolute numbers value, the value builds up within fuzzy scale as shown in Table 4.3. For the purpose of weight acquisition from the expert, a simplified form of fuzzy scale is developed in the questionnaire and the expert were asked questions which are related to the relative importance between the criteria as shown by the example in Figure 4.6.

Table 4.3.

Fuzzy Pairwise Comparison Scale

Pairwise Comparison	Explanation	Linguistic Variables	Fuzzy Scale	Reciprocal Fuzzy Scale
Equal Importance	Two activities contribute equally to the objective	EI	(1,1,1)	(1,1,1)
Moderate importance compared to	Experience and judgement slightly favour one activity over another	MI	(2,3,4)	(1/4,1/3,1/2)
Strong importance compared to	Experience and judgement strongly favour one activity over another	SI	(4,5,6)	(1/6,1,5,1/4)
Very strong importance compared to	An activity is favoured very strongly over another; its dominance demonstrated in practice	VSI	(6,7,8)	(1/8,1/7,1/6)
Extreme importance compared to	The evidence favouring one activity over another is of the highest possible order of affirmation	ESI	(8,9,10)	(1/10,1/9,1/8)

Example of questions (Kindly, please tick once only for each question)
With respect to ECONOMIC PERFORMANCE

	ESI	VSI	SI	MI	EI	MI	SI	VSI	ESI	
Green Manufacturing										Lean Manufacturing

Figure 4.6. Example of Questions in FANP Questionnaire

Step 4. Defuzzification method establishment

This research used the FPP method because this method can acquire the consistency ratios of fuzzy pairwise comparison matrices without additional steps (Mikhailov, 2003; Zhou, 2012). Thus, FPP is chosen as the defuzzification method in this research. The stages of Mikhailov's fuzzy prioritization approach are given as follows (Mikhailov, 2003).

Consider a prioritization problem with n elements, where the pairwise comparison judgments are represented by fuzzy sets. Suppose that decision-maker can provide a set of fuzzy comparison judgments, F represented as TFN, $\tilde{a}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$.

$$F = \{\tilde{a}_{ij}\} \text{ of } m \leq n(n-1)/2, \tag{4.2}$$

where $i = 1,2, \dots, n-1; j = 2,3, \dots, n; j > i$

The problem is to extract a crisp priority value in the form of vector, $w = (w_1, w_2, \dots, w_n)^T$, such that priority ratios w_i/w_j are approximately within the range of the fuzzy scale,

$$l_{ij} \leq \frac{w_i}{w_j} \leq u_{ij} \tag{4.3}$$

Each crisp priority vector w satisfies the double-side inequality (4.3) with some degree, which can be measured by a linear membership function with respect to the unknown ratio w_i/w_j

$$u_{ij}\left(\frac{w_i}{w_j}\right) = \begin{cases} \frac{(w_i/w_j) - l_{ij}}{m_{ij} - l_{ij}}, & \frac{w_i}{w_j} \leq m_{ij} \\ \frac{u_{ij} - (w_i/w_j)}{u_{ij} - m_{ij}}, & \frac{w_i}{w_j} \geq m_{ij} \end{cases} \tag{4.4}$$

The membership function (4.4) is linearly increasing over the interval $(-\infty, m_{ij})$ and linearly decreasing over the interval (m_{ij}, ∞) .The function takes negative values when $w_i/w_j \leq l_{ij}$ or $w_i/w_j \geq m_{ij}$ and has a maximum value $u_{ij} = 1$ at $w_i/w_j = m_{ij}$. The range (l_{ij}, u_{ij}) of the membership function (4.4) corresponds with TFN judgment (l_{ij}, m_{ij}, u_{ij}). The solution to the prioritization problem by the FPP method is based on 2 assumptions.

Assumption 1

Requires the existence of non-empty fuzzy feasible area *P* on the (*n*-1) dimensional simplex $Q^{(n-1)}$ defined as an intersection of the membership functions, similar to (4.4) and the simplex hyper plane (4.5).

$$Q^{(n-1)} = \{(w_1, w_2, \dots, w_n) | w_i > 0, \textstyle\sum_{i=1}^{n} w_i = 1\} \tag{4.5}$$

The membership function of the fuzzy feasible area is given by

$$u_p(w) = \min_{ij} \left\{u_{ij}(w) \middle| i = 1,2, \dots, n-1; j = 2,3, \dots, n; j > i\right\} \tag{4.6}$$

If the fuzzy judgments are inconsistent, then $u_p(w)$ may take negative values for all normalized priority vectors $w \epsilon Q^{(n-1)}$.

Assumption 2

Specifies a selection rule, which determines a priority vector, having the highest degree of membership in the aggregated membership function (4.6.). It is proven that $u_p(w)$ is a convex set, so there is always a priority vector $w \epsilon Q^{(n-1)}$ that has a maximum degree of membership

$$\lambda^* = u_P(w^*) = \max_{w \epsilon Q^{(n-1)}} \min_{ij} \{u_{ij}(w)\} \tag{4.7}$$

The maximum prioritization problem (4.7) can be represented as

$$\text{Max}\,\lambda \tag{4.8}$$

$$\lambda \leq u_{ij}(w), i = 1,2, \dots, n-1; j = 2,3, \dots, n; j > i,$$

$$\textstyle\sum_{k=1}^{n} w_k = 1, w_k > 0, k = 1,2, \dots n$$

Inserting membership function (4.4) into (4.8), bilinear programming equation is obtained

$$\text{Max}\,\lambda \tag{4.9}$$

$$(m_{ij} - l_{ij})\lambda w_j - w_i + l_{ij} w_j \leq 0,$$

$$(u_{ij} - m_{ij})\lambda w_j + w_i - u_{ij} w_j \leq 0,$$

$$\textstyle\sum_{k=1}^{n} w_k = 1, w_k > 0, k = 1,2, \dots n$$

$$i = 1,2, \dots, n-1; j = 2,3, \dots, n; j > i$$

The optimal solution to (4.9) (w^*, λ^*) can be derived by numerical method for non-linear optimization. If the optimal value λ^*, is positive (the maximum value is one), it shows that all solution ratios satisfy the fuzzy judgment completely, which means that the initial set of fuzzy judgments is relatively consistent. A negative value of λ^* shows that the solutions ratios approximately satisfy all double-side inequalities (4.3). Therefore, optimal value λ^* can be used for measuring the consistency of the initial set of fuzzy judgments. Based on weights obtained from FPP, a supermatrix is formed.

Step 5. Supermatrix Formation

Construct three types of supermatrix which are:

1. The unweighted supermatrix
2. The weighted supermatrix.
3. The limit supermatrix is the final version of the supermatrix obtained by raising the weighted supermatrix to powers (with modifications depending on the model structure).

From the FPP process, the unweighted and weighted supermatrix is formed. The limit supermatrix is developed via computing limit priorities of the stochastic supermatrix and synthesizing the limiting priorities by weighting each idealized limit vector by the weight of its criterion and adding the resulting vector.

Step 6. Obtain the Overall Ranking of Criteria

The best selection of alternatives between the lean manufacturing, green manufacturing and sustainable manufacturing are decided.

In Initialization phase, a knowledge that is produced is the weighted criteria, which is classified as the lowest level knowledge of Level 3 as summarized in Table 4.4.

Table 4.4.

Initialization Phase - Knowledge Base Level 3

Input	Inference Engine	Output
Pairwise comparison from experts	FANP Model	Weighted Criteria

4.3.2 Selection Phase

In the selection phase, the weighted criteria associated with sustainability indicator are established. At this phase, all the indicators are presupposed can be applied to all types of organizations. The set of indicators considered with respect to criteria is compiled into Table 4.5.

Table 4.5.

Indicators with Respect to Criteria

Dimension	**Criteria**	**Indicators**
Economic Sustainability	Economic Performance	1. Direct economic value generated and distributed 2. Financial implications and other risks and opportunities for the organization's activities due to climate change 3. Coverage of the organization's defined benefit plan obligations 4. Financial assistance received from government
	Indirect Economic Impact	5. Development and impact of infrastructure investments and services supported 6. Significant indirect economic impacts, including the extent of impacts
	Market Presence	7. Ratios of standard entry level wage by gender compared to local minimum wage at significant locations of operation 8. Proportion of senior management hired from the local community at significant locations of operation
	Procurement Practice	9. Proportion of spending on local suppliers at significant location and operation

Table 4.5 continued

Environmental Sustainability	Material	10. Materials used by weight or volume 11. Percentage of materials used that are recycled input materials
	Energy	12. Energy consumption within the organization 13. Energy consumption outside of the organization 14. Energy intensity 15. Reduction of energy consumption 16. Reductions in energy requirements of products and services
	Water	17. Total water withdrawal by source 18. Water sources significantly affected by withdrawal of water 19. Percentage and total volume of water recycled and reused
	Biodiversity	20. Operational sites owned, leased, managed in, or adjacent to, protected areas and areas of high biodiversity 21. Description of significant impacts of activities, products, and services on biodiversity in protected areas and 22. Habitats protected or restored 23. Total number of IUCN Red List species and national conservation list species with habitats in areas affected by operations, by level of extinction risk
	Emissions	24. Direct greenhouse gas (GHG) emissions 25. Energy indirect greenhouse gas (GHG) emissions 26. Other indirect greenhouse gas (GHG) emissions 27. Greenhouse gas (GHG) emissions intensity 28. Reduction of greenhouse gas (GHG) emissions 29. Emissions of ozone-depleting substances (ODS) 30. NOX, SOX, and other significant air emissions

Table 4.5 continued

	Effluents And Waste	31. Total water discharge by quality and destination 32. Total weight of waste by type and disposal method 33. Total number and volume of significant spills 34. Weight of transported, imported, exported, or treated waste deemed hazardous under the terms of the Basel Convention2 Annex I, II, III, and VIII, and percentage of transported waste shipped internationally 35. Identity, size, protected status, and biodiversity value
	Product And Services	36. Extent of impact mitigation of environmental impacts of products and services 37. Percentage of products sold and their packaging materials that are reclaimed by category
	Environmental Compliance	38. Monetary value of significant fines and total number of non-monetary sanctions for non-compliance with environmental laws and regulations
	Transport	39. Significant environmental impacts of transporting products and other goods and materials for the organization's operations, and transporting members of the workforce
	Overall	40. Total environmental protection expenditures and investments by type
	Supplier Environmental Assessment	41. Percentage of new suppliers that were screened using environmental criteria Significant actual and potential negative environmental impacts in the supply chain and actions taken

Table 4.5 continued

	Environmental Grievance Mechanism	42. Number of grievances about environmental impacts filed, addressed, and resolved through formal grievance mechanisms
Social Sustainability	Labour Practices And Decent Work	43. Employment 44. Labour/Management Relations 45. Occupational Health and Safety 46. Training and Education 47. Diversity and Equal Opportunity 48. Equal Remuneration for Women and Men 49. Supplier Assessment for Labour Practices 50. Labour Practices Grievance Mechanisms
	Human Rights	51. Investment 52. Non-discrimination 53. Freedom of Association and Collective Bargaining 54. Child Labour 55. Forced or Compulsory Labour 56. Security Practices 57. Indigenous Rights 58. Assessment 59. Supplier Human Rights Assessment 60. Human Rights Grievance Mechanisms
	Society	61. Local Communities 62. Anti-corruption 63. Public Policy 64. Anti-competitive Behavior 65. Society Compliance 66. Supplier Assessment for Impacts on Society 67. Grievance Mechanisms for Impacts on Society

Table 4.5 continued

	Product Health And Responsibility	68. Customer Health and Safety 69. Product and Service Labelling 70. Marketing Communications 71. Customer Privacy 72. Product Compliance

Based on this set of indicators, a selection is done using the rule base type of knowledge base to ensure that only indicators relevant to respective organizations should be implemented. The option of this question is divided into True and False. From this fact, the answer is developed as a rule. To recap, a rule is consists of two parts of antecedent which is the fact's hypotheses and the consequent which specifies the actions if the facts' hypotheses value is true or false. The rules are developed into series of question for the user to answer and the outcome of the question is divided into two options of True and False. This phase consist of Section 1 which is dedicated to manufacturing organization and Section 2 which applied to general organization. Section 1 uses the weight derived from FANP model 2 and Section 2 uses the weight obtained from FANP model 1.

Section 1: Example

Does your company practices lean manufacturing practice?
IF True, **THEN** use ANP weight for Lean - ANP model 2

Does your company practices green manufacturing practice?
ELSEIF True, **THEN** use ANP weight for Green - ANP model 2
ELSE use ANP weight for general sustainability only – ANP Model 1

The process of the inference strategy for Selection phase is described in the form of a simple algorithm.

Let C_n = Criteria,
W_n = Weight from FANP,
I_n = Indicator,

IF C_n is True;
THEN $I_n = W_n C_n \times 1$
ELSE $I_n = 0$
Repeat $\forall n$
End

Example– Indicator Selection

Criteria : **Economic Performance**
Indicator : **Direct Economic Value Generated**
Sub indicator : **Revenue**

Does your company profit oriented?
IF True, **THEN** Revenue = True (1)

Does your company get any donation or fund by the government?
ELSEIF True, then Revenue=Fund = True (1)
ELSE Revenue = False (0)

In this phase, a knowledge that is produced is the applicable indicators, which is in the middle level knowledge of Level 2 as summarized in Table 4.6.

Table 4.6.

Selection Phase – Knowledge Base Level 2

Input	Inference Engine	Output
Weighted Criteria	Rule Base for Indicators	Applicable Indicators

4.3.3 Evaluation Phase

In the Evaluation phase, the applicable sustainability indicator has been established. The indicators are then being used to measure the sustainable performance of each associated criteria. Among the given criteria provided in the ANP model, there exist indicators which are associated with it. The indicator as defined in Chapter 1 is what is used to measure the threshold of each criterion in numerical value and usually every indicator has its own variety of scales and units.

A normalization method is a suitable method that can be used to unify the basic indicators into a single standardized indicator in order to make them comparable (Phillis & Koukioglou, 2009). Overall, there are four basic types of threshold which are lower is better (LB), higher is better (HB), normal is better (NB) and report only. Normalization method provides three linear interpolation equations for each of these thresholds except report only as it is assigned for non-numerical value. These indications showed the level where the output value should be, in order for them to be appropriate as the example shown in Table 4.7. The normalization method has started to be acknowledged due to its flexibility and the simplicity of the method to assign the indicators value to a single score from 0 – 1 (Liu, 2014; Ostasiewicz, 2012; Phillis & Kouikoglou, 2009; Pislaru & Trandabat, 2012)

Table 4.7.

Indicator Thresholds

Threshold	**Example**	**Min value**	**Max value**	**Linear interpolation equation**
LB	Cost, CO2 emission	0	+∞	$x_c = \begin{cases} 1, & x_c \leq T_c \\ \frac{U_c - z_c}{U_c - T_c}, & T_c < z_c < U_c \\ 0, & z_c \geq U_c \end{cases}$
HB	Profit, sales, revenue	-∞	0	$x_c = \begin{cases} 0, & z_c \leq v_c \\ \frac{z_c - v_c}{\tau_c - v_c}, & v_c < x_c < \tau_c \\ 1, & z_c \geq \tau_c \end{cases}$
NB	Gender ratio, salary	Varied	Varied	$x_c = \begin{cases} 0, & z_c \leq v_c \\ \frac{z_c - v_c}{\tau_c - v_c}, & v_c < x_c < \tau_c \\ 1, & \tau_c \leq z_c \leq T_c \\ \frac{U_c - z_c}{U_c - T_c}, & T_c < z_c < U_c \\ 0, & z_c \geq \tau_c \end{cases}$
Report only	Documentation	n/a	n/a	n/a

where v_c , τ_c , T_c, U_c are the coefficients of indicators.

