ANALYSIS OF ENERGY EFFICIENT SUSTAINABLE MANUFACTURING SYSTEMS

THESIS

submitted in fulfillment of the requirement of the degree of

DOCTOR OF PHILOSOPHY

J. C. BOSE UNIVERSITY OF SCIENCE & TECHNOLOGY, YMCA

by

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APRIL 2021

CANDIDATE'S DECLARATION

I hereby declare that this thesis entitled **"ANALYSIS OF ENERGY EFFICIENT SUSTAINABLE MANUFACTURING SYSTEMS"** *by* **SUBRATA KUMAR PATRA** being submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in DEPARTMENT OF MECHANICAL ENGINEERING under Faculty of Engineering and Technology of J.C. Bose University of Science and Technology, YMCA Faridabad, during the academic year 2019-2020, is a bonafide record of my original work carried out under guidance and supervision of **Dr. TILAK RAJ, PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING, JCBUST, YMCA FARIDABAD** and **Dr. B. B. ARORA, PROFESSOR, DEPARTMENT OF MECHANICAL ENGINEERING, DELHI TECHNOLOGICAL UNIVERSITY, BAWANA ROAD, ROHINI, DELHI** has not been presented elsewhere.

I further declare that the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

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CERTIFICATE OF THE SUPERVISORS

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We further declare that to the best of our knowledge; the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

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ABSTRACT

Exponential rise in world's population has resulted in increased demand for various goods and products. In order to meet the growing demand, rapid industrialization is inevitable. A plethora of raw materials extracted from natural environment are used as input to produce finished goods. The resources on earth are fast depleting. Apart from resource depletion, the escalating environmental degradation as a result of rapid automation is a matter of grave concern. The mounting issues such as climate change, global warming, ozone depletion, generation of hazardous waste especially e-waste, emission of poisonous gases, depletion of natural resources including energy resources, as a result of rapid industrialization is already threatening the very survival of the humanity on this planet.

Manufacturing industries are experiencing a multitude of challenges including global competition, increased customer expectations, government regulations, lack of skilled manpower, resources, capital, technologies and so on. Manufacturers need to upgrade technologies, formulate new strategies and initiate a number of steps to tackle many of these challenges. An extensive study of manufacturing systems and practices with the focus to align manufacturing operations towards improving their efficiency, sustainability, productivity etc. are therefore essential.

The present research is aimed towards the implementation of energy efficient sustainable manufacturing systems. The study draws inputs from academia and industry in order to frame strategic framework for Sustainable Manufacturing System (SMS). Resource conservation, manufacturing efficiency, use of alternate energy in manufacturing etc. are vital for the progress of SMS. This work focuses on various issues of manufacturing with the aim to enhance the manufacturing sustainability. An extensive literature survey of various manufacturing practices was carried out and experts' opinion were sought to identify various enablers and barriers linked to SMS. A questionnaire-based survey was developed to identify various challenges and critical success factors (enablers), barriers of manufacturing systems from sustainability viewpoint. A systematic and comprehensive assessment had been carried out by incorporating these factors towards the development of SMS. Various Multi-criteria Decision Making (MCDM) techniques have been used for the present analysis. Risk mitigation model for SMS has been developed by incorporating the barriers using Interpretive Structural Modeling (ISM) technique. Various barriers have been categorized and mathematical modeling done by using Graph Theoretic

Approach (GTA). AHP methodology has been used for the selection of best manufacturing system among selected alternatives in Indian manufacturing context. The survey data has been validated using Analysis of Variance (ANOVA) technique. An AHP and R^3I (Relative Reliability Risk Index) based combined methodology has been used for the analysis of critical success factors towards SMS. The study will help in addressing various issues and challenges towards enhancing the sustainability of manufacturing systems. The insights obtained from the modeling and analysis will help the management in formulating suitable strategies for the smooth transition towards SMS.

Keywords: *SD; sustainable development; sustainability; SMS; sustainable manufacturing system; traditional manufacturing; barriers; ISM; interpretive structural modeling; transitivity; GTA; graph theoretic approach; AHP; analytic hierarchy process; ANOVA; analysis of variance;* R^3I *(Relative Reliability Risk Index)*

TABLE OF CONTENTS

LIST OF FIGURES/GRAPHS

LIST OF TABLES

LIST OF ABBREVIATIONS

SL. NO.	ABBREVIATION	MEANING
1.	ANOVA	Analysis of Variance
2.	AHP	Analytical Hierarchy Process
3.	AMHS	Automated Material Handling Systems
4.	CIP	Capital Improvement Plan
5.	CMS	Cellular Manufacturing system
6.	CI	Consistency Index
7.	CR	Consistency Ratio
8.	CSR	Corporate Social Responsibility
9.	CSF	Critical Success Factors
10.	DFE	Design for Environment
11.	EV	Electric Vehicles
12.	EMS	Environmental Management System
13.	ECM	Environmentally Conscious Manufacturing
14.	ECMPRO	Environmentally Conscious Manufacturing and Product Recovery
15.	FMS	Flexible Manufacturing System
16.	GTA	Graph Theoretic Approach
17.	GM	Green Manufacturing
18.	GHG	Greenhouse Gas
19.	IT	Information Technology
20.	IOB	Intensity of Barrier
21.	ISM	Interpretive Structural Modeling
22.	KM	Knowledge Management
23.	LM	Lean Manufacturing
24.	LCA	Life Cycle Analysis
25.	MICMAC	Cross-Impact Matrix Multiplication Applied to Classification

SL. NO.	ABBREVIATION	MEANING
26.	MCDM	Multi Criteria Decision Making
27.	OEM	Original Equipment Manufacturers
28.	RM	Reachability Matrix
29.	RMT	Reconfigurable Machine Tools
30.	RMS	Reconfigurable Manufacturing System
31.	3-R’s	Reduce, Reuse and Recycle
32.	6-R’s	Reduce, Reuse, Recycle, Redesign, Recover, Remanufacture
33.	R^3I	Relative Reliability Risk Index
34.	R&D	Research and Development
35.	ROHS	Restriction of the use of Hazardous Substances
36.	ROI	Return on Investment
37.	SRB	Socially Responsible Business
38.	SRM	Socially Responsible Manufacturing
39.	SSIM	Structural Self-Interaction Matrix
40.	SCM	Supply Chain Management
41.	SD	Sustainable Development
42.	SDGs	Sustainable Development Goals
43.	SM	Sustainable Manufacturing
44.	SMS	Sustainable Manufacturing System
45.	TPM	Total Preventive Maintenance
46.	TQM	Total Quality Management
47.	TPS	Toyota Production System
48.	TM	Traditional Manufacturing
49.	UN	United Nations
50.	VPF	Variable Permanent Function
51.	WM	Waste Management
52.	WIP	Work in Process