Each of specified indicators has its own level of indication or threshold value. The accepted range of threshold value together with the units is obtained from either the literature or the experts. After the indication of each accepted range is gathered, a rule is developed. For example:

Indicator	: **Direct Economic Value Generated**
Sub indicator	: **Revenue**
IF	the company is classified as a large size company
OR	the number of full time employees is more than 150
AND	the company annual revenue is more than RM 5 million
THEN	the revenue performance is high (3)
ELSEIF	the company is classified as a medium size company
OR	the number of full time employees is less than 150
AND	the company annual revenue is between than RM 500 thousand RM 5 million
THEN	the revenue performance is medium (2)
ELSE	the revenue performance is low (1)

In this phase, a knowledge that is produced is the sustainable performance level, which is the high level knowledge of Level 1 as summarized in Table 4.8.

Table 4.8.

Evaluation Phase - Knowledge Base Level 1

Input	**Inference Engine**	**Output**
Applicable Indicators	Indicators Performance Level	Sustainable Performance Level

4.3.4 Prioritization Phase

The result that is obtained from the Evaluation phase is aggregated with the criteria weight from Knowledge Base Level 3 and is sorted accordingly in ascending order. The sustainable performance level is ranked as a guide for the organizations, on which aspect should be given priority, as improvement area together with related explanation. The process of the inference strategy in this phase is described in a form of a simple algorithm.

Let W_n = Weight from Initialization phase,
I_n = Indicator,
Sort $W_n I_n$ in ascending order %%Using any sort algorithm
Repeat $\forall n$

Example:
Indicator : **Direct Economic Value Generated**
Sub indicator : **Revenue**
Performance : Your company revenue is low
Your company should focus on increasing sales, cut more cost etc.

The outcome of this algorithm is the list of related aspect of indicators that needs to be prioritized in consideration with the organizations' decision making. Then, the list is provided to the user as a final result along with explanation as reasoning fact, and if possible suggestion which maybe included in order to aid the understanding of the result. In this phase, a knowledge that is produced is the sustainable performance level, which is the highest level of knowledge as summarized in Table 4.9.

Table 4.9.

Prioritization Phase

Input	Inference Engine	Output
Sustainable Performance Level	Sorting algorithm	Improvement area

4.4 KBFANP System Implementation

The KBFANP system was tested by implementing it to the real world manufacturing industry with sustainable manufacturing initiatives. Besides, the system was also tested with additional experimental data to represent dummy companies that was divided into three categories. The categories of the experimental data are company with the perfect sustainability performance, company with the worst sustainability performance and a company with random sustainability performance. In order to generate the experimental data, the normalization method was referred.

For the perfect company, the answer input for the system's question was being made as the best value for the indicators' threshold for a particular question, which were the minimum value for LB, maximum value for HB and normative value for NB. In contrast, a worst company's answer input was the worst value for the indicators' threshold of a particular question, which were the maximum value for LB, minimum value for HB, and non-normative value for NB. Lastly, the random company's answer input was randomly generated as long as the value was within the indicators' threshold.
The experimental data is anticipated to support the real world implementation data in order to tweak the capabilities of the KBFANP system. The performance of this system

has been observed and analyzed to ensure that it is reliable enough to be used as a tool to measure the progress of sustainable manufacturing performance.

4.4.1 KBFANP System Verification

The proposed KBFANP system needs to be validated to ensure their effectiveness to represent the sustainability manufacturing indicator and the end results of the model. Therefore, the solution from this model must fulfil certain conditions. The objective of KBFANP system is to provide a sustainability manufacturing indicator for the overall performance manufacturing. The validation of the indicator is based on these conditions:

1. The indicator obtained from the literature is being examined by the industry practitioner and being cross checked until it is been agreed and aligned as much as possible.

On the other hand, the outcome of KBFANP system is to provide related indicator with accordance to priority. The validation of the end results was based on this condition:

2. Suppose that the result of Initialization phase is true, then the ascending order of weight must be similar with the ascending order in Selection phase, given all the indicators value is true.
3. Suppose that the result of Selection phase is true, then only rules for the performance level of applicable indicators is considered in Evaluation phase.
4. Suppose that the result of Evaluation phase is true, then the ascending order of weight must be similar with the ascending order in Prioritization phase, given all the performance level of applicable indicators is true.

If the solution from the proposed KBFANP system violates any of the conditions, then it can be concluded that this model are not verified and cannot be used to solve the problem effectively. However, moderation should be considered for condition (1) because it is almost impossible to determine the effectiveness of a new sustainability indicator as the progress of this field is still under progress.

4.4.2 KBFANP System Validation

The proposed KBFANP system needs to be checked for their competency to solve sustainability manufacturing indicator efficiently. Based on the literature review done on this problem field, none of the researches provided their own method of indicators efficiency. In spite of that, Saaty (2006) stated that the ANP model efficiency can be made if the actual ranking has already exist in the real world.

Therefore, the KBFANP system was compared with the existing sustainability ranking systems if any. Based on Saaty (1996), Saaty and Vargas, (2006), and Saaty (2010), the ANP managed to provide more accurate results than AHP for the case of a complex problem where there may exist some inter-relationship among the criterion. The FANP efficiency is also claimed to be better than crisp ANP for the case of unstructured and ambiguous problem description.

The KBFANP system validation process is deemed to be tough, but it is not impossible. The solutions from the proposed model can be compared if the case company agreed to implement the system’s solution. Then, after a continuous monitoring of the implementation, a conclusion regarding the efficiency of the model can be made. Besides, an extra effort may be done if there is any manufacturing company case which has already implements the practice of sustainable manufacturing although the search maybe limited. The reason is because it is still considered to be a relatively new manufacturing paradigm, where the actual potential results cannot be seen if the sustainability indicators or even sustainable audit have not yet been acknowledged**.**

CHAPTER FIVE
RESULTS AND DISCUSSIONS

The previous chapter presented the proposed KBFANP methodology as a basis to solve the problem of non-standardized sustainability indicator for manufacturing. In this chapter, the implementation of the model to a real world problem is explained and discussed. Based on the Research Design phase, a refined sustainable manufacturing indicator model is proposed which is adapted from GRI G4 Sustainability Reporting Guidelines (GRI, 2013a, 2013b, 2013c). The model is being verified and validated continuously with the assistance of the experts from the manufacturing. A refinement and improvement of the model is done based on the feedbacks received to produce the best possible indicator model.

5.1 Overview of Case Company

Four companies were selected as the case company for this research. The criteria used for the selection of the companies and their respective experts were based on two aspects. The first one was on the manufacturing paradigm practiced in the company. As this research suggested the integration of lean and green manufacturing as a foundation for a successful sustainable manufacturing implementation as mentioned in Section 2.5, any manufacturing company that has been practicing or en route of practicing lean, green or sustainable manufacturing paradigm was chosen as the case company. The second factor was subject to the availability and the willingness of the company to cooperate with the researcher in terms of sharing necessary information and knowledge needed for the requirement of this research. A brief description regarding the company is embedded in Table 5.1.

Table 5.1.

Case Company Profiles

Company	**Location**	**Main operation**
A	Bukit Kayu Hitam, Kedah	Manufacturing of structure composite bond assemblies for aerospace industries for the components of airplane, jets, and helicopter.
B	Serendah, Selangor	Manufacturing and the assembly processes of motor vehicle.
C	Serendah, Selangor	Manufacturing of plastic molded auto parts for motor vehicles
D	Shah Alam, Selangor	Manufacturing and the assembly processes of motor vehicle

5.1.1 Observation

Direct observation was done only in Company A within a period of one month during June 2013. Furthermore, quick observation was done in Company B and C as an industrial visit session concurrently with the interview session. Based on the observation process, Company A and C emphasized lean manufacturing as their main manufacturing paradigm. These companies also implements 'Kaizen' to continuously eliminate waste and to improve the quality of their products. In addition, the concept of JIT was also being highly utilized without compromising the quality and the price of their products throughout their business operations.

Company A exhibited efforts in the implementation of green manufacturing paradigm by the existence of the environmental department. This department is responsible to ensure that the company complies with the environmental standards of ISO14001 as their Environmental Management System (EMS). However, other aspects of green manufacturing that includes remanufacturing, closed-loop manufacturing and green product design were almost non-existent. Although green manufacturing was not practiced vigorously in this company, the practice of lean manufacturing did show significant improvements towards ISO14001 compliance from year 2010 until 2013 as exhibited in the company's records. In terms of sustainable viewpoint, this company did not implement sustainable manufacturing as their main paradigm.

5.1.2 Interview Session

The interview session was held in separate occasions with all of the four manufacturing case companies with six experts. A brief description regarding the experts profile according to the company, position or expertise and their respective working experience is embedded in Table 5.2. The interview questions are embedded in Appendix A.

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Table 5.2.

Manufacturing Experts Profile

Experts ID	Company	Position/Expertise	Working Experience (years)
1	A	Lean Manager Lean Department	12
2		Senior Manager Business Support Department	21
3	B	Senior Manager Purchasing and Localization Department	15
4	C	Manager Engineering Department	n/a
5	D	Manager Environment Department	10
6		Senior Manager Logistic Department, Production Control Division	25

5.1.3 Interview Findings

After the interview session was completed, a transcription of the interview was made and classified into themes as included in this research. The following sections are the summary of interview findings with the experts.

5.1.3.1 Question 1: Does your company have a sustainability report?

From all companies, only company D has sustainability report. In addition, the enforcement to report the sustainability performance was being made compulsory by the influence of their global counterparts. The global companies of B and D did follow the standard of practice (SOP) assessment of GRI G4 or GR1 G3 sustainability reporting guideline (Nissan, 2013; Toyota, 2013). This also proves that the adaptation of GRI as the sustainable manufacturing indicator is more practical compared to other indicators. Despite of that, the experts from company D did not aware that their sustainability assessment was actually being influenced by the GRI standards.

Researcher: Currently we are doing the development for the sustainable manufacturing from the perspective of GRI. So we really sure company D is also using GRI indicators to measure this sustainable aspects of performance.
Respondent: What is GRI?
Researcher: Its Global Reporting Initiatives.
Researcher: So from the company D global report 2013, sustainability report, they used GRI G3 sustainability reporting guideline which is the past performance indicators. So what we want to do today is we want to know for this company, not the global one, does this company have this kind of sustainability report. That's our first question.
Researcher: Yes we do have sustainability report.

In addition, all of the case companies implemented Quality Management System (QMS) of ISO9001 and Environmental Management System (EMS) of ISO14001. In addition, experts from company B, C and D highlighted the importance of JD Power ratings which is a certification of a global market research company and suggested its implementation into the current manufacturing practice should be made compulsory (J. D. Power, 2014).

5.1.3.2 Question 2: How sustainability influences the overall strategic plan of your company?

In this question, the company of the experts was assumed to practice sustainability with the exception of lean and green manufacturing to determine the insignificance between lean and green with sustainability. The introduction of sustainability concept into the companies was mainly because of the cost saving factor and good sense of business. Thus, the transition for the manufacturing companies to shift their operations towards sustainable thinking was indeed motivated by profit oriented and cost reduction factor (Onsrud & Simon, 2013; Scapolo et al., 2003)

> **Respondent**: Overall strategic plan? It all go back about costing. If we have to reduce all the four elements mentioned just now, we do basically reduce cost of manufacturing, number one.

5.1.3.3 Question 3: How sustainability influences lean and green manufacturing operations in your company?

In this question, the company of the experts was assumed to practice sustainability with the inclusion of lean and green manufacturing. Based on these four companies, all of the experts admitted to practice lean manufacturing. This shows that lean manufacturing is deemed as compulsory in today's manufacturing.

Respondent: Yes we have to. It is not sesuai. It is wajib. We have to do lean manufacturing.

Respondent: So we have to go to lean. We are not effective if we don’t do...we are not competing among ourselves..we are not competing in Malaysia...we are competing with the world.

However, based on direct observation and interview process, these companies tend to perceive lean and green as a separate notion. Although lean paradigm was justified to be mutually supportive paradigm and even catalyst to green paradigm, in a real world practice, this shown to be implemented separately and the positive effect of lean paradigm towards green may happen involuntarily without the awareness of the company itself (Bergmiller et al., 2009; Dues et al., 2013).

In addition, company A and C did not practice green manufacturing and only make EMS as a compliance factor rather than as the original strategic operations. In term of sustainable manufacturing concept, experts from company D was well versed with the concept of sustainability, and agreed that lean and green paradigm is sustainable into their manufacturing operations.

Researcher: The concept of sustainability, alright, is not really only include environmental factor, correct? So it focused on the economic as well as society. So to be frank, is lean sustainable for you?

Respondent: Yes it sustainable for us.

The implementation of sustainable manufacturing comprises of lean and green manufacturing was also because of the cost saving factor and good sense of business. The summary of lean, green and sustainable paradigm implementation of all the companies is shown in Table 5.3.

Respondent: So going back to your third question, how the sustainability influence green and lean in our company. So it always falls down to, still falls down to business sense, good business sense, meaning to say here, if you can throw the gain green manufacturing... can assist in creating lean manufacturing environment, business environment, maybe companies will be going ... for that. Meaning to say, if I can … to sustainable project or effort that are not only able to reduce greenhouse gas emission, things like that ..and that reduce the cost of manufacturing. So that will be the very good business. So this will be balance. Sometimes, no. Sometimes when you see the effort that can take to is too much...for the business.

Table 5.3.

Summary of Lean, Green and Sustainable Paradigm Implementation in Case Companies

Company	**Lean Manufacturing**	**Green Manufacturing**	**Sustainable Manufacturing**
A	Yes	No	No
B	Yes	Yes	No
C	Yes	No	No
D	Yes	Yes	Yes

5.1.3.4 Question 4: How your company measure sustainability performance in each criteria of indicators?

1. What is the current performance
2. What is the Key Performance Indicator (KPI) target or the ideal state of each of the performance (if any)?

The answer for these questions is summarized in Appendix F and the information from this question was being used for the development of Knowledge Base Level 1 in the KB-FANP model.

5.1.3.5 Question 5: Given the scope of this interview, is there any important information that we have not yet covered?

In this question, the experts were asked for any personal thoughts regarding any problems or suggestions for future research in the field of sustainable manufacturing. The main topic of concern is divided into three aspects, which are the education and culture of society, continuous enforcement of regulations and leadership.

5.1.3.5.1 Education and Culture of Society

The experts claimed that the implementation of sustainable thinking into the organizations should be empowered by the involvement of society. This hints that the society dimension maybe more important compared with the economic and environment dimensions.

Respondent: Culture. It is mindset, how to educate people about the environmental. If we did not take care of water, or we throw things inside the drain, what's going to happen, because we don't look very far, when people throw chemicals in the ... drain they don't realized that …at the sea. Then you will have the chemicals, they don't realized that when they're fishing, one of your food, comes from that sea. Hence that fish is affected by that chemicals. ..., the life cycle chain is not in the back of their mind's mind. They're subconscious. Then they realized, oh, is it like that'?

Researcher: So this is about Malaysian culture?

Respondent: Yes

Researcher: So what is the best strategy to overcome, I know it is hard?

Respondent: Through education.