CHAPTER I

INTRODUCTION

1.1 BACKGROUND

With the exponential rise in world's population, the need for variety of goods and products are also rising steadily. These goods and products are manufactured in industries using several natural resources. To cope with the rising demand, rapid industrialization is the need of the hour. Resources on earth are fast depleting due to rapid industrialization. Apart from resource depletion, the escalating environmental problems as a result of rapid automation is a matter of grave concern. Issues such as climate change, global warming, ozone depletion, generation of hazardous waste specially e-waste, emission of poisonous gases, depletion of natural resources including energy resources are already threatening the very survival of humanity.

Hutchinson (2014) cited that manufacturing helps to convert design concepts into tangible products using raw materials, energy and manpower. Any manufacturing process involves men, machine and raw materials coupled with appropriate work environment. Raw materials are converted into various kind of goods and products through the adoption of suitable technologies. Prominent industries contributing to environmental degradation are: Steel, aluminum, automobile, petrochemicals, chemical, aerospace, heavy machinery, IT, textile, footwear, building and construction, furniture, pharmaceutical, cement, polymer, printing industry etc.

Manufacturing organizations employ various resources viz. economic, human, natural and information resources to carry out their operations (Rosen and Kishawy, 2012).

From this chapter, following paper has been published:

1. Patra, S. K., Raj, T., & Arora, B. B. (2015). Sustainability issues in energy efficient manufacturing systems - A review. *International Journal of Engineering & Manufacturing Science, 5(1),* 1 - 8.

A manufacturing system transforms inputs into a range of value-added products (output) under suitable environment. Figure 1.1 represents a typical manufacturing process.

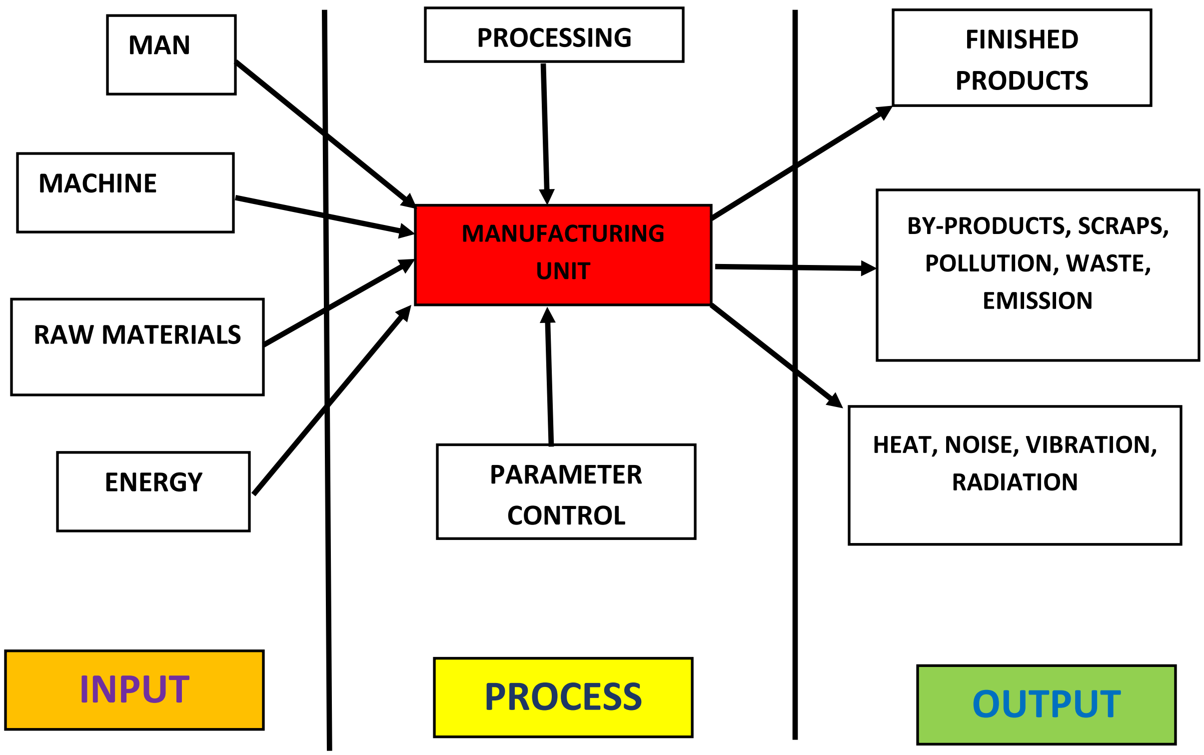

Figure 1.1: A typical manufacturing process

Traditional manufacturing processes give rise to numerous wastes, emission or harmful by-products that tend to degrade the natural environment. A critical focus on manufacturing systems and practices are therefore essential to address many of these issues. Emerging trends of globalization and environmental concerns have forced organizations to revamp and redesign their manufacturing systems (Shankar et al., 2017). An extensive study of the manufacturing systems and practices with the aim to align manufacturing operations towards improving their efficiency, sustainability, productivity etc. is therefore urgently required. Manufacturing processes have gone through a revolutionary change over the years for reasons attributable to the followings:

- Increasing global competition
- Stringent environmental regulations
- Changes in customer aspirations
- Focus on resource conservation

- Minimization of waste
- Need for operational flexibility etc.

With the growing customer awareness for eco-friendly products, manufacturers are under increasing pressure to redesign and innovate their manufacturing practices through the adoption of strategic planning and infusing sustainability concepts in their manufacturing practices. Adopting sustainable manufacturing practices are essential for long term sustainable development. Rashid (2017) considered sustainable manufacturing practices as significant initiatives towards the protection of environment apart from improving the quality of life.