However, the issue that happens in the society today is the lack of education to the society about the benefits of sustainable thinking. This problem was inhibited with the culture of the community which makes it harder to implement the system. Thus, the society criteria and indicators should be emphasized more as stressed out by Fan et al. (2010).

5.1.3.5.2 Continuous Enforcement of Regulations

The experts also claimed that the implementation of sustainable manufacturing in their company was hampered by the irregular enforcement of the technology.

Respondent: I think.... for example you introduced.....where is it now? Where is bio fuel? Let say they have logistics transporters, they are using diesel but their end is to find the best route, shortest route, they've done a good efficiencies of loading their lorries so what's next .We keep hoping to reduce CO2 every year , then suddenly somebody introduces bio fuel which is very good but how accessible is that bio fuel to our transporters . Sometimes it was monopolized by certain. This is not open (laugh). Sometimes it is good but it is not feasible in the long time. The maintenance cost would be higher so we got to look at the balance. Someone came out with good technology like solar 3, 4 years now...err...before the efficiency of converting solar energy to electricity was 70 percent but now reaching up to 80 percent.

Researcher: Availability?

Respondent: The availability of the resources. NGV very good very cheap but only available at certain. But to me I think the most important is that manufacturing ...as the people...the culture.... people are willing to change. That is very important.

Although the technology has been proven to bring significant benefits in their operation specifically in terms of overall environment aspect in some cases, the enforcement of the technology was being repressed due to unknown reason. Possibly, this problem happens due to the lack of society's interest in embracing the technology.

5.1.3.5.3 Leadership

Another opinion addressed by the experts regarding the sustainable manufacturing implementation is the leadership. As the lean manufacturing paradigm implementation is always halted by the poor leadership in the organization, this matter is supposed to be true for the sustainable paradigm as well (Chen & Bo, 2010; Liker, 2014; Mann, 2014).

Respondent: Ahh ok. We are dealing with people, alright? So we are dealing people so this is where as a lean or as a person who wants to bring changes you must be able to influence the people.

Researcher: So he agrees that one of the main criteria in executing the lean ideas is the leadership, he said.

Respondent: Yes I agree (cough). Previously we have program to make everybody lean thinking. When he came he removes the program. Then he said he will do it through his department and now he fails.

Respondent: Of course people also, in general, people are people. Some people are subject to change some people are not subject to change, small percentage the hard core they don't want to change. Kalau boleh change pun dia purposely don't want to change. Awareness must be very effective. As a leader if you talk one time then you expect it to move then susah. As a leader you must follow up

5.2 Development of KBFANP System

In this section, the implementation of KBFANP system is divided according to the phases in KBFANP system model as exhibited in Section 1.3, which are the Initialization, Selection, Evaluation and Prioritization Phase.

5.2.1 Description of KBFANP System

The KBFANP model was implemented into a system prototype which was developed using MATLAB language. The prototype required the user to answer two types of questions which are multiple choice and numerical input as shown in Figure 5.1 and 5.2.

Figure 5.1. Multiple Choice Question

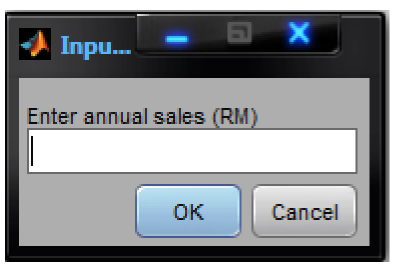

Figure 5.2. Numerical Input Question

The multiple choice question requires the user to click upon their choices whereas the numerical input question requires the user to put in an acceptable range of numerical value. The numerical input question only involves with the numerical input beyond a simple yes or no answers where yes is coded as 1 and no as 0 in the system. If the user inserts a value which is not within the acceptable range a warning dialog will ask the user to insert another value until an acceptable value is being inserted as shown in Figure 5.3. Furthermore, a descriptive dialog is a menu which does not inquire the user to make a choice or answer as in Figure 5.4. The descriptive dialog only has one menu button which needs to be clicked to proceed with the system.

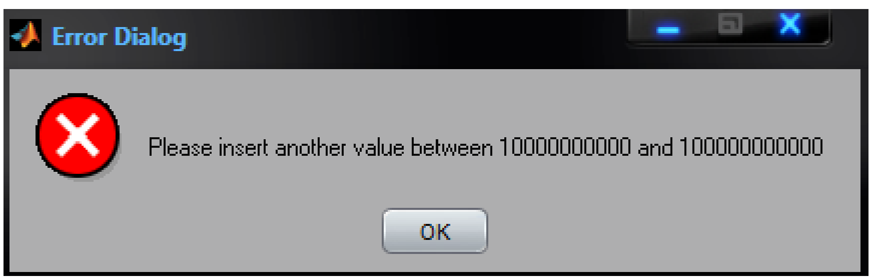

Figure 5.3. Warning Dialog

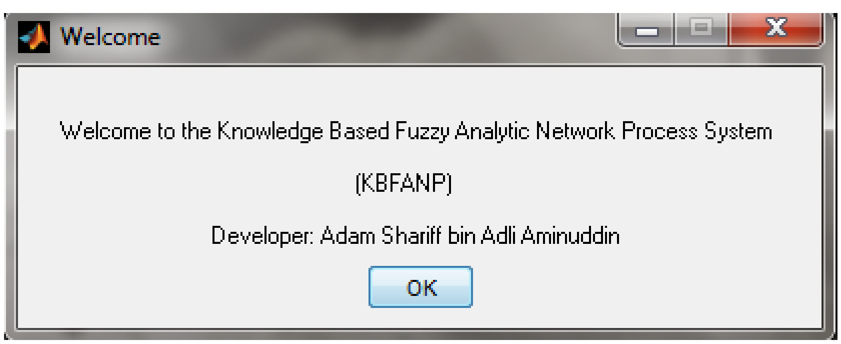

Figure 5.4. Descriptive Dialog

5.3 Initialization Phase

In the initialization phase, the criteria associated with sustainability indicators were implemented. For the progress of this phase, the input from fuzzy pairwise comparison was utilized into FANP model using the FPP method. The outcome of this process is the final ranking of the criteria.

5.3.1.1 FANP Model Implementation

The FANP model was developed using SuperDecisions and the criteria involved were based on latest the GRI latest sustainability criteria, which were embedded in the G4 Sustainability Reporting Guidelines as shown in Figure 5.5 and 5.6. FANP Model 1 consists of three clusters of economic, environment and society with the exception of alternatives whereas FANP Model 2 includes the alternative cluster with lean and green manufacturing nodes.

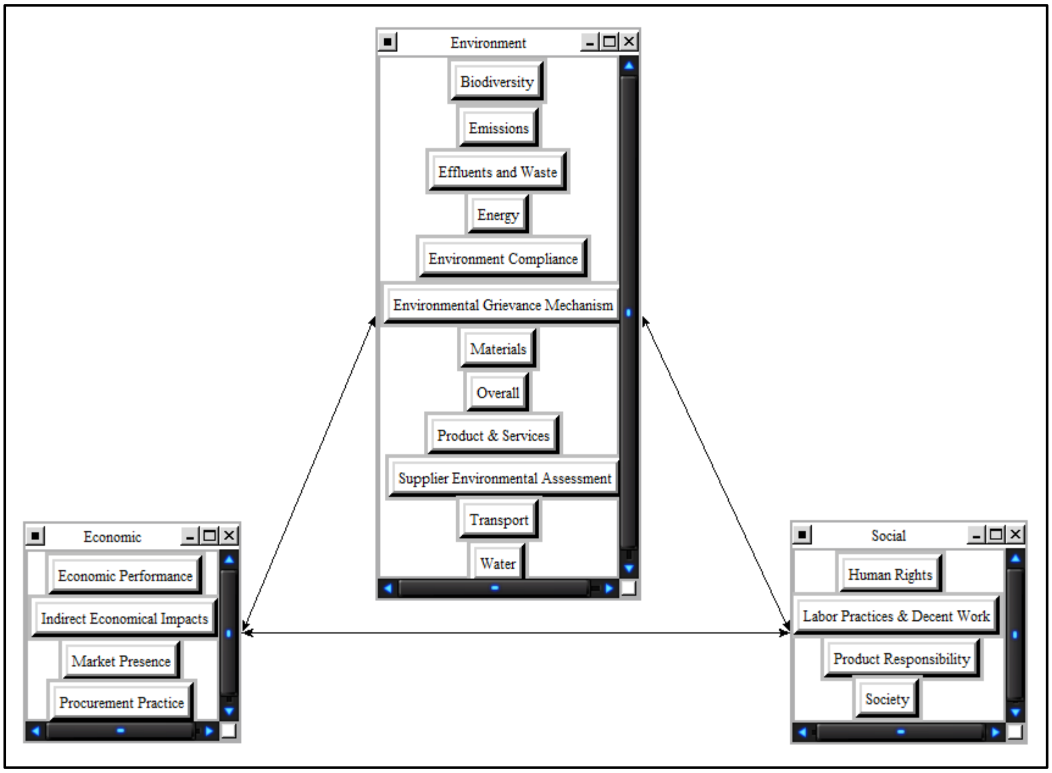

Figure 5.5. FANP Model 1 using SuperDecision

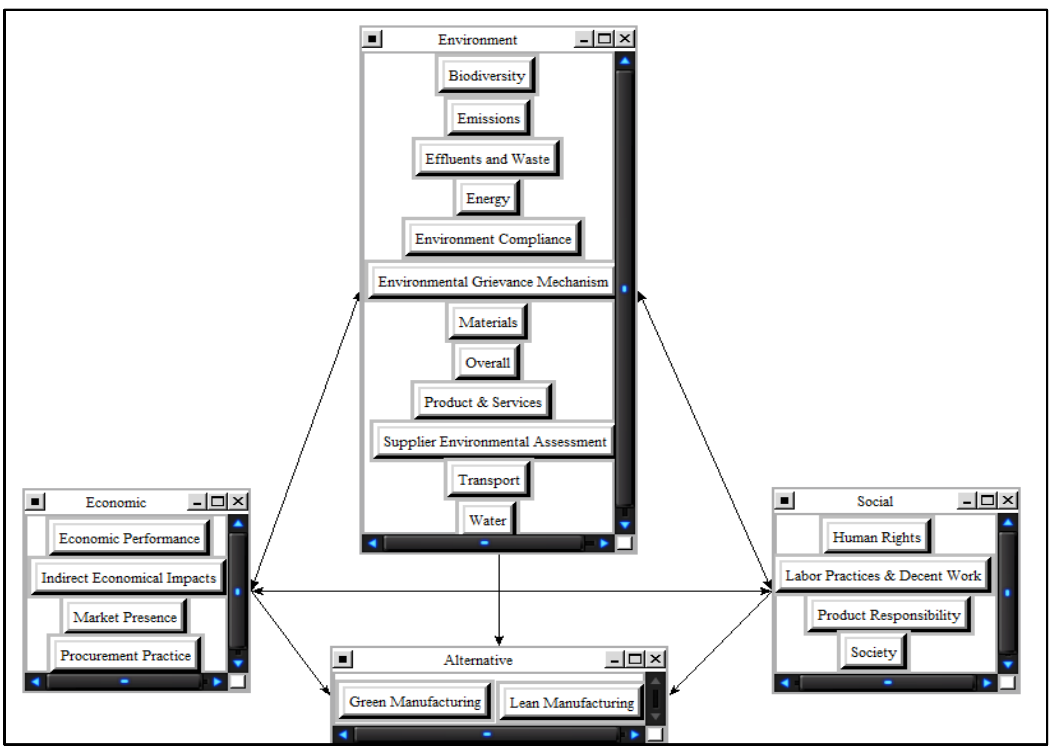

Figure 5.6. FANP Model 2 using SuperDecision

5.3.1.2 FANP Questionnaire for Fuzzy Pairwise Comparison

Based on FANP models, two types of questionnaire was developed namely FANP questionnaire for sustainability experts for FANP model 1 and FANP questionnaire for lean and green manufacturing experts for FANP model 2. FANP questionnaire for sustainability experts contains 319 pairwise comparisons as embedded in Appendix B whereas FANP questionnaire for lean and green manufacturing experts contains 20 pairwise comparisons as embedded in Appendix C.

The FANP questionnaire was distributed via online and manually to 12 experts who specialize in sustainability and lean or green manufacturing as recognized by the researcher. Unfortunately, only four experts responded to the questionnaire. From these four experts, two of them are sustainability experts and two other experts are from the lean and green expert's category. A brief description regarding the sustainability, lean and green manufacturing experts profile according to their affiliation, expertise and their respective knowledge experience is embedded in Table 5.4.

Table 5.4.

Sustainability, Lean and Green Manufacturing Experts

Experts ID	Affiliation	Expertise	Knowledge Experience (years)
7	Construction and Earth Sciences Department, Escuela Politécnica del Ejército, Avenida General Rumiñahui s/n, Sangolquí, Ecuador	Sustainability	15
8	Universiti Teknologi Malaysia (UTM)	Sustainability Lean and green	6
9	Universiti Utara Malaysia	Lean and green	10
10	Universiti Utara Malaysia	Lean and green	5

5.3.1.3 Fuzzy Preference Programming Implementation

The fuzzy pairwise comparison input from the experts was defuzzified into crisp values via FPP method. FPP process was being done using MATLAB and the source code was adapted from Zhou (2012). The general source code used is shown in Figure 5.7, 5.8 and 5.9.

.

```
tic
Aeq=[1 1 … 1 0];
beq=[1];
VLB=[0;0; … 0;-inf];
VUB=[];
x0=[1;1; …;1];
OPT=optimset('LargeScale','off');
[x,fval]=fmincon('networkf',x0,[],[],Aeq,beq,VLB,VUB,'networkorder',OPT)
toc
```

Figure 5.7. networkmain.m

```
function f=networkf(x);
f= -x(n+1);
```

Figure 5.8. networkf.m

```
function [c,ceq]=networkordern(x);
c = [
(m12-l12)*x(n+1)*x(2)-x(1)+(l12)*x(2);
(u12-m12)*x(n+1)*x(2)+x(1)-(u12)*x(2);
…
(m1n-l1n)*x(n+1)*x(n)-x(1)+(l1n)*x(2);
(u1n-m1n)*x(n+1)*x(n)+x(1)-(u1n)*x(2);
…
(m(n-1)n-l(n-1)n)*x(n+1)*x(n)-x(n-1)+(l(n-1)n)*x(n);
(u(n-1)n-m(n-1)n)*x(n+1)*x(n)+x(n-1)-(u(n-1)n)*x(n);
];
ceq = [ ];
```

Figure 5.9. networkorder.m

5.3.1.4 FANP Results

The crisp weight obtained from the FPP results was then computed using the SuperDecision. The calculation was not done directly using MATLAB because SuperDecision provided a better representation of the FANP results. The FANP results which consists of the overall ranking of the criteria with its respective weights according to the experts are presented separately into three sections which includes Sustainability Expert 1, Sustainability Expert 2 and Group Judgment, which was the collective pairwise comparison judgment given by the sustainability experts. The global weight of the criteria was then developed as the indicator's weight parameter of the Knowledge Base Level 3. Additionally, the remaining results from FANP can be seen in Appendix D.

5.3.1.4.1 Sustainability Expert 1

The sustainability expert 1 (Expert ID 7) gave the pairwise comparison between the sustainability criteria whereas the lean and green expert 1 (Expert ID 9) provided the pairwise comparison in terms of the alternatives. Their judgments were combined to produce the global weight of the criteria together with its respective ranking as shown in Table 5.5. This process was repeated with the other lean and green expert 2 (Expert ID 10) and the outcome is shown in Table 5.6.