Warner (2018) emphasized that manufacturing sectors play key role towards the creation of such products that can conserve energy and natural resources and can minimize the negative environmental impact. Adoption of sustainable practices is stated as vital for the firms to reduce greenhouse gas emissions, enhancement of brand image, building confidence among customers, investors and regulators, competitive advantage etc. He suggested five strategies for the adoption of sustainable manufacturing practices. These are elucidated below:

i. Evaluation and optimization of fossil fuel used:

It is essential to assess firm’s energy consumption and to conduct regular audits to improve their energy efficiency. Identification of loopholes in the production process and optimization of fuel use can reduce manufacturing cost as well as help to abate negative effects on the environment.

ii. Implementation of waste management practices:

Industrial waste comprises of various hazardous and non-hazardous by-products. Improper waste treatment can cause toxic substances and chemicals to get mixed to the clean environment, thus causing lasting damage to the environment. Sustainable manufacturing practices are vital for effective waste management and recycling practices thus causing improvement in operational efficiency and minimizing the environmental footprint.

iii. Use of energy-efficient equipment:

Energy efficiency is the efficient conversion and use of energy. Energy efficient devices and practices consume less energy for the same task or function. A fluorescent bulb is more energy efficient as compared to an incandescent bulb of same wattage. Energy conservation is the saving of energy by means of energy efficient devices or processes or by reducing the waste of energy by simply turning off electrical appliances when not in use. Replacement of old and inefficient equipment or components with energy-efficient ones can improve energy efficiency. All such practices are can reduce the operating costs, conserve natural resources, minimize carbon footprint etc., that are vital towards the adoption of sustainable manufacturing system.

iv. Switchover to renewable sources of energy:

Switching to renewable sources of energy (solar, wind, water) can enable manufacturers in minimizing their dependence on fossil fuel, boosting profitability, enhancing their corporate image and are important towards the progress of sustainable manufacturing practices.

v. Employ pollution-prevention strategies:

Employing pollution-prevention strategies can save considerable amount of waste, energy, time and money thus enabling to foster a sustainable future. Companies promoting sustainable methods of production can greatly contribute to a healthy environment.

1.2 CLASSIFICATION OF MANUFACTURING SYSTEMS

Manufacturing sectors are the backbone of society. Organizations use tools and processes for the transformation of raw materials into desired products and components. Various inputs in manufacturing systems are: raw materials, machines, tooling, manpower, energy, information etc. Outputs are obtained by using suitable processes and controlling the process parameters. Output may be in the form of various finished or semi-finished products, services to customers, scraps, undesirable waste, noise, heat etc. Manufacturing systems are complex in nature. They can differ in their layout or machines, technologies, processes used.

Based on physical layouts classical manufacturing systems are categorized as: job shop, project shop, flow shop and continuous process shop. Manufacturing systems that are rapidly being accepted in modern industries are cellular manufacturing, flexible manufacturing, lean manufacturing, green manufacturing, sustainable manufacturing etc. These have replaced the traditional manufacturing systems and are the preferred choice in modern industries. Various manufacturing systems are represented in Figure 1.2.

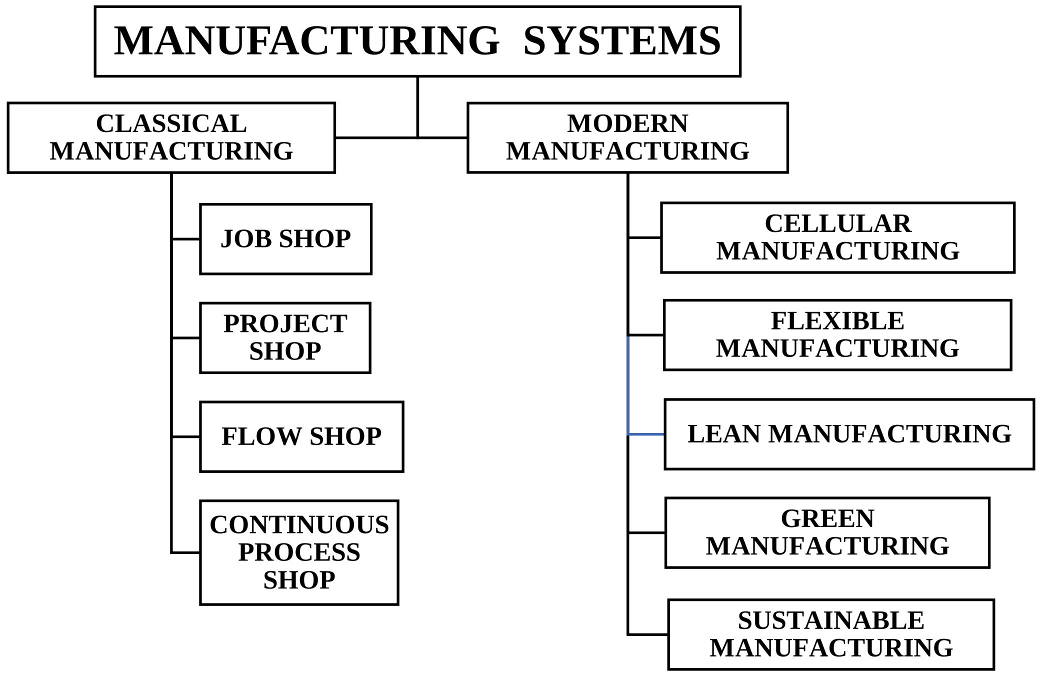

Figure 1.2: Various manufacturing systems

Manufacturers are under compulsion from the government and the society to maintain a clean, safe and healthy environment. Important steps to attain the goal of sustainability are:

i. Adoption of clean, efficient technologies
ii. Alternative materials and improved design
iii. Macro, micro and nano manufacturing technologies
iv. Near-net shape forming technology, digital technology
v. Research and development for new and innovative materials and technologies
vi. Development of energy efficient and emission reduction technologies
vii. Efficient use of natural resources and recycling practices.

1.3 SUSTAINABLE DEVELOPMENT, SUSTAINABILITY AND SUSTAINABLE MANUFACTURING

The United Nations organized a conference on environment and development with a focus on sustainable development at Rio De Janeiro in 1992. The summit was considered as a pioneering international attempt to promote sustainable development. It was universally accepted that sustainable development is the solution to the problems of environmental degradation as enunciated by the Brundtland Commission in its 1987 report.

Subsequently, the world summit on sustainable development was held in Johannesburg in 2002 that was attended by many countries, UN organizations, global financial institutions and other groups to take stock of the progress in this direction since the Rio summit. Key outcomes of this summit are listed as under:

- A political declaration
- The Johannesburg plan of implementation
- A range of partnership initiatives.

Key commitments included those on sustainable consumption and production, water, sanitation and energy. The most frequently quoted definition of sustainable development from 'Our common future' (the Brundtland report) is "Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Sustainable development goals (SDGs) are global agenda that address global challenges so as to achieve a more sustainable future for all. These relate to poverty, inequality, climate change, environmental degradation, prosperity, peace and justice.

Sustainability is synonymous with sustainable development. Sustainability is the study of how natural systems function, remain diverse and produce everything it needs for the ecology to remain in balance. Sustainability focuses on how the people of this earth can live in harmony with their surroundings while protecting it from any kind of damage or destruction. Sustainability is aimed at maintaining natural or man-made processes indefinitely without degrading or endangering natural biotic systems. Sustainability is aimed towards improving the quality of human life within the carrying capacity of earth's ecosystem. Environment, economy and society are the three pillars of sustainability.

Environmental sustainability refers to the ability of ecosystem to balance the human consumption of natural resources so that the resources can replenish themselves. It ensures that various natural resources such as raw materials, fuel, water, land etc. are utilized or consumed in a sustainable manner. Economic sustainability ensures that businesses use resources efficiently and in a sustainable manner to consistently generate profits. Social sustainability refers to the ability of society to relentlessly achieve social well-being. Social sustainability ensures that people have access for various resources and amenities to keep them healthy and happy.

From manufacturing point of view, sustainability reflects the objectives of manufacturing organizations to formulate suitable strategies and operations in order to grow and to remain globally competitive.

Westkamper et al. (2001) suggested five typical drivers for sustainability. These are:

(i) The shortages of natural resources
(ii) The dramatic increase of world population
(iii) Global warming
(iv) Pollution
(v) An unstoppable global economy

Sustainable development goals set by UN in 2015 considered sustainable manufacturing as one of the key aspects toward sustainable development. Although manufacturing activities are likely to cause several negative impacts on the environment, it essentially creates job opportunities apart from meeting the societal needs for food, shelter, comfort, healthcare etc.

Kopac (2009) discussed various benefits achievable through sustainable machining. These are: enhanced environment friendliness, reduced cost, reduced power consumption, reduced waste, effective waste management, enhanced operational safety, improved personnel health.

The role of manufacturing sectors through the adoption of sustainable work practices can be helpful towards the conservation of resources, control of waste, pollution, use of renewable energy and the like. Sustainable manufacturing thus is crucial towards addressing many of the burning global challenges that are vital for sustainable development worldwide.

Sustainable manufacturing results in the creation of manufactured products using economically sound processes that minimize negative environmental impacts, conserves natural resources and energy and also enhances safety of employees, community and consumers. With the growing concern for environmental protection and customers' demand for eco-friendly products, manufacturers are bound to reinvent their manufacturing systems. This can be made possible through the adoption of strategic planning and infusing sustainability concepts in their manufacturing practices.

1.3.1 Evolution of sustainable manufacturing

The early work on sustainable manufacturing was labelled as environmentally conscious manufacturing (ECM). It has considerations for source reduction, design for manufacturing and assembly, dismantling and cradle-to-reincarnation concepts (Owen, 1993). Later on, Sarkis identified product, process and technology as three dimensions towards ECM strategies. These strategies constitute the famous R's namely reduction, remanufacturing, recycling and reuse (Sarkis, 1995; Sarkis and Rasheed, 1995).

Manufacturing has evolved through several generations namely traditional manufacturing, lean manufacturing, green manufacturing and the most developed sustainable manufacturing phase. Figure 1.3 represents the same.

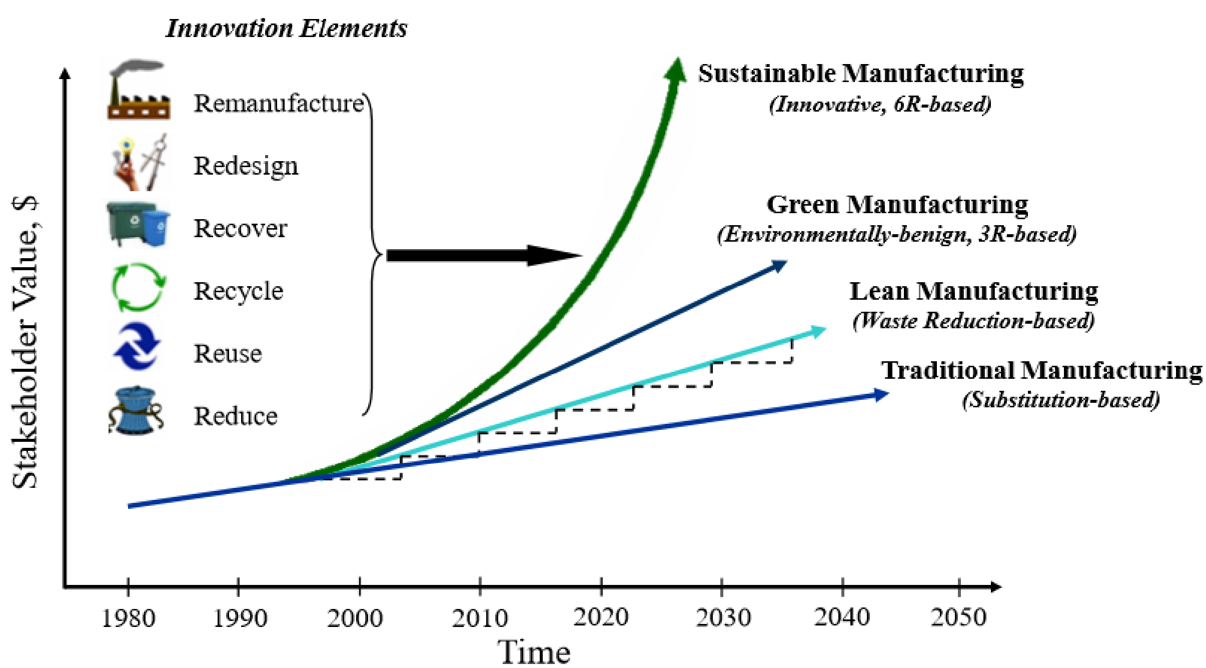

Figure 1.3: Evolution of sustainable manufacturing

(Source: http://www.ncsl.org/Portals)

Three significant phases towards developing sustainability-based models are:

i. Research- It supports in the development, evaluation and examination of the specific sustainability requirements like use of energy and resources, impact of pollution, climate change etc.

ii. Development- Appropriate methods and tools help to improve the environmental performance like life cycle analysis (LCA), environmental footprint assessment, design for environment (DFE) etc.

iii. Commercialization- Refinement of earlier phases and cooperation with suppliers, retailers and customers.