Table 5.5.

Sustainability Expert 1 Lean and Green Expert 1

	Criteria	Local Weight	Cluster Ranking	Global Weight	Overall Ranking
Alternatives	Green Manufacturing	0.55498	1	0.210184	1
	Lean Manufacturing	0.44502	2	0.168537	2
Economic	Economic Performance	0.18641	2	0.0443	4
	Indirect Economic Impacts	0.06646	3	0.015794	8
	Market Presence	0.04127	4	0.009808	13
	Procurement Practice	0.70586	1	0.167749	1
Environment	Biodiversity	0.00526	12	0.000855	20
	Effluents and Waste	0.01934	9	0.003144	17
	Emissions	0.01715	11	0.002789	19
	Energy	0.01808	10	0.00294	18
	Environment Compliance	0.08649	6	0.014064	12
	Environmental Grievance Mechanism	0.05777	7	0.009394	15
	Materials	0.10200	2	0.016585	7
	Overall Environmental	0.08889	5	0.014454	11
	Product & Services	0.09037	4	0.014694	10
	Supplier Environmental Assessment	0.39533	1	0.064282	3
	Transport	0.09562	3	0.015548	9
	Water	0.02371	8	0.003855	16
Social	Human Rights	0.04424	4	0.009778	14
	Labour Practices & Decent Work	0.65966	1	0.1458	2
	Product Responsibility	0.18249	2	0.040335	5
	Society	0.11361	3	0.02511	6

Table 5.6.

Sustainability Expert 1 Lean and Green Expert 2

	Criteria	Local Weight	Cluster Ranking	Global Weight	Overall Ranking
Alternatives	Green Manufacturing	0.65631	1	0.2485	1
	Lean Manufacturing	0.34369	2	0.1301	2
Economic	Economic Performance	0.18641	2	0.0443	4
	Indirect Economic Impacts	0.06646	3	0.015794	8
	Market Presence	0.04127	4	0.009808	13
	Procurement Practice	0.70586	1	0.167749	1
Environment	Biodiversity	0.00526	12	0.000855	20
	Effluents and Waste	0.01934	9	0.003144	17
	Emissions	0.01715	11	0.002789	19
	Energy	0.01808	10	0.00294	18
	Environment Compliance	0.08649	6	0.014064	12
	Environmental Grievance Mechanism	0.05777	7	0.009394	15
	Materials	0.102	2	0.016585	7
	Overall Environmental	0.08889	5	0.014454	11
	Product & Services	0.09037	4	0.014694	10
	Supplier Environmental Assessment	0.39533	1	0.064282	3
	Transport	0.09562	3	0.015548	9
	Water	0.02371	8	0.003855	16
Social	Human Rights	0.04424	4	0.009778	14
	Labour Practices & Decent Work	0.65966	1	0.1458	2
	Product Responsibility	0.18249	2	0.040335	5
	Society	0.11361	3	0.02511	6

Based on Table 5.5 and Table 5.6, it can be perceived that the weight and the ranking of criteria in the dimensions of economic, environment and social are similar. This happened due to the fact that the pairwise judgment was given from the same person. The criterion that has the highest weight thus the highest ranking is the procurement practice from the economic dimension. In addition the, the criterion which exhibits the lowest weight thus the lowest ranking is the biodiversity from the environment dimension.

However, the weight and the ranking was not the same with the alternatives. The weights for the green and lean manufacturing were different in both cases though the rankings were the same. The lean and green expert 2 inflicted the green manufacturing to be more sustainable compared with the lean and green expert 1. As the outcome yield consistent ranking, it can be comprehended that the green manufacturing is better than the lean manufacturing based on the sustainability criteria considered.

5.3.1.4.2 Sustainability Expert 2

Similar to the previous process, the sustainability expert 2 (Expert ID 8) also contributed the pairwise comparison between the sustainability criteria whereas the lean and green expert 1 (Expert ID 9) provided the pairwise comparison in terms of the alternatives. Their judgments were combined to produce the global weight of the criteria together with its respective ranking as shown in Table 5.7. This process was repeated with the other lean and green expert 2 (Expert ID 10) and the outcome is shown in Table 5.8.

Table 5.7.

Sustainability Expert 2 Lean and Green Expert 1

	Criteria	Local Weight	Cluster Ranking	Global Weight	Overall Ranking
Alternatives	Green Manufacturing	0.65118	1	0.242602	1
	Lean Manufacturing	0.34882	2	0.129956	2
Economic	Economic Performance	0.34483	2	0.072486	3
	Indirect Economic Impacts	0.34907	1	0.073377	2
	Market Presence	0.21105	3	0.044364	8
	Procurement Practice	0.09504	4	0.019979	10
Environment	Biodiversity	0.02639	10	0.00484	19
	Effluents and Waste	0.05635	8	0.010334	17
	Emissions	0.0639	6	0.011719	15
	Energy	0.05565	9	0.010206	18
	Environment Compliance	0.08631	3	0.015828	11
	Environmental Grievance Mechanism	0.06526	5	0.011968	14
	Materials	0.12353	2	0.022654	9
	Overall Environmental	0.08631		0.015828	11
	Product & Services	0.28615	1	0.052476	5
	Supplier Environmental Assessment	0.00827	11	0.001517	20
	Transport	0.07803	4	0.014309	13
	Water	0.06384	7	0.011708	16
Social	Human Rights	0.32815	1	0.076737	1
	Labour Practices & Decent Work	0.23304	2	0.054496	4
	Product Responsibility	0.21446	4	0.05015	7
	Society	0.22436	3	0.052465	6

Table 5.8.

Sustainability Expert 2 Lean and Green Expert 2

	Criteria	Local weight	Cluster Ranking	Global Weight	Overall Ranking
Alternatives	Green Manufacturing	0.54615	1	0.203472	1
	Lean Manufacturing	0.45385	2	0.169086	2
Economic	Economic Performance	0.34483	2	0.072486	3
	Indirect Economic Impacts	0.34907	1	0.073377	2
	Market Presence	0.21105	3	0.044364	8
	Procurement Practice	0.09504	4	0.019979	10
Environment	Biodiversity	0.02639	10	0.00484	19
	Effluents and Waste	0.05635	8	0.010334	17
	Emissions	0.0639	6	0.011719	15
	Energy	0.05565	9	0.010206	18
	Environment Compliance	0.08631	3	0.015828	11
	Environmental Grievance Mechanism	0.06526	5	0.011968	14
	Materials	0.12353	2	0.022654	9
	Overall Environmental	0.08631		0.015828	11
	Product & Services	0.28615	1	0.052476	5
	Supplier Environmental Assessment	0.00827	11	0.001517	20
	Transport	0.07803	4	0.014309	13
	Water	0.06384	7	0.011708	16
Social	Human Rights	0.32815	1	0.076737	1
	Labour Practices & Decent Work	0.23304	2	0.054496	4
	Product Responsibility	0.21446	4	0.05015	7
	Society	0.22436	3	0.052465	6

Based on Table 5.7 and Table 5.8, it can be realized that the weight as well as the ranking differ significantly with the previous sustainability expert 1. From the perspective of sustainability expert 2, the criterion which has the highest weight thus the highest ranking is the human rights from the social dimension. Besides, the criterion which exhibits the lowest weight thus the lowest ranking is the supplier environmental assessment from the environment dimension.

The results were different as any MCDM technique depends heavily on the individual's preference in making decision. Hence, the credibility of the subject or the experts should be taken into account. Based on Table 5.4, the reliability of the experts was defined in terms of their knowledge experience in sustainability, lean and green manufacturing in years respectively. The outcomes for the alternatives were the same as the previous case as the judgment came from similar lean and green experts. Therefore, it can be understood that the green manufacturing is better than the lean manufacturing based on the sustainability criteria considered.

5.3.1.4.3 Group Judgment

The separate individual expert's judgment was also aggregated to determine a more generalized judgment for the criteria weights and ranking. A generalized judgment is important for the foundation of the Initialization phase where a unified consensus of the criteria weight is more desirable (Saaty & Peniwati, 2007). The aggregation of the sustainability expert for the group judgment was calculated using geometric mean via Aggregation of Individual Judgments (AIJ) (Forman & Peniwati 1998).

The geometric mean formula used was adapted from Adamcsek (2008) and Ssebuggwawo, Hoppenbrouwers and Proper (2009) as provided in Equation 5.1.

$$w^{[G]} = \left(w_i^{[G]}\right), \text{ where } w_i^{[G]} = \left(\prod_{j=1}^{n} a_{ij}^{[G]}\right)^{1/n}, i, j \in \{1, n\} \quad (5.1)$$

Notation:

$w^{[G]} =$ Weight of group's judgment

$w_i^{[G]} =$ Weight of row for criteria i

n = Total number of individuals in the group

j = Individual j in the group

$a_{ij}^{[G]}$ = Individual j judgment for criteria i

The group judgment of sustainability expert 1 and 2 were aggregated to yield the local and global weight of the criteria, together with its respective ranking as shown in Table 5.9 and Table 5.10. Besides, the group judgment between sustainability experts and lean and green expert 1 and 2 were also aggregated as compiled in Table 5.11 and 5.12.

Table 5.9.

Group Judgement for Local Weight

	Local Weight	**Expert 1**	**Expert 2**	**Geometric Mean**	**Rank**
Economic	Economic Performance	0.18641	0.34483	0.253535	2
	Indirect Economic Impacts	0.06646	0.34907	0.152313	3
	Market Presence	0.04127	0.21105	0.093328	4
	Procurement Practice	0.70586	0.09504	0.259008	1
Environment	Biodiversity	0.00526	0.02639	0.011782	12
	Effluents and Waste	0.01934	0.05635	0.033012	10
	Emissions	0.01715	0.0639	0.033104	9
	Energy	0.01808	0.05565	0.031720	11
	Environment Compliance	0.08649	0.08631	0.086400	4
	Environmental Grievance Mechanism	0.05777	0.06526	0.061401	6
	Materials	0.10200	0.12353	0.112250	2
	Overall Environmental	0.08889	0.08631	0.087591	3
	Product & Services	0.09037	0.28615	0.160809	1
	Supplier Environmental Assessment	0.39533	0.00827	0.057178	7
	Transport	0.09562	0.07803	0.086378	5
	Water	0.02371	0.06384	0.038906	8
Social	Human Rights	0.04424	0.32815	0.120488	4
	Labour Practices & Decent Work	0.65966	0.23304	0.392081	1
	Product Responsibility	0.18249	0.21446	0.197830	2
	Society	0.11361	0.22436	0.159654	3

Table 5.9 displayed the local weight for each criterion as well as its ranking. The local weight yields the rank within each of the economic, environment and social dimension. The local weight results gave an understanding on the relative importance within the dimension itself, which is a surplus for the global ranking result. Further discussion regarding comparison between the dimensions is shown in Section 5.3.1.5.3.

Table 5.10.

Group Judgment for Global Weight

	Global Weight	Expert 1	Expert 2	Geometric Mean	Rank
Economic	Economic Performance	0.044300	0.072486	0.056667	3
	Indirect Economic Impacts	0.015794	0.073377	0.034043	6
	Market Presence	0.009808	0.044364	0.02086	9
	Procurement Practice	0.167749	0.019979	0.057892	2
Environment	Biodiversity	0.000855	0.00484	0.002034	20
	Effluents And Waste	0.003144	0.010334	0.005700	18
	Emissions	0.002789	0.011719	0.005717	17
	Energy	0.002940	0.010206	0.005478	19
	Environment Compliance	0.014064	0.015828	0.014920	12
	Environmental Grievance Mechanism	0.009394	0.011968	0.010603	14
	Materials	0.016585	0.022654	0.019383	10
	Overall Environmental	0.014454	0.015828	0.015125	11
	Product & Services	0.014694	0.052476	0.027768	7
	Supplier Environmental Assessment	0.064282	0.001517	0.009875	15
	Transport	0.015548	0.014309	0.014916	12
	Water	0.003855	0.011708	0.006718	16
Social	Human Rights	0.009778	0.076737	0.027392	8
	Labour Practices & Decent Work	0.145800	0.054496	0.089138	1
	Product Responsibility	0.040335	0.05015	0.044976	4
	Society	0.025110	0.052465	0.036296	5

By referring to Table 5.10, the criterion which has the highest and ranking is shifted from the procurement practice and human rights to the labour practices and decent work from the social dimension. Conversely, the criterion which has the lowest weight and rank has remained similar with the sustainability expert 1 which was the biodiversity. Further discussion regarding comparison between the criteria is shown in Section 5.3.1.5.2.

Table 5.11.

Group Judgment for Alternatives (Local Weight)

Alternatives	S1LG1	S1LG2	S2LG1	S2LG2	Geometric Mean	Ranking
Green Manufacturing	0.55498	0.65631	0.65118	0.54615	0.59993	1
Lean Manufacturing	0.44502	0.34369	0.34882	0.45385	0.39447	2

Table 5.12.

Group Judgment for Alternatives (Global Weight)

Alternatives	S1LG1	S1LG2	S2LG1	S2LG2	Geometric Mean	Ranking
Green Manufacturing	0.21018	0.24850	0.24260	0.20347	0.22534	1
Lean Manufacturing	0.16854	0.13010	0.12996	0.16909	0.14816	2

Caption:

S1LG1: Sustainability expert 1 and lean and green expert 1

S1LG2: Sustainability expert 1 and lean and green expert 2

S2LG1: Sustainability expert 2 and lean and green expert 1

S2LG1: Sustainability expert 2 and lean and green expert 2

Table 5.11 and 5.12 displayed consistent findings between the individual judgments and group judgment which portrayed the green manufacturing to be more sustainable than lean manufacturing. Although this research advocates the integration between these two manufacturing paradigms, these results suggested that the manufacturing company which already implemented green manufacturing should performed better in terms of sustainability context.

5.3.1.5 Evaluation of FANP Results

The FANP result was evaluated by looking upon the consistency of the expert's judgment. Then, the criteria weight and ranking from each experts and the group judgment was compared. An additional evaluation was made by comparing the FANP result with crisp ANP results to experiment on the validity of the fuzzy integration with ANP.

5.3.1.5.1 Consistency of the Expert's Judgment

In order to check if the expert's judgments were consistent, Consistency Ratio (*CR*) was used, which is a comparison between Consistency Index (*CI*) and Random Consistency Index (*RI*) (Saaty, 2010). The calculation for *CR* is given as

$$CR = \frac{CI}{RI} \text{ where } = \frac{\lambda_{max} - n}{(n-1)}, \ n = \text{size of matrix} \qquad (5.2)$$

The value of *RI* differs according to the size of matrix as shown in Table 5.13.

Table 5.13.

Value of Random Index (RI)

n	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RI	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45

If the value of *CR* is smaller or equal to 10% or 0.1, the inconsistency is acceptable. Conversely, if the *CR* is greater than 10% or 0.1, the experts' judgment is recommended to be reconsidered. Table 5.14 exhibits the consistency of the expert's judgment for each pairwise comparison. Note that some of the *CR* value is not available because some of the intra-relationship and inter relationship among the criteria in the cluster was not considered as clarified by the experts and the GRI documentation.

Table 5.14.