1.3.2 Metrics for Sustainable Manufacturing

Various ‘metrics’ can be used as quantitative assessment to measure, evaluate or compare performance of any system under consideration. Metrics are typically used by the management or analysts to review performance assessment or progress towards successful business.

Dreher et al. (2009) carried out a report on sustainable manufacturing metrics in General Motors. The report proposes five criteria that the metrics must address. These are:

- Need of the stakeholders
- Enablers for innovation and growth
- Harmony among manufacturing units of different locations
- Compatibility with current value adding business systems
- Compatibility with the related measurement needs.

Jawahir et al. (2006) emphasized that sustainable manufacturing metrics provides better decision-making criteria for optimizing process and system designs.

According to Haapala et al. (2011) metrics are necessary for the evaluation of performance in manufacturing systems from sustainability perspective. For pursuing sustainability, the interactions among the three pillars of sustainability must be analyzed. They discussed that environmental issues like release of toxic chemicals, energy consumption and carbon footprint are getting increasing attention in recent past. A variety of metrics e.g., cost, profit, cost per unit etc. are used as metrics for assessing the economic pillar of sustainability. The social pillar of sustainability has however got less attention because social aspects are typically subjective in nature and requires qualitative evaluation rather than quantitative ones.

Jawahir and Dillon (2007) proposed six major elements that significantly affect the sustainability of manufacturing processes. These are:

(i) Manufacturing cost
(ii) Energy consumption
(iii) Waste management
(iv) Environmental impact
(v) Personnel health
(vi) Operator safety.

1.4 MERITS OF SUSTAINABLE MANUFACTURING

While traditional manufacturing prioritizes on cost-effectiveness and increased profit with little concern towards environmental impact, sustainable manufacturing promotes resource conservation and reduction of waste. Sustainable manufacturing (SM) aims at creating products that have minimal negative influences on the environment. By adopting sustainable practices, it is possible to create environment friendly products that are safe and non-hazardous during their useful life period and beyond that. Integrating sustainable manufacturing in business can improve resource productivity along-with environmental and financial benefits for short as well as long-term. Moreover, such practices can establish a safe work environment for the society and employees as well. Because of several benefits, more and more industries (small to large scale) are espousing sustainable business practices in their policy and operations to succeed in their growth and global competitiveness.

There exist several benefits which motivates manufacturers to pursue sustainability. These are:

a) Compliance to regulations and regulatory guidelines
b) Competitive advantage through closer interaction with customers
c) Long-term viability and success of business
d) Improved operational efficiency through cost reduction and elimination of waste
e) Promotion of company's goodwill, reputation and building of public trust.

A shift towards sustainability can boost the company's image and its brand name. Socially responsible business can earn more profits using less resources, adopting energy efficient technologies, creating innovative products, controlling waste, emission, pollution etc. Companies adopting sustainable practices are also eligible for tax incentives that serve as incentives for them.

1.5 CHALLENGES IN SUSTAINABLE MANUFACTURING

Natural resources are limited. With the population explosion, the demand for customer goods and other products are increasing at a fast pace. Manufacturing industries are under growing challenges as a result of global competition, increased customer expectations, government regulations, lack of skilled manpower, resources, capital, technologies and so on. Manufacturers need to upgrade technologies, formulate new strategies and to initiate appropriate steps to tackle many of these challenges. Judicial use of resources and incorporating sustainability concepts in manufacturing are vital for achieving the goals of 'sustainability'. Sustainability issues in manufacturing can encompass various aspects such as environmental, economic and social considerations.

Garetti and Taisch (2012) suggested that manufacturing is crucial for modern civilized world and for establishing a sustainable future. They viewed that industries face several constraints and challenges to implement sustainability. They further highlighted the importance of innovative technologies and research and development to offer appropriate solutions in this direction.

Various challenges towards the adoption of sustainable manufacturing systems (SMS) are:

- Lack of innovative technologies
- Lack of research and knowledge to effectively implement SMS
- Fear of risk and failure in adopting SMS
- Lack of willingness of the management towards investment decisions in adopting SMS
- Lack of capital, financial incentives towards implementing SMS
- Lack of government support etc.

1.6 MOTIVATION FOR THE CURRENT RESEARCH

Current manufacturing practices are based on traditional cost/profit models that are primarily focused on making high quality products without much attention on sustainability issues. In view of mounting environmental and other issues associated with traditional manufacturing practices, it is imperative to re-invent traditional manufacturing practices aligned towards environmental, economic and social dimensions of sustainability. In order to comply with environmental legislations, new guidelines or standards, customer aspirations, societal requirement etc., manufacturers have to opt sustainable practices. Economic motivation for cost reduction, financial and other incentives offered by government for the adoption of eco-friendly practices are encouraging manufacturers to incorporate sustainability in their corporate strategy and business ethics. Sustainable business practices create business excellence through economic gain, healthy work environment, conservation of resources, development of strong community etc. Survey of literatures and experts' opinion reveal that many organizations are not keen to go for SMS because of following reasons:

i. Initial investment cost for adopting sustainable manufacturing system is quite high
ii. Industries have doubt about the rate of return on their huge investment
iii. Customers are not keen to spend more money for products made by sustainable practices

The concept of sustainability in the design of SMS are widely accepted in theory and principle; but its implementation in current manufacturing set-ups is abysmally low because of the challenges faced by the manufacturers. The current research endeavors have to find appropriate solutions for these challenges through systematic analysis of existing systems from sustainability point of view. Such research will aid in the transformation of traditional manufacturing systems into sustainable one. All the above reckonings are ample ground to carry-out the current research.

1.7 OBJECTIVES OF RESEARCH

The present research is intended to enable the transformation of existing manufacturing systems into an energy efficient sustainable manufacturing system. The study commences with the review of literatures on ‘sustainable manufacturing’. Various elements that affect the development of SMS are also identified. The main objectives of this research are enunciated as under:

(i) To study current manufacturing practices and to identify challenges towards the development of sustainable manufacturing

(ii) To recognize important barriers towards sustainable manufacturing system (SMS)

(iii) Development of relationships among the barriers and formulation of interpretive structural modeling (ISM)

(iv) Quantitative analysis of barriers using graph theoretic approach (GTA)

(v) To identify critical success factors for SMS and their analysis using analytic hierarchy process (AHP) and relative reliability risk index (R^3I)

(vi) To identify best manufacturing system among alternatives using AHP methodology.

1.8 RESEARCH METHODOLOGY

Any manufacturing system consists of several tangible and intangible parameters that can vary from industry to industry based on products, location of plant, adopted technology, process used etc. Literature review suggests that many of the environmental, economic, social or other issues due to non-sustainable manufacturing practices can be resolved through a detailed and structured analysis of the system. Salient features of the present research are:

- Review of current manufacturing practices: A study of diverse manufacturing systems to analyze the prevailing manufacturing practices

- Identification of various elements in sustainable manufacturing system: Various enablers and barriers are identified from environmental, economic, social and other important dimensions
- ISM modelling of barriers towards SMS: Based on mutual relationships among the identified barriers, an ISM based hierarchical model is developed. Their driving/dependence power are also evaluated
- Quantitative analysis of barriers: GTA analysis is done for the evaluation of various barriers integral to the system for the development of SMS in numerical terms
- Analysis of critical success factors: A combined methodology using AHP and R^3I techniques are employed for the analysis of enablers for SMS
- Selection of best manufacturing system: An AHP based methodology is used for the selection of best manufacturing system among alternatives in Indian context.

The proposed framework for the analysis is shown in Figure 1.4.

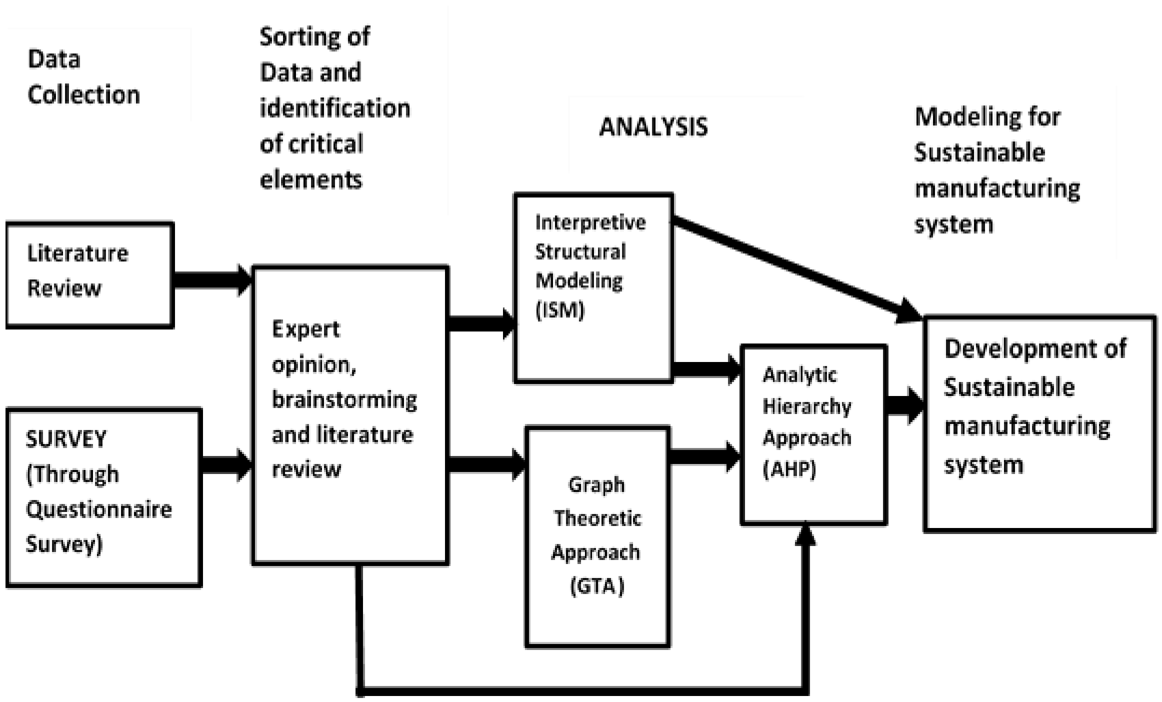

Figure 1.4: Integrated framework using ISM, GTA and AHP methodology

It comprises of the followings:

a) Stage I: Collection of Data

The current research employs primary and secondary data for the analysis. The primary data are collected from questionnaire-based survey involving industry personnel. Secondary data are obtained from literatures on various issues related to sustainable manufacturing.

The questionnaire survey approach is an established method to know the respondent's perception related to research problems. This approach is therefore used to get broad insights towards the development of SMS. The questionnaire is prepared in consultation with a panel of experts consisting of academicians and industry experts. The questionnaire gives due weights to environmental, social, economic, technological and other issues. Responses obtained from the survey are compiled for further analysis.

b) Stage II: Sorting of data and identification of critical elements

From the questionnaire-based survey data, enablers and barriers that are critical for the transition towards SMS have been segregated. These are further categorized in environmental, social, economic and other aspects of sustainability for further analysis.

c) Stage III: Analysis

In this stage ISM, GTA and AHP techniques have been primarily used. ISM technique is used to systematically analyze the barriers. Driving power and dependence power of barriers are recognized through ISM and MICMAC analysis.

Mathematical analysis of various barriers is done using GTA technique. The intensity of barriers can predict the difficulty in adopting sustainable manufacturing system. The outcome of ISM and GTA analysis are vital for the managers willing to promote SMS. The selected enablers are analyzed using AHP and R_3I techniques.

d) Stage IV: Modelling for SMS

Based on the ISM analysis, an ISM model is developed incorporating the barriers. The ISM hierarchy portrays the relationships among the barriers. GTA is used for evaluation of intensity of barriers in numerical terms. AHP helps to determine the best manufacturing system in Indian manufacturing context.