FANP Consistency Ratio Results

Cluster	With respect to	***CR***	>0.1 (Not consistent)
Alternative	Green Manufacturing	n/a	-
	Lean Manufacturing	n/a	-
Economic	Economic Performance	n/a	-
	Indirect Economic Impacts	n/a	-
	Market Presence	n/a	-
	Procurement Practice	n/a	-
	Biodiversity	n/a	-
	Effluents and Waste	n/a	-
	Emissions	n/a	-
	Energy	n/a	-
	Environment Compliance	0.01126	-
	Environmental Grievance Mechanism	0	-
	Materials	0.03390	-
	Overall Environmental	0.03390	-
	Product & Services	0.03390	-
	Supplier Environmental Assessment	0.03390	-
	Transport	0.03390	-
	Water		-
	Human Rights	0	-
	Labour Practices & Decent Work	0	-
	Product Responsibility	0	-
	Society	0.17374	/

Table 5.14 continued

Environment	Economic Performance	0	-
	Indirect Economic Impacts	0.00195	-
	Market Presence	n/a	-
	Procurement Practice	0	-
	Biodiversity	n/a	-
	Effluents and Waste	n/a	-
	Emissions	n/a	-
	Energy	n/a	-
	Environment Compliance	n/a	-
	Environmental Grievance Mechanism	n/a	-
	Materials	n/a	-
	Overall Environmental	n/a	-
	Product & Services	n/a	-
	Supplier Environmental Assessment	n/a	-
	Transport	n/a	-
	Water	n/a	-
	Human Rights	n/a	-
	Labour Practices & Decent Work	n/a	-
	Product Responsibility	0.05908	-
	Society	0	-
Social	Economic Performance	0	-
	Indirect Economic Impacts	0	-
	Market Presence	0	-
	Procurement Practice	0	-
	Biodiversity	0	-
	Effluents and Waste	0.00219	-
	Emissions	0	-
	Energy	0.00212	-
	Environment Compliance	0.00212	-
	Environmental Grievance Mechanism	0.00212	-
	Materials	0	-
	Overall Environmental	0	-
	Product & Services	0	-
	Supplier Environmental Assessment	0	-
	Transport	0.00212	-
	Water	0.00184	-
	Human Rights	n/a	-
	Labour Practices & Decent Work	n/a	-
	Product Responsibility	n/a	-
	Society	n/a	-
Average *CR*		0.013376	-
Maximum *CR*		0.17374	-

Based on Table 5.14, there is only one pairwise comparisons which is not consistent as the value is larger than 0.1 with a value of 0.17374. Rectification to improve the value was not made due to the considerable gap with the acceptable value (+0.07374) and limited time to recollect the expert's judgment. On a more positive note, the other 31 pairwise comparisons were justified to be consistent.

5.3.1.5.2 Comparison of Criteria and Alternative Ranking

The ranking of the criteria and alternatives obtained from each expert was compared with the ranking obtained from the group judgment to determine if there exists significant difference between them. The result is embedded in Table 5.15.

Table 5.15.

Ranking Comparison by Global Weight

Alternative	Expert 1	Expert 2	Group Judgment
Green Manufacturing	1	1	1
Lean Manufacturing	2	2	2
Criteria			
Economic Performance	4	3	3
Indirect Economic Impacts	8	2	6
Market Presence	13	8	9
Procurement Practice	1	10	2
Biodiversity	20	19	20
Effluents and Waste	17	17	18
Emissions	19	15	17
Energy	18	18	19
Environment Compliance	12	11	12
Environmental Grievance Mechanism	15	14	14
Materials	7	9	10
Overall Environmental	11	11	11
Product & Services	10	5	7
Supplier Environmental Assessment	3	20	15
Transport	9	13	12
Water	16	16	16
Human Rights	14	1	8
Labour Practices & Decent Work	2	4	1
Product Responsibility	5	7	4
Society	6	6	5

Based on Table 5.15, there was some dispute regarding eight of the criteria rankings which are indirect economic performance, market presence, procurement practice, emissions, product and services, supplier environmental assessment, transport and human rights. The alternative rankings were definite consistent. Thus, the ranking obtained from the group judgment method is highly recommended and should be considered.

From the perspectives of alternatives, the green manufacturing paradigm is shown to be more sustainable than the lean manufacturing. Therefore, the manufacturing company who practices green manufacturing paradigm is more likely to become sustainable compared with lean manufacturing practice. Nonetheless, both of the paradigms are proven to have significance relative importance to all of the sustainability criteria.

5.3.1.5.3 Comparison of Dimensions

In terms of the ranking, the best dimension was determined by using the averaging method as demonstrated by Khorasani, Mirmohammadi, Motamed, Fereidoon, Tatari, Reza, and Fazelpour (2013). This method was used to specify the best dimensions which should be given higher priority prior to sustainability as shown in Table 5.16 and Table 5.17. The averaging method algorithm is given as follows.

Step 1. Calculate the average weight within each of the dimension by Equation 5.2.

$$\overline{w_i} = \frac{\sum_{j=1}^{n} w_j}{n}, \text{where } i = 1,2, \ldots n \tag{5.2}$$

Step 2. Compute the average weight between the dimensions by Equation 5.3

$$\overline{W} = \frac{\sum_{i=1}^{m} \overline{w_i}}{m} \tag{5.3}$$

Step 3. Determine the difference of average using Equation 5.4

$$\Delta A_i = |\overline{W} - \overline{w_i}|, \text{ where } i = 1,2, \ldots m \tag{5.4}$$

Step 4 Sort the difference of average in ascending order. The value which is closer to zero is the best dimension. The calculation for difference of ranking is similar but the notation was changed to *r* instead of *w*.

Notation:

n = Number of criteria within dimension

m = Number of dimension

w_j = Weight of criterion

$\overline{w_i}$ = Average weight within dimension

$\bar{W}$ = Average weight between dimensions

ΔA_i = Difference of average

r_j = Ranking of criterion

$\overline{r_i}$ = Average ranking within dimension

$\bar{R}$ = Average ranking between dimensions

Table 5.16.

Dimension Comparison by Weight

Dimension	Criteria	w_j	$\overline{w_i}$	$\overline{W}$	ΔA_i
Economic	Economic Performance	0.05667	0.04237	0.03445	0.00792
	Indirect Economic Impacts	0.03404			
	Market Presence	0.02086			
	Procurement Practice	0.05789			
Environment	Biodiversity	0.00203	0.01152	0.03445	0.02293
	Effluents and Waste	0.00570			
	Emissions	0.00572			
	Energy	0.00548			
	Environment Compliance	0.01492			
	Environmental Grievance Mechanism	0.01060			
	Materials	0.01939			
	Overall Environmental	0.01513			
	Product & Services	0.02777			
	Supplier Environmental Assessment	0.00988			
	Transport	0.01492			
	Water	0.00672			
Social	Human Rights	0.02739	0.04945	0.03445	0.01501
	Labour Practices & Decent Work	0.08914			
	Product Responsibility	0.04498			
	Society	0.03630			

Table 5.17.

Dimension Comparison by Ranking

Dimension	Criteria	r_j	$\bar{r_i}$	$\bar{R}$	ΔA_i
Economic	Economic Performance	3	5	7.88333	2.88333
	Indirect Economic Impacts	6			
	Market Presence	9			
	Procurement Practice	2			
Environment	Biodiversity	20	14.15	7.88333	6.26667
	Effluents and Waste	18			
	Emissions	17			
	Energy	19			
	Environment Compliance	12			
	Environmental Grievance Mechanism	14			
	Materials	10			
	Overall Environmental	11			
	Product & Services	7			
	Supplier Environmental Assessment	15			
	Transport	12			
	Water	16			
Social	Human Rights	8	4.5	7.88333	3.38333
	Labour Practices & Decent Work	1			
	Product Responsibility	4			
	Society	5			

Both of these results have indicated that the economic criteria have the highest collective weight and rank and therefore it can be concluded to be the most important dimension in sustainability from this method's perspective. This finding differs with the hypotheses of Fan et al. (2010), Amrina and Yusof (2011) and Dornfeld et al. (2013) which stated that the social dimension actually plays a bigger role to attain overall sustainability objectives compared with the other two dimensions. As opposed to the original understanding which indicated that the sustainable paradigm is motivated by the case of environmental dimension, the economic criteria should be given the highest priority.

5.3.1.5.4 Comparison with Crisp ANP

The FANP result was compared with crisp ANP results to establish the validity of the FANP method. The crisp value of ANP was generated by considering three types of situations which are the smallest possible value (l), the most possible value (m) and the largest possible value (u). Table 5.18 exhibits the comparison between FANP and the most possible crisp value in terms of CR. Note that there are some values that are not available because the intra-relationship between the criteria was not considered based on GRI sustainability indicator documentations. The other situation of the smallest possible value and the largest possible value can be seen in Appendix D.

Table 5.18.

FANP and Most Possible Value Crisp ANP Consistency Ratio Comparison

Cluster	**With respect to**	**ANP Consistency**	**>0.1 (Not consistent)**	**FANP Consistency**	**>0.1 (Not consistent)**
Alternatives	Green Manufacturing	n/a	-	n/a	-
	Lean Manufacturing	n/a	-	n/a	-
Economic	Economic Performance	n/a	-	n/a	-
	Indirect Economic Impacts	n/a	-	n/a	-
	Market Presence	n/a	-	n/a	-
	Procurement Practice	n/a	-	n/a	-
	Biodiversity	n/a	-	n/a	-
	Effluents and Waste	n/a	-	n/a	-
	Emissions	n/a	-	n/a	-
	Energy	n/a	-	n/a	-
	Environment Compliance	0.30723	/	0.01126	-
	Environmental Grievance Mechanism	0	-	0	-
	Materials	0.48077	/	0.03390	-
	Overall Environmental	0.48077	/	0.03390	-
	Product & Services	0.48077	/	0.03390	-
	Supplier Environmental Assessment	0.48077	/	0.03390	-
	Transport	0.48077	/	0.03390	-
	Water	n/a	-		-
	Human Rights	0.21842	/	0	-

Table 5.18 continued

	Labour Practices & Decent Work	0.15936	/	0	-
	Product Responsibility	0	-	0	-
	Society	0.15936	/	0.17374	/
Environment	Economic Performance	0.26578	/	0	-
	Indirect Economic Impacts	0.08374	-	0.00195	-
	Market Presence	n/a	-	n/a	-
	Procurement Practice	0	-	0	-
	Biodiversity	n/a	-	n/a	-
	Effluents and Waste	n/a	-	n/a	-
	Emissions	n/a	-	n/a	-
	Energy	n/a	-	n/a	-
	Environment Compliance	n/a	-	n/a	-
	Environmental Grievance Mechanism	n/a	-	n/a	-
	Materials	n/a	-	n/a	-
	Overall Environmental	n/a	-	n/a	-
	Product & Services	n/a	-	n/a	-
	Supplier Environmental Assessment	n/a	-	n/a	-
	Transport	n/a	-	n/a	-
	Water	n/a	-	n/a	-
	Human Rights	n/a	-	n/a	-
	Labour Practices & Decent Work	n/a	-	n/a	-
	Product Responsibility	0.08217	-	0.05908	-
	Society	0.09101	-	0	-

Table 5.18 continued

Social	Economic Performance	0.06948	-	0	-
	Indirect Economic Impacts	0.16327	/	0	-
	Market Presence	0.00885	/	0	-
	Procurement Practice	0	-	0	-
	Biodiversity	0.11053	/	0	-
	Effluents and Waste	0.15397	/	0.00219	-
	Emissions	0.00454	-	0	-
	Energy	0.137	/	0.00212	-
	Environment Compliance	0.137	-	0.00212	-
	Environmental Grievance Mechanism	0.14911	/	0.00212	-
	Materials	0.00065	-	0	-
	Overall Environmental	0.095292	-	0	-
	Product & Services	0.00388	-	0	-
	Supplier Environmental Assessment	0.00613	-	0	-
	Transport	0.12666	/	0.00212	-
	Water	0.23529	/	0.00184	-
	Human Rights	n/a	-	n/a	-
	Labour Practices & Decent Work	n/a	-	n/a	-
	Product Responsibility	n/a	-	n/a	-
	Society	n/a	-	n/a	-
Average *CR*		0.23529	-	0.01337625	-
Maximum *CR*		0.48077	-	0.17374	-

Based on Table 5.18, it is proven that the FANP results yield a better consistent pairwise comparison compared with crisp ANP. Hence, the integration of FST with ANP was justified to be better than crisp ANP alone.

5.4 Selection Phase

Based on the GRI G4 Sustainability Reporting guideline and the discussion with the manufacturing experts, a set of rules for the selection of applicable indicators which can suit the requirement of each organization is developed. The example for the rules in this phase is shown in Figure 5.10 and the full set of rule is shown in Appendix E. These rules were then developed as the Knowledge Base Level 2.

```
True = 1
False = 0

IF the company is a profit-oriented company (including product and services)
OR the company have source of income from government, shareholders, fund etc
        THEN G4-EC1 = True
                G4-EC1-1 = True
                G4-EC1-2 = True
                G4-EC1-3 = True
                G4-EC1-4 = True
                G4-EC1-5 = True
                G4-EC1-6 = True
                G4-EC1-7 = True
                G4-EC1-8 = True
                G4-EC1-9 = True
                G4-EC1-10 = True
                G4-EC1-11= True
        THEN G4-EC2 = True
ELSE G4-EC1 = False
```

Figure 5.10. Example of Rule Base for Knowledge Base Level 2

5.5 Evaluation Phase

Based on the GRI G4 Sustainability Reporting guideline and the discussion with the manufacturing experts, the indicators and sub-indicators considered were assigned to its own threshold for the numerical assessment of sustainability performance. The example for the indicators threshold is shown in Table 5.19, Table 5.20 and Table 5.21. The full set of the indicators threshold is embedded in Appendix F.

Table 5.19.

Example of Indicators Threshold (*Economic*)

Criteria	**Indicators**	**Sub-indicators**	**Key points**	**Threshold**
Economic Performance	G4-EC1 Direct economic value generated and distributed	Revenue	Net sales	HB
			Revenue from financial investment	HB
			Revenue from sales of assets	HB
		Operating Cost	Cash payments	HB
		Employee wages	Employee salary	NB
			Total benefits for employee	NB
		Payment to capital providers	Dividends to shareholders	NB
			Interest payment to loan provider	LB
		Payment to government	Tax	LB
		Community investments	Donation to community	HB
			Infrastructure investment	NB

Table 5.20.

Example of Indicators Threshold (*Environment*)

Criteria	Indicators	Sub-indicators	Key points	Threshold
Materials	G4 EN1 Materials used by weight or volume	Weight/volume of materials	Non-renewable material	HB
			Renewable material	LB
	G4-EN2 Percentage of materials used that are recycled input materials	Fuel consumption	Non-renewable material	HB
			Renewable material	LB
		Electricity consumption		LB
		Heating consumption		LB
		Steam consumption		LB
		Total energy consumption		LB
		Fuel sold	Non-renewable material	HB
			Renewable material	HB
		Electricity sold		HB
		Heating sold		HB
		Cooling sold		HB
		Steam sold		HB
		Standards and methodology		Report only
		Source of conversion used		Report only

Table 5.21.

Example of Indicators Threshold (*Society*)

Criteria	Indicators	Sub-indicators	Key points	Threshold
Labour practice and decent work	G4-LA1 total number and rates of new employee hires and employee turnover by age group, gender and region	New employee hires	Total number	NB
			Rate	NB
		Employee turnover	Total number	LB
			Rate	LB
	G4 –LA2 benefits provided to full-time employees that are not provided to temporary or part-time employees, by significant locations of operation	Benefits for full-time employees of the organization but are not provided to temporary or part-time employees.	Life insurance	Report only
			Health care	Report only
			Disability and invalidity coverage	Report only
			Parental leave	Report only
			Retirement provision	Report only
			Stock ownership	Report only
			Others	Report only

By referring to the threshold value for the indicators, a set of rules for the evaluation by the applicable indicators were developed. The example for the rules in this phase is shown in Figure 5.11. These rules were then developed as the Knowledge Base Level 1.