1.9 ORGANIZATION OF THE THESIS

The thesis consists of nine chapters. A brief description of the same is given below:

Chapter I: INTRODUCTION

This chapter includes background, various manufacturing systems, description of important terminologies, evolution of sustainable manufacturing, merits and challenges in sustainable manufacturing, motivation for the research, research objectives, methodology adopted, organization of the thesis, summary and conclusions.

Chapter II: LITERATURE REVIEW

This chapter provides introduction, current status of research on various issues, gaps in literatures, methodologies used in the present analysis. It also gives brief description on various SMS issues, benefits in implementing SMS, problems associated in the implementation of SMS etc.

Chapter III: DEVELOPMENT AND ADMINISTRATION OF QUESTIONNAIRE

This chapter deals with the development of questionnaire on various issues of sustainable manufacturing, administration of questionnaire, survey response and observations obtained thereof. The survey also sought data on general parameters like the number of employees, turnover of the organization, number of production shops in the organization, variety of components manufactured etc. This chapter provides an overview of analysis of variance (ANOVA) and the methodology adopted for the validation. The survey data has been verified at different significant levels by using ANOVA analysis.

Chapter IV: INTERPRETIVE STRUCTURAL MODELING FOR MITIGATING BARRIERS TOWARDS SMS

This chapter contributes towards the development of an ISM model for mitigating barriers. It encompasses various barriers of SMS, discussion of ISM methodology, development of ISM model for SMS, MICMAC analysis and important conclusions from the analysis.

Chapter V: QUANTITATIVE ANALYSIS OF VARIOUS BARRIERS USING GTA

This chapter provides an analysis of various categories of barriers using graph theoretic approach. It covers various barriers and their categorization, analysis of barriers through the development of digraphs, matrix representation, variable permanent function (VPF) representation, determination of intensity of barriers (IOB’s) by evaluating permanent value of VPF, result, discussion and important conclusions.

Chapter VI: ANALYSIS OF CRITICAL SUCCESS FACTORS FOR SMS USING AHP AND R^3I BASED METHODOLOGY

This chapter provides a critical examination of various enablers for the development towards SMS. A combined methodology based on AHP and R^3I techniques have been used for the analysis. This chapter encompasses the overview of these methodologies, analysis of critical success factors for SMS, comparative analysis of the results and the conclusion.

Chapter VII: AN AHP ANALYSIS FOR THE SELECTION OF BEST MANUFACTURING SYSTEM IN INDIAN MANUFACTURING CONTEXT

This chapter is dedicated towards the selection of best manufacturing system out of alternatives in context with Indian manufacturing industries. The analysis is done by using AHP methodology. It describes alternative manufacturing systems namely traditional manufacturing (TM), lean manufacturing (LM), green manufacturing (GM) and sustainable manufacturing (SM). Various steps of AHP methodology, attributes and sub-attributes in alternative manufacturing systems, AHP analysis for the evaluation of suitability index for alternative manufacturing systems are also discussed in this chapter.

Chapter VIII: SYNTHESIS OF THE RESEARCH WORK

This chapter present a comprehensive picture of different studies and analysis done in previous chapters. It also establishes a linkage among all the studies done in this work.

Chapter IX: SUMMARY, KEY FINDINGS, IMPLICATIONS AND SCOPE FOR FUTURE RESEARCH

This chapter presents the summary of the research, major contribution of this research, key findings of this research, major implication, limitation and future scope of research and lastly conclusion of the research work.

1.10 SUMMARY

The main focus of this research is to provide systematic analysis of sustainable manufacturing systems. The implementation of SMS is a challenging task especially for developing countries like India due to the presence of several challenges and apprehensions. Various issues, enablers and barriers related to the implementation of SMS are identified through literature review and experts' opinion. ISM technique is used to determine their inter-relationships among the barriers through the development of ISM hierarchy model. GTA evaluates their intensity in numerical values. Critical success factors are analyzed through AHP and R^3I methodology. AHP is used to select the best manufacturing systems out of selected alternatives based on their suitability index.

CHAPTER II
LITERATURE REVIEW

2.1 INTRODUCTION

Manufacturing is the value-added production of commodities for use or sale using labor and machines, tools, chemical and biological processing or formulation. It refers to a wide range of human activities from handicraft to high-tech, but most commonly applied to industrial production, in which raw materials are transformed into finished goods on a large scale. Manufacturing is known as engine for wealth generation and societal well-being for any nation (Jawahir and Bradley, 2016).

Manufacturing operations closely interact with the surrounding natural environment. Apart from growth, productivity and profit generation, environmental aspects are gradually been perceived as important considerations in manufacturing sectors. In order to evaluate manufacturing systems from sustainability point of view and to develop sustainable manufacturing system (SMS), it is essential to review literatures related to various manufacturing practices, sustainability issues in manufacturing, enablers and barriers of SMS, various case studies related to the implementation of SMS etc. In view of several benefits, sustainable manufacturing is the favored choice for the manufacturers across the globe. The following section pronounces various issues and challenges in sustainable manufacturing.

2.2 ISSUES AND CHALLENGES IN SUSTAINABLE MANUFACTURING

There exist several challenges for the development of SMS. Literature review on some of these issues and challenges towards the implementation of SMS are described below:

Kopac (2009) discussed that manufacturing industries are undergoing increasing global competition, stringent environmental regulations and supply-chain demand for improved sustainability performance. He had presented the modelling and optimization of sustainable machining of high temperature alloys (e.g., nickel and titanium alloys) that pose significant difficulty in machining due to their unique thermo-mechanical properties. He evaluated two sustainable machining alternatives namely cryogenic machining and high pressure assisted machining in comparison to conventional machining. The sustainability performance attributes were: environmental impact, energy consumption, safety, personal health, waste management and cost.

Rosen and Kishawy (2012) concluded that manufacturers are gradually shifting their focus towards incorporating sustainability concepts in their manufacturing practices. Achieving sustainability in manufacturing is however a complex and challenging task. Development of sustainable manufacturing system requires a good balance and integration of economic, environmental and societal objectives, related policies and practices.

Jayal et al. (2010) suggested that a holistic approach incorporating appropriate metrics for sustainability evaluation, modelling and optimization at product, process and system level might help in promoting SMS.