G4-EC1-1 = Net Sales
hi_sales = 100000000000
low_sales = 100000000
IF sales < = 100000000000 or sales >100000000
THEN G4_EC1_1 = (sales - low_sales)/(hi_sales - low_sales);
ELSE insert another value between 55773897519 and 401270746035
G4-EC1

Figure 5.11. Example of Rule Base for Knowledge Base Level 1

5.6 Prioritization Phase

The outcome from Knowledge Base Level 1 was aggregated with the criteria weight from Knowledge Base Level 3 and is sorted accordingly in ascending order. This phase produce the prioritized area of improvement based on the sorted aggregated score. The example for the rules in this phase is shown in Figure 5.12.

G4-EC1-1 = Net sales
G4-EC1-2 = Revenue from financial investment
G4-EC1-3 = Revenue from sales of assets
Economic Performance weight = 0.05667

G4-EC1-1 = 0.30 * 0.056667 = 0.017000
G4-EC1-2 = 0.25 * 0.056667 = 0.014167
G4-EC1-3 = 0.75 * 0.056667 = 0.042500

Sort indicators in ascending order

G4-EC1-2
G4-EC1-1
G4-EC1-3

Improve these area based on this priority order

1. Revenue from financial investment
2. Net sales
3. Revenue from sales of assets

Figure 5.12. Example of Rule Base for Prioritization Phase

5.7 KBFANP System Implementation

The KBFANP system was developed via MATLAB and the full source code was shown in Appendix G. The KBFANP system was implemented and tested for two companies which are company B and D as they have all of the information needed by the system except for the operating cost, interest payment to loan provider and tax information. This system was also tested with three other different experimental data symbolized as Data 1, Data 2 and Data 3 which were self-generated to determine the performance of the system based on its flexibility to cater all types of organizations inputs as mentioned in Section 4.4. Data 1 represents a perfect company with perfect sustainability score. Next, Data 2 exemplify a worst company with the lowest sustainability score and Data 3 was a company with random sustainability performance.

Table 5.22 shows the questions given by the system for the economic dimension. Table 5.23 shows the answers given for these five cases. The KBFANP system question for the environment and social dimensions will be done as future research due to the excessive time needed to develop this system. The current implementation has already involved 1136 lines of code and it is estimated that a complete system will involve approximately 20000 lines of code. In spite of that, the current result has already shown the effectiveness of the KBFANP system implementation for all Knowledge Base levels as proposed in the KBFANP model.

Table 5.22.

KBFANP System Question for Economic Dimension

Question ID	Description
1	Does your company profit-oriented (including product and services)?
2	Does your company has source of income from government, shareholder, fund, etc.
2	Enter annual sells (RM)
3	Enter revenue from financial investment (RM)
4	Enter revenue from sales of assets (RM)
5	Enter operating cost (RM)
6	Enter average salary for employees (RM)
7	Enter total benefit for employees (RM)
8	Enter dividend for shareholders (%)
9	Enter interest rate payment for loan provider (%)
10	Enter annual tax payment (RM)
11	Enter annual donation to community (RM)
12	Enter total investment for infrastructure (RM)
13	Does your company has coverage of benefit plans obligations such as pensions, benefit plan, contribution plan or retirement benefits?
14	Enter percentage of salary contributed by employee/employer (%)
15	Enter level of participation for retirement plan (%)
16	Does your company 2 gender based
17	Enter proportion of male gender (%)
18	Enter proportion of senior management (%)

Table 5.23.

Answers from Five Implementation Cases

Question ID	Company B	Company D	Data 1	Data 2	Data 3
1	Yes	Yes	Yes	No	Not applicable
2	-	-	-	Yes	No
3	2582300000	7282100000	100000000000	100000000	-
4	1432000000	7500000000	100000000000	100000000	-
5	267000000	1277200000	100000000000	100000000	-
6	500000	500000	10000	1000000000	-
7	3892	4730	5000	1000	-
8	2800	3000	5000	1000	-
9	8.5	8.5	5	1	-
10	10	10	0	20	-
11	50000	50000	10000	100000	-
12	5570000	7440000	10000000	5000000	-
13	298180	354000	500000	100000	-
14	Yes	Yes	Yes	Yes	Not applicable
15	0	2	20	0	-
16	20	25	50	20	-
17	Yes	Yes	Yes	No	Yes
18	78	72	50	20	48
19	10	15	10	5	18

The gathered information from Table 5.23 was entered into the KBFANP system. Figure 5.13 and Figure 5.14 were some of the example of the actual execution of question and answer from the KBFANP system which displayed the result as in Figure 5.15. The outcome of this process was the sustainability performance for each five implementations was shown in Table 5.24.

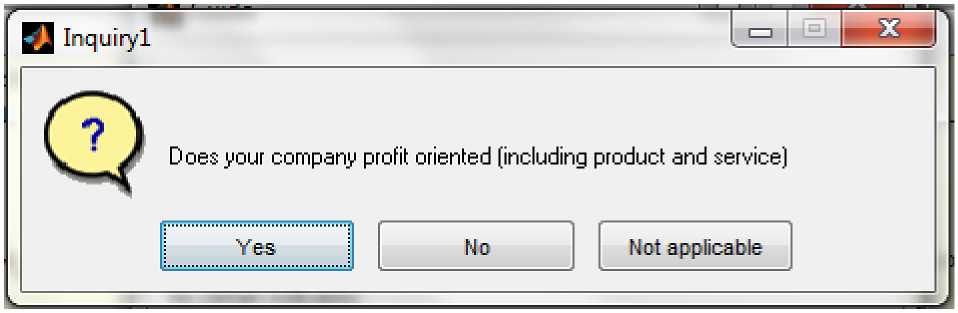

Figure 5.13. Example of Multiple Choice Question in KBFANP System

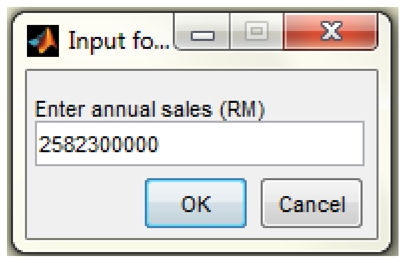

Figure 5.14. Example of Numerical Input Question in KBFANP System

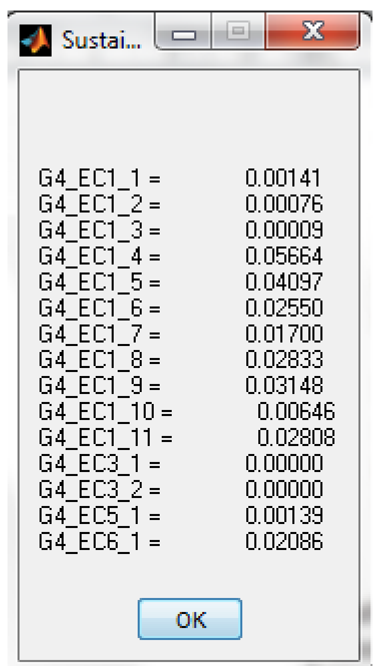

Figure 5.15. Example of Evaluation Phase Result in KBFANP System

Table 5.24.

Sustainability Performance for Five Implementation Cases

Indicators ID	Indicators	Company B	Company D	Data 1	Data 2	Data 3
G4_EC1_1	Net sales/ income	0.00141	0.00407	0.05667	0.00000	-
G4_EC1_2	Revenue (financial investment)	0.00076	0.00420	0.05667	0.00000	-
G4_EC1_3	Revenue (sales of assets)	0.00009	0.00067	0.05667	0.00000	-
G4_EC1_4	Operating cost	0.05664	0.05664	0.05667	0.00000	-
G4_EC1_5	Employee salary	0.04097	0.02833	0.05667	0.00000	-
G4_EC1_6	Employee benefits	0.02550	0.01700	0.05667	0.00000	-
G4_EC1_7	Dividend to shareholders	0.01700	0.02833	0.05667	0.00000	-
G4_EC1_8	Interest to loan provider	0.02833	0.03148	0.05667	0.00000	-
G4_EC1_9	Tax	0.03148	0.02765	0.05667	0.00000	-
G4_EC1_10	Donation to community	0.00646	0.03598	0.05667	0.00000	-
G4_EC1_11	Infrastructure investment	0.02808	0.00567	0.05667	0.00000	-
G4_EC3_1	Percentage of salary contributed (employee)	0.00000	0.00944	0.05667	0.00000	-
G4_EC3_2	Participation in retirement plan (employee)	0.00000	0.00556	0.05667	0.00000	-
G4_EC5_1	Proportion of gender	0.00139	0.02086	0.02086	-	0.01947
G4_EC5_2	Proportion of senior management	0.02086	0.00407	0.02086	-	0.02086
Average score		0.017264	0.018663	0.05189	0	0.020165
Ranking		4	3	1	5	2

The result of sustainability performance from Table 5.24 was sorted in ascending order in the prioritization phase and the priority ranking for room of improvement was shown in Table 5.25. Additionally, Figure 5.16 was the actual result displayed in the KBFANP system. Figure 5.17 and Figure 5.18 demonstrated the reasoning mechanism and system's guide of the KBFANP system in giving advice to the user in order to improve their company's sustainable performance especially for the low performed areas.

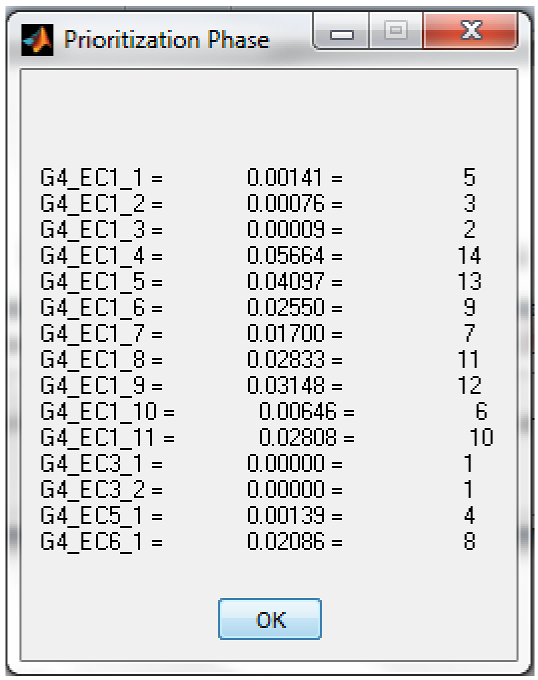

Figure 5.16. Example of Prioritization Phase Result in KBFANP System

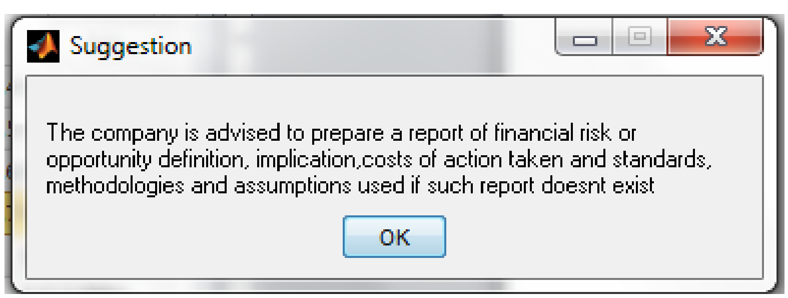

Figure 5.17. Example of Suggestion Provided by the KBFANP System

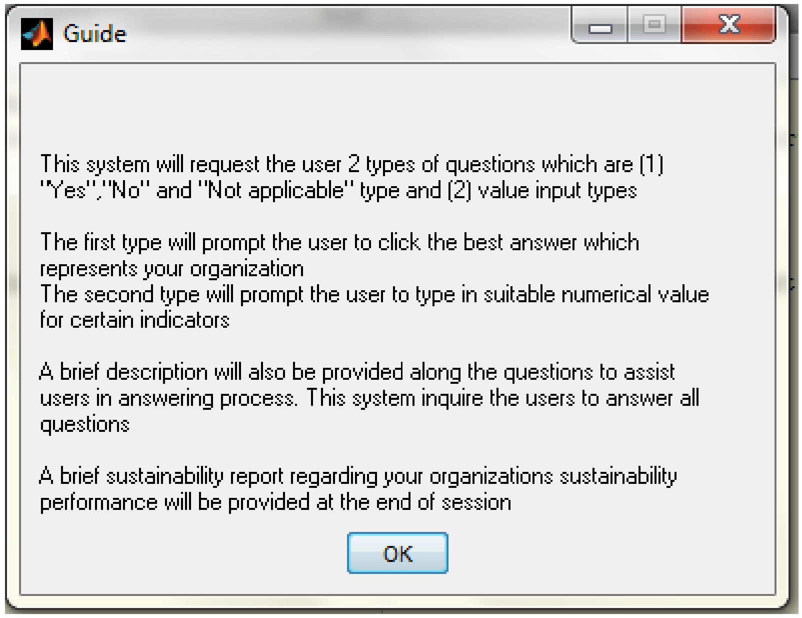

Figure 5.18. Example of Guide Provided by the KBFANP System

Table 5.25.

Prioritization of Indicators for Five Implementation Cases

Indicators ID	Indicators	Company B	Company D	Data 1	Data 2	Data 3
G4_EC1_1	Net sales	5	2	2	1	-
G4_EC1_2	Revenue (financial investment)	3	3	2	1	-
G4_EC1_3	Revenue (sales of assets)	2	1	2	1	-
G4_EC1_4	Operating cost	14	14	2	1	-
G4_EC1_5	Employee salary	13	13	2	1	-
G4_EC1_6	Employee benefits	9	10	2	1	-
G4_EC1_7	Dividend to shareholders	7	7	2	1	-
G4_EC1_8	Interest to loan provider	11	10	2	1	-
G4_EC1_9	Tax	12	11	2	1	-
G4_EC1_10	Donation to community	6	9	2	1	-
G4_EC1_11	Infrastructure investment	10	12	2	1	-
G4_EC3_1	Percentage of salary contributed (employee)	1	5	2	1	-
G4_EC3_2	Participation in retirement plan (employee)	1	6	2	1	-
G4_EC5_1	Proportion of gender	4	4	1	2	1
G4_EC5_2	Proportion of senior management	8	8	1	2	2

5.7.1 KBFANP System Verification

The KBFANP system was verified to ensure their effectiveness to represent the sustainability manufacturing indicator and the outcome of the system. Based on Section 4.4.1, the solution from this system must fulfil certain conditions which are

1. The indicator obtained from the literature is being examined by the industry practitioner and being cross checked until it is been agreed and aligned as much as possible.

As mentioned in Section 4.4.1, moderation should be considered for condition (1) because it is almost impossible to determine the effectiveness of the KBFANP system which is based on GRI G4 Sustainability Reporting Guideline. Although it is the most used sustainability indicator across the globe, it does not guarantee the effectiveness of this indicator as no comparative research among the indicators has been done yet.

2. Suppose that the result of Initialization phase is true, then the ascending order of weight must be similar with the ascending order in Selection phase, given that all the indicators value is true.

The criteria weight used in the KBFANP system was sorted in ascending order and the outcome of the selection phase was also in ascending order as shown in Table 5.26. Thus, condition (2) was satisfied.

Table 5.26.

Ascending Order of Initialization and Selection Phase

Criteria	**FANP weight**	**FANP ranking**	**Indicators ID**	**Indicators**	**Data 1**	**Selection phase ranking**
Economic performance	0.05667	1	G4_EC1_1	Net sales/ income	0.05667	1
Market presence	0.02086	2	G4_EC3_1	Proportion of gender	0.02086	2

3. Suppose that the result of Selection phase is true, then only rules for the performance level of applicable indicators is considered in Evaluation phase.

By referring to Table 5.22 and 5.23, the selection phase for Data 1 was true for all indicators and all of the applicable indicators were examined. In contrast, the selection for Data 3 was true only for Question 17, 18 and 19 and only proportion of gender (G4_EC5_1) and proportion of senior management (G4_EC5_2) were measured. Hence, condition (3) was satisfied.

4. Suppose that the result of Evaluation phase is true, then the ascending order of sustainability performance score must be similar with the ascending order in Prioritization phase, give that all the performance level of applicable indicators is true.

The result from the Evaluation phase was sorted in ascending order and the outcome of the prioritization phase was also in ascending order as shown in Table 5.27 for all implementation case. Therefore, condition (4) was satisfied.

Table 5.27.

Ascending Order of Evaluation and Prioritization Phase

Indicators ID	**Indicators**	**Evaluation Phase (Sustainability Performance Score)**	**Prioritization Phase (Ranking)**
G4_EC3_1	Percentage of salary contributed (employee)	0.00000	1
G4_EC3_2	Participation in retirement plan (employee)	0.00000	1
G4_EC1_3	Revenue (sales of assets)	0.00009	2
G4_EC1_2	Revenue (financial investment)	0.00076	3
G4_EC5_1	Proportion of gender	0.00139	4
G4_EC1_1	Net sales	0.00141	5
G4_EC1_10	Donation to community	0.00646	6
G4_EC1_7	Dividend to shareholders	0.01700	7
G4_EC5_2	Proportion of senior management	0.02086	8
G4_EC1_6	Employee benefits	0.02550	9
G4_EC1_11	Infrastructure investment	0.02808	10
G4_EC1_8	Interest to loan provider	0.02833	11
G4_EC1_9	Tax	0.03148	12
G4_EC1_4	Operating cost	0.05664	14
G4_EC1_5	Employee salary	0.04097	13

As all of the conditions were satisfied except for condition (1) which was still ambiguous, it can be concluded that the KBFANP system is effective and can be utilized for any types of problem settings.

5.7.2 KBFANP System Validation

The proposed KBFANP system was validated to check for its competency to solve sustainability manufacturing indicator efficiently. Previously, none of the researches provided their own method of indicators efficiency. The KBFANP system validation process was not compared within the case companies as the implementation was not done yet in their current manufacturing setting. On a positive note, the results from the KBFANP system was compared with the findings from the 2014 Interbrand 4th Annual Best Global Green Brands Press Release (Interbrand, 2014).

The finding from Interbrand was preferred as it is the world's leading brand consultancy organization for sustainability assessment and it was claimed to be the major reference for global organizations. The report's overall sustainability scores were calculated by combining the standardized performance and perception scores. A discount factor was also applied in those cases where positive perceptions of the brand outweigh a company's actual green performance. The final ranking is based on companies' overall scores relative to other companies and previous years' results to ensure that brands were credited with prior years' achievements and improvements to those achievements.

The comparison was not done in terms of sustainability score, as the methodology of Interbrand was different and it is not based on GRI G4 Sustainability Reporting Guideline. Moreover, the Interbrand's methodology did not consider the relative importance weight of each sustainability criteria. The comparison was only being made in terms of the company's ranking as shown in Table 5.28 and Table 5.29.

Table 5.28.

Comparison of Actual Ranking between KBFANP System and Interbrand

Company/Indicators	**KBFANP**	**Interbrand**
Company B	4	4
Company D	3	2

Table 5.29.

Comparison of Standardized Ranking between KBFANP System and Interbrand

Company/Indicators	**KBFANP**	**Interbrand**
Company B	2	2
Company D	1	1

By referring to Table 5.29, the result produced by KBFANP system was consistent with the findings from Interbrand. This proves that KBFANP system was sufficiently reliable and based on this fact, it can be concluded that the KBFANP system is substantially valid. The advantages and disadvantages of KBFANP and Interbrand were concluded into Table 5.30.

Table 5.30.

Advantages and Disadvantages of KBFANP System and Interbrand

Indicators	Advantages	Disadvantages
KBFANP system	Utilize the relative importance weight between criteria	Did not consider perception scores
	The notion of applicable indicators	Implemented only for two companies and three experimental data
	Criteria was based on GRI G4 Sustainability Reporting Guideline which was globally used	Data was collected on individual experts basis and two company reports
Interbrand	Standardized performance and perception scores	Did not utilize the relative importance weight between criteria
	Implemented for 100 companies	Indicators was made compulsory to all problem settings
	Wide source of data collection	Used self-defined criteria

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CHAPTER SIX
CONCLUSION

Organizations, be it whether from the public or private sectors, have called for the need to involve sustainability thinking into their decision making process. An appropriate sustainability decision making process will ensure the overall long-term improvement of the organization from three perspectives of economic, environment and society. This requirement is more relevant to the manufacturing world today, as it is infamously held responsible for current degeneration of environmental health. The negative impact from the manufacturing industry did not only affect the Mother Nature, but it expands to the economic and society as well. Thus, the idea of sustainability emerged based on this problem of concern.

During this sustainability conscious era, the manufacturing paradigm has started to evolve towards sustainable manufacturing paradigm. In order for the industry to shift their current paradigm towards sustainable paradigm, the development of indicators was highly required as it was enclosed within the planning stage of sustainability decision making process. As the previous indicators was not standardized and can suit the specific requirement of various manufacturing organizations, a novel KBFANP system was introduced via this research to improve the existing sustainable manufacturing indicators mechanism.

The system is based on the KBFANP model, which is the integration of three separate techniques of KBS, FST and FANP. The KBFANP model exploited the advantages of these techniques which were represented in four levels of indicators mechanism of Initialization, Selection, Evaluation and Prioritization. The system was implemented into two case companies and three experimental data and it was proven that this system managed to behave effectively and was able to match the results from the real world implementation.

This chapter begins with the summary of the research which includes the achievement of research objectives. Next, the limitations of the research and the recommendation for future work are prescribed before a final conclusion is made. At the end of this chapter, it is hoped that the reader will be able to understand the journey of this research and recognized the potential contribution that this research has made.

6.1 Summary of the Research

As a recap, this research has four objectives which are:

1. To examine the best practices of sustainable manufacturing applied from the literature and the actual manufacturing industry
2. To suggest a sustainable manufacturing indicator model of Sustainable manufacturing based on the chosen sustainable manufacturing practices.
3. To develop a Knowledge Based Fuzzy Analytic Network Process system for sustainable manufacturing indicator
4. To implement and validate the Knowledge Based Fuzzy Analytic Network Process system for sustainable manufacturing indicator

Based on the literature review, observation and interview process, it was justified that the synthesis between lean and green manufacturing paradigm can initiate the development of sustainable manufacturing practice. The experts who participated in the interview were also agreed that lean and green practice has made their company to perform better in terms of sustainability manufacturing as exhibited in Section 5.1.3. Ergo, the investigation made on the real world manufacturing process was aligned and validated with the knowledge gained from the literature in Section 2.2. Subsequently, the FANP results justified that both of the paradigms were shown to have significant relative importance with the sustainability criteria although green manufacturing was more sustainable than the lean manufacturing paradigm as shown in Section 5.3.1.4.3. The results obtained had accomplished research objective (1).

Section 2.4.1, 2.4.2 and 2.5 revealed that the GRI G4 Sustainability Reporting Guideline was the most used sustainability indicators across the globe. As a pioneer and the leader of the sustainability assessment area, the GRI indicators was standardized for all types of organization as its instrument involves various expertise from prominent organizations of the United Nations Environment Program (UNEP), the UN Global Compact, the Organization for Economic Co-operation and Development (OECD), the International Organization for Standardization (ISO) and international company stakeholders. The interview findings from Section 5.1.3 also confirmed this matter as case company B and D were complied with the GRI standards.

However, GRI indicator was always misunderstood as a reporting guideline only, rather than the appraisal of the organizations sustainability (Sherman, 2011). Thus, this research reestablishes this matter as KBFANP system employed GRI criteria as its foundation in the Initialization phase. The implementation also was justified to be more relevant as previous sustainable manufacturing indicator created their own indicator's criteria, which may result an inappropriate assessment to the organizations that already assimilated with GRI. Based on this outcome, research objective (2) is accomplished.

The KBFANP system was developed based on the KBFANP model as demonstrated in Section 4.3. The Initialization phase consisted of criteria weight which was obtained from FANP result. The FANP model was developed using SuperDecisions into 2 models namely FANP Model 1 which contained three clusters of economic, environment and society without the alternatives whereas FANP Model 2 includes the alternative cluster with lean and green manufacturing. Based on FANP models, fuzzy pairwise comparison questionnaire was developed and distributed to expert who specializes in sustainability and lean or green manufacturing. The input from the fuzzy pairwise comparison questionnaire was defuzzified using FPP method with the assistance of MATLAB. The crisp local criteria weight was then being processed concurrently with SuperDecision to display the global weight and the final ranking of the criteria. The FANP results was then evaluated by the consistency of the experts judgment, ranking comparison with group judgment which was aggregated using geometric mean and crisp ANP as displayed in Section 5.3.1.5.4. Based on the result, the Initialization phase was complete.

The Selection and Evaluation phases used the rule based type of knowledge base capabilities of KBS. Based on the GRI G4 Sustainability Reporting guideline and the discussion with the manufacturing experts, a set of rules for the selection of applicable indicators which can suit the requirement of each organization was developed. The Evaluation phase also involved normalization method as advocated by Phillis and Kouikoglou (2009). From the Selection and Evaluation phases, a set of applicable indicators was being made ready to be used to appraise the sustainability performance.

The final phase of Prioritization was developed using a simple sorting algorithm to arrange the sustainability score into accordance of lowest to highest score. This arrangement was being made as a guide to the organizations on which aspect should be given priority as improvement area. All of the phases of KBFANP model were programmed into a system using MATLAB. Based on this effort, research objective (3) is accomplished

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The KBFANP system was implemented for two case companies of company B and D with three other experimental data to determine the performance of the system as shown in Section 5.7. By referring to the input provided from these five separate cases, the system managed to provide information for the prioritization for the areas of improvement. The improvement was suggested based on the sorted sustainability score which was calculated from the set of applicable indicator related remotely among the implementation cases. The indicator was also being assigned uniquely according to its own criteria with different weights to distinguish the importance between each indicator.

The KBFANP system passed all of the verification conditions and the system was concluded to be effective as demonstrated in Section 5.7.1. The results produced via implementation process was validated as it is consistent the findings from the 2014 Interbrand 4th Annual Best Global Green Brands Press Release (Interbrand, 2014). The comparison between KBFANP and Interbrand for the validation process can be seen in Section 5.7.2. Based on these procedures, research objective (4) is accomplished.

6.2 Implication of the Research

The outcome of this research has several implications to the areas of Decision Science/Operations Research and manufacturing industry. The implications are described in the following section.

6.2.1 Decision Science/Operations Research

This research managed to prove that the methodology of Decision Science or Operations Research can be applied to solve the real world problem. The KBFANP system is introduced as a novel standardized indicator mechanism which can suit the specific requirement of any problem setting. In this research, the KBFANP system was competent in solving the sustainable manufacturing indicator problem effectively and efficiently. The system which was based on KBFANP model contains all the essence of KBS, FST and FANP which was unified into a single approach, has successfully solved one of the applications in sustainability decision making process. The idea of Initialization, Selection, Evaluation and Prioritization has shown that the indicator mechanisms can actually being made standardized yet applicable regardless of organization.

6.2.2 Manufacturing Industry

An ideal planning in sustainable manufacturing execution can enhance the overall performance of the manufacturing organization. Based on the guideline provided by UNESCO (2006), UNEP (2009) and OEDC (2008), the planning stage requires the organization to map the impact and priorities before choosing the indicators pertinent to them. The chosen indicator is then used to evaluate their sustainability performance in the area of concern. These tasks have been made simpler with the KBFANP system which can be made as a decision support system (DSS) which facilitates the organization's decision making process. The KBFANP system was made for the organization to be able to suit its own problem requirement. As a result, the organization will be able to learn on which criteria and indicator related to them and which area that needs to be improved.

This research also promotes awareness to the manufacturing organization by emphasizing the importance of sustainable practice in their organizations. Furthermore, this research also support the previous research findings which suggest the integration of lean and green paradigm as a fundamental key for sustainable manufacturing implementation. The support was done by the findings of FANP, which exhibited significant relative importance between the sustainability criteria and lean and green paradigms. The findings from this research should be able to convince the organization to upgrade their philosophy and operations towards sustainability orientation.

6.3 Limitations of the Research

Although this research has achieved its objectives and yield several new findings in the field of sustainable manufacturing and Decision Science/Operations Research especially in FMCDM area via the introduction of KBFANP system, this research still does not bypass certain limitations. The limitation of the research and the discussion regarding this matter are addressed as follows:

1. The number of criteria used for the development of KBFANP indicator is large with a total of 20 criterions. This outcome conflict with the problem motivation, which insisted that the indicator should being developed in a small manageable number between 10 and 20 criterions. The involvement of these 20 criteria cannot be avoided because these criterions is considered to be compulsory in the context of sustainability appraisal (GRI, 2013c). Regrettably, the numbers of indicator criteria is expected to be growing for the need of a more accurate assessment of sustainable manufacturing performance (Reich-Weiser et al., 2013).
2. As this research already implemented 20 criteria in KBFANP model, four sub-criteria of social dimension as listed by GRI is neglected as shown in Table 6.1.

Table 6.1.

List of Sub-criteria of Social Dimension

Sub-criteria	List of Sub-criteria
Labour Practices and Decent Works	1. Employment 2. Labour/Management Relations 3. Occupational Health and Safety 4. Training and Education 5. Diversity and Equal Opportunity 6. Equal Remuneration for Women and Men 7. Supplier Assessment for Labour Practices 8. Labour Practices Grievance Mechanisms
Human Rights	9. Investment 10. Non-discrimination 11. Freedom of Association and Collective Bargaining 12. Child Labour 13. Forced or Compulsory Labour 14. Security Practices 15. Indigenous Rights 16. Assessment 17. Supplier Human Rights Assessment 18. Human Rights 19. Grievance Mechanisms
Society	20. Local Communities 21. Anti-corruption 22. Public Policy 23. Anti-competitive Behaviour 24. Compliance 25. Supplier Assessment for Impacts on Society 26. Grievance Mechanisms for Impacts on Society
Product Responsibility	27. Customer Health and Safety 28. Product and Service Labelling 29. Marketing Communications 30. Customer Privacy 31. Compliance

Based on Table 6.1, there are 31 sub-criteria under four criteria in social dimension that was excluded from KBFANP model since it will further add up to 71 criteria for indicator which is not desirable due to its large number. In addition, the involvement of these sub-criteria will increase a node to the FANP model 1 and 2 as exhibited in Figure 4.1 and Figure 4.2, which later will create and unbalanced structure in the network. Furthermore, there are no sub-criteria for the economic and environment under the GRI framework and the inclusion of the social sub-criteria may result an inconsistent FANP model.

3. The large number of criterions included in the FANP model has resulted in numerous numbers of pairwise comparisons in FANP questionnaire for the experts. FANP questionnaire for sustainability experts has 319 and lean and green expert has 20 pairwise comparisons that need to be answered even after simplification and refinement of the relationship between the criteria. If all of the relationship was considered, the model will involves 1554 pairwise comparisons even without the inclusion of social sub-criteria. This large number was expected, as FANP model investigates local dependency among the nodes as well as the inter-dependency between the nodes (Saaty & Vargas, 2006). In comparison to AHP method, only 230 pairwise comparisons will be involved. In addition, one of the sustainability experts, Expert ID 8 commented that the questionnaire took him a very long time to be able to complete it. Thus, the integration of FST with ANP is highly encouraged, as it reduced the number of original ANP pairwise comparison scale from nine to five, which will lessen the burden of the experts and increased the pairwise comparison consistency especially if the problem is vague as shown in Section 5.3.1.5.4.

4. The logic of the rule bases in knowledge base Level 1 and Level 2 developed in the KBFANP model were still highly subjective. It means that some of the knowledge may not be agreed with other individuals, as the knowledge is only obtained from certain experts with the support from the literature. This situation was also expected, as the validation of the experts credibility is one of the limitations of the KBS. However, the KBFANP model managed to include quantitative factor by the utilization of FANP in Level 3, which may reduce the subjectivity, and the uncertainty of the problem.

6.4 Recommendation for Future Work

Based on the limitations on the research, there are few suggestions for the future work in the problem field which are:

1. The application of Factor Analysis (FA) method with ANP to reduce the number of criteria. FA is a statistical method used to describe variability among observed, correlated variables in terms of a potentially lower number of unobserved variables (Decoster & Hall, 1998; Suhr, 2006). FA can be used to reduce the number of variables and to detect the structure in the relationships between variables for variable classification. Although ANP is a favorable MCDM method as it consider the complex inter-relationship among the criteria in the decision problem, the method always result a large number of pairwise comparison even with a small number of criteria. Therefore, FA should be able to overcome the ANP limitation by compressing the number of criteria, which will further reduce the number of pairwise comparison needed.

2. The FANP model in this research can be extended to investigate the relative importance of the sustainability criteria with other manufacturing paradigm such as agile, flexible, rapid, and reconfigurable manufacturing to further validate the fact that the lean and green manufacturing paradigms were the most related paradigm with sustainable manufacturing as shown in Figure 6.1. Besides, the relative importance between different types of manufacturing industry for example the automotive, electrical and chemical manufacturing industry can also be explored as shown in Figure 6.2. In addition, the alternative section may also be substituted with any types of organizations other than manufacturing environment for the same intention as shown in Figure 6.3.

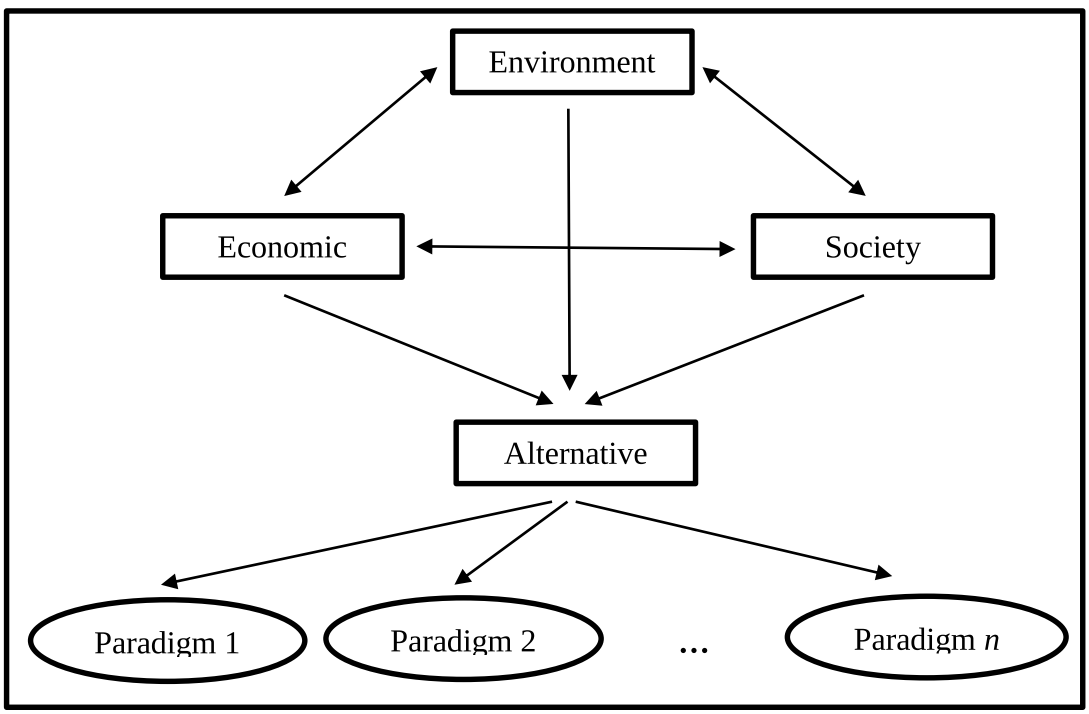

Figure 6.1. FANP Model 3 based on Manufacturing Paradigm

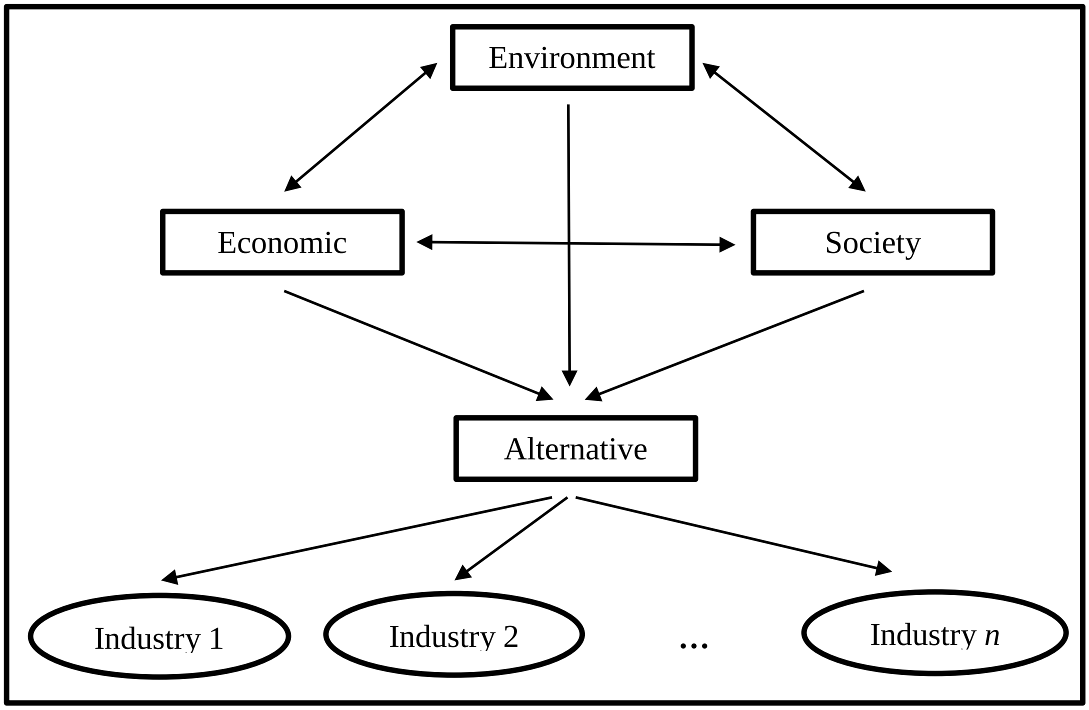

Figure 6.2. FANP Model 4 based on Types of Manufacturing Industries

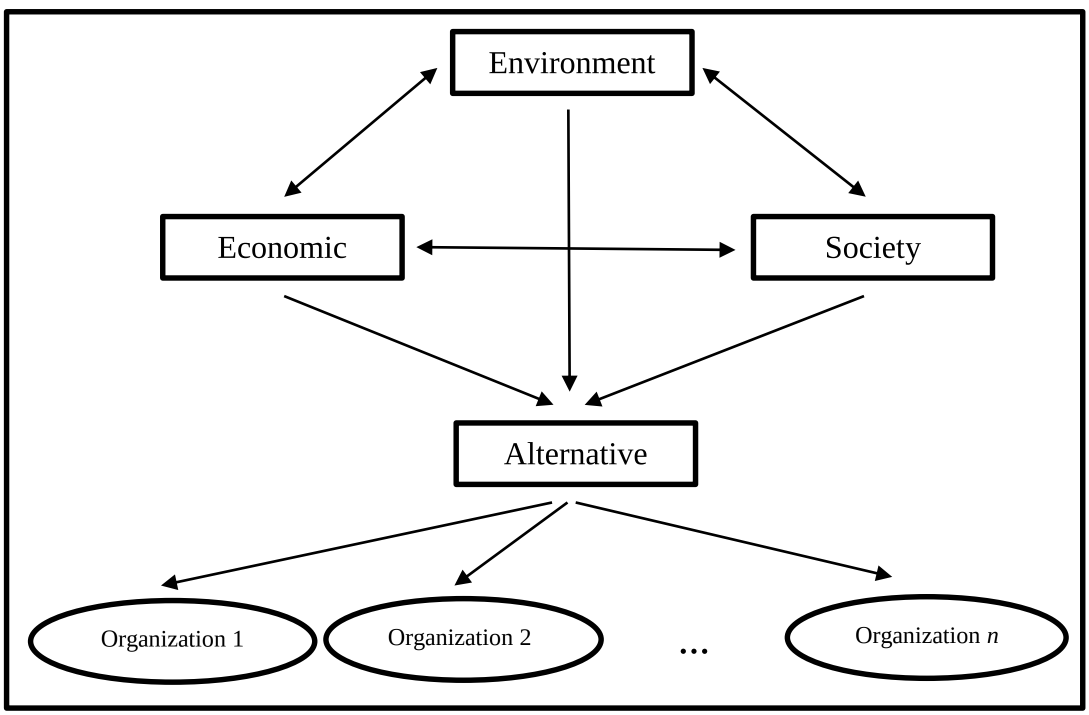

Figure 6.3. FANP Model 5 based on Types of Organization

3. The employment of Delphi or focus group interview methods to reestablish the rules in knowledge base. Deplhi method is a widely used method for gathering data from respondents within their domain of expertise by using a set of open-ended questionnaire for a specific issue (Hsu & Sandford, 2007; Linstone & Turoff, 2011). On the other hand, focus group interview involves the use of in-depth group interviews in which participants from various background are selected based on the expertise for a given topic (Brief & Problem, 2004; Morgan, 2002). Both methods are designed as a group communication process, which aims to achieve a convergence of opinion on a specific real-world issue. In the future, the researcher intends to implement these methods with the GRI representatives to further validate the KBFANP model.
4. The KBFANP model can be reestablished by the assimilation with other methods in any of the Knowledge Base levels as shown in Figure 6.4. The assimilation is an attempt to extend the model by generalizing it for a wider implementation.

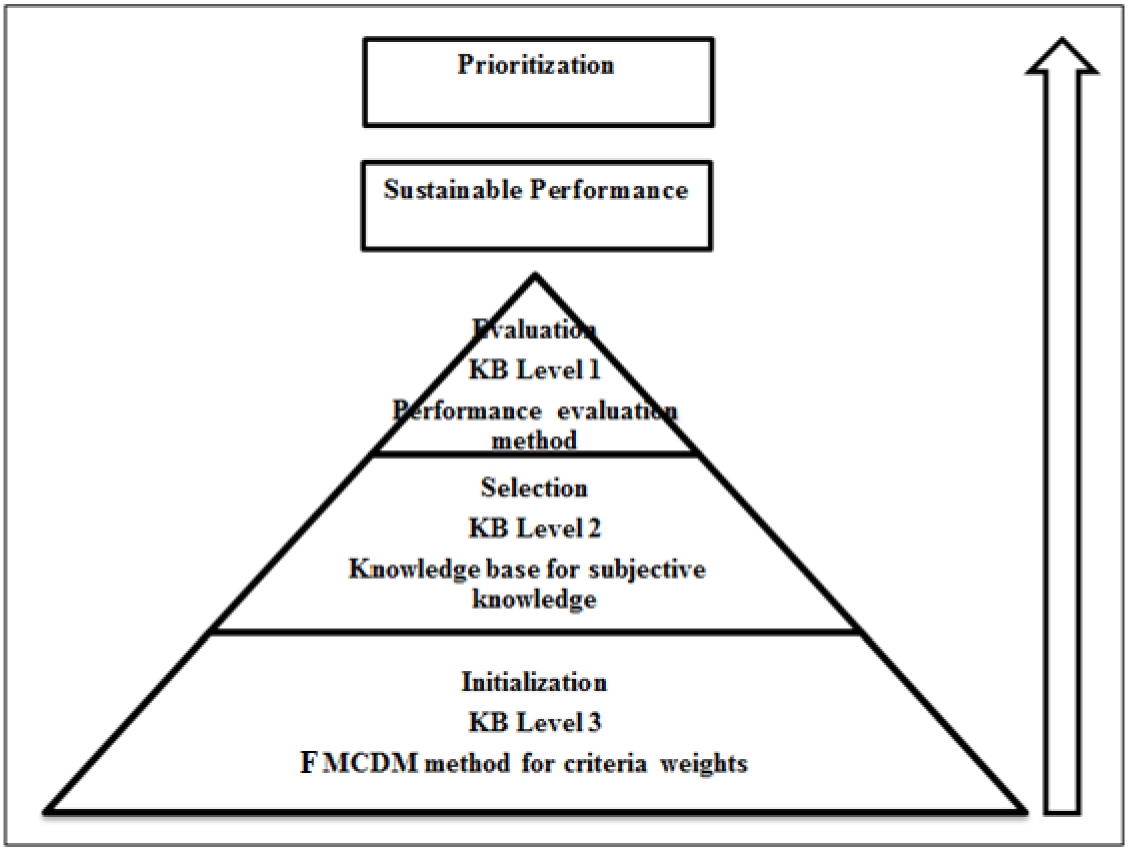

Figure 6.4. KBFANP Model Generalization

The generalization of the KBFANP model is intended to explore other alternative methods to solve any indicator model regardless of problem. This shows that the KBFANP model is more flexible than the researcher previously imagined. Table 6.2 lists the potential methods that can be utilized at each level of the model.

Table 6.2.

List of Suggested Method for each Knowledge Base level

Knowledge Base Level	**Methods**
Initialization	1. AHP 2. TOPSIS 3. Outranking (ELECTRE, PROMETHEE) 4. Other FMCDM methods
Selection	5. Delphi 6. Focus group 7. Decision tree 8. Heuristic classification 9. Conceptual mapping 10. Other knowledge acquisition methods
Evaluation	11. DEA 12. Balance scorecard 13. SWOT analysis 14. Other performance evaluation methods

6.5 Conclusion

The overall aim of this research was to develop a Knowledge Based Fuzzy Analytic Network Process System (KBFANP) system which can assist in the decision making process of sustainable manufacturing by the development of sustainable manufacturing indicators. This thesis resolved this subject, and it is hoped that it can be used as a guide, with significant novel contribution is made to all parties especially to the Decision Science/Operation Research field, the manufacturing industry and last but not least, the reader.

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