Kleindorfer et al. (2005) highlighted that operations management researchers and practitioners are facing new challenges in integrating issues of sustainability with their traditional areas of interest. They made a review on various "sustainability" themes and highlighted future research challenges in sustainable operations management.

Manojlovic et al. (2011) discussed that the need for implementation of sustainable development principles has increased manifold especially due to stringent requirements for efficient utilization of energy resources within the transport industry. He had carried out a study on public procurement procedures for fleet renewal regarding the road vehicles' operational lifecycle costs. He assessed the influence of specific parameters on the operational lifecycle costs especially energy costs. The analysis comprised the costs for vehicle ownership, energy, carbon dioxide and pollutant emissions. He concluded that the implementation of sustainable principles will allow for energy efficient vehicles and vehicles with notable positive environmental impacts.

Bi (2011) mentioned that a system paradigm is an abstract representation of a system that includes system architecture used to determine the types and numbers of components and their relations in the system.

A lot of researchers have done studies on various aspects of manufacturing. They have highlighted the need for sustainability-based manufacturing practices. Literature review on sustainability and related issues reveal the benefits of adopting SMS. It also divulges current manufacturing practices, various enablers, associated barriers, challenges in the adoption of sustainable manufacturing practices. Various literatures related to sustainable manufacturing and sustainability issues have been categorized below.

a. Environment related issues
b. Economic issues
c. Social issues
d. Technology related issues
e. Implementation and operational issues

The following section gives brief review on these issues.

2.2.1 Environment related issues

Mohanty (2011) stated that in order to tackle the scarcity of natural resources and conserving the eco-system, the following measures might be helpful:

i. Reduction of the consumption of virgin materials during manufacturing
ii. Increased focus on recycling
iii. Use of waste as resource
iv. Improvement of resource efficiency.

According to Gungor and Gupta (1999) environmentally conscious manufacturing and product recovery (ECMPRO) has become an obligation to the environment and to the society itself, enforced primarily by governmental regulations and customer perspective on environmental issues. They had presented the development of research in ECMPRO and provided a state-of-the-art survey of published work.

Miller et al. (2010) carried out a study in a small furniture manufacturing unit. They studied integrated lean tools and sustainability concepts to make a positive impact on the environment, society and economic success. They had applied the principles of lean manufacturing in meeting ever-increasing customer demands while preserving valuable resources for future generations.

Field and Sroufe (2007) explored the implications of recycled versus virgin materials. Based on an in-depth case study of a containerboard mini-mill and supplementary interviews with three other mini-mill managers, they proposed their recommendations with regard to the use of recycled materials, supply chain structure, supplier relationships and operations strategy.

Heilala et al. (2008) proposed an integrated simulation tool to maximize production efficiency and balance environmental constraints in the system design phase. They proposed that lean manufacturing, identification and elimination of waste and production losses and environmental considerations are all needed during development of a sustainable manufacturing system.

2.2.2 Economic issues

In view of mounting competitions, manufacturers need to invest as well as invent new technologies, modern machineries and sound manufacturing practices. Mutingi et al. (2017) highlighted that high costs and inadequate funding are the key barriers towards the establishment of sustainable manufacturing systems. According to Ghisetti et al. (2017) financial barriers are detrimental towards environmental innovation investment decisions. They further analyzed important sub-barriers towards meeting cleaner production choices.

2.2.3 Social issues

In order to meet the increasing demand of the world populace, rapid industrialization is essential. An active participation of public, government, industry and all stakeholders are essential for development that will be truly sustainable.

Han et al. (2012) in their pursuit towards sustainable urban future analyzed three major issues. These are: (i) Attainment of a low carbon society (ii) Increased living age and (iii) Enhancement of urban– rural fringe. They proposed various advancements in order to achieve low carbon society. Some of these are hybrid cars, intelligent systems, electric vehicles for transportation, improved design, efficient use of natural materials, energy efficient devices for buildings, innovative manufacturing techniques etc. They also anticipated a compact city with responsive transportation system, more greenness, infrastructure and services to fulfil the needs of the elderly. Conception of eco-industries has also been proposed to enhance job and business opportunities for the urban– rural fringe.

2.2.4 Technology related issues

Zhongde et al. (2012) discussed the importance of manufacturing technologies and allied equipment towards sustainable development. They discussed key roles of new technologies like clean production process, digital manufacturing, development of new materials, near-net shape forming, waste-free manufacturing, remanufacturing, reuse technologies etc. for this purpose. They suggested that technological upgradation will be beneficial for the conservation of resources and building an environment-friendly society.

Chen (2006) conducted a sustainability case study in an engine (Volkswagen Santana-2000) remanufacturing plant at Shanghai. He discussed the significance of technological innovation practices. He observed that remanufacturing an engine saved 113 kWh of electricity apart from reduction of various air emissions (565 kg of CO_2, 6.09 kg of CO, 1.01 kg of nitrogen oxide and 3.985 kg of sulfur oxide). He highlighted that raw material consumption as well as solid-waste generation also reduced significantly.

Morioka et al. (2006) opined that sustainable development is essential for present and future generations, but its attainment is a real challenge. They highlighted the initiatives towards global sustainability primarily through restructuring and reorganization of the existing technological model. In this model industry plays a critical linking between technology and society. They discussed about technology transition to realize sustainability through technology push (supply side), demand pull (demand side) and institutional design. A new model to quantify progress in sustainability has also been suggested.

Dhingra et al. (2010) discussed the myriad applications of nanotechnology. They emphasized the need to conduct LCA based assessments as early as possible during the new product development. Nanomanufacturing are often associated with environmental and human health impacts, which must be critically examined while evaluating nanoproducts for their greenness. Incorporating life-cycle thinking at the product design stage, combining life cycle and risk analysis, adopting sustainable manufacturing practices and employing green chemistry alternatives were perceived as possible solutions to address these issues.

Nowosielski and Spilka (2011) explored the possibility of sustainable development realization through sustainable technological process design and implementation. They had analyzed nickel and chromium coatings on metals. They had presented technical solutions which minimize the influence of galvanic treatment process on the environment by upgrading the process towards sustainability.

Diegel et al. (2010) discussed that the advent of additive manufacturing technologies presented a number of opportunities that had the potential to greatly benefit designers and contribute to the sustainability of products. Additive manufacturing technologies removed many of the manufacturing restrictions that might have led to compromise a designer's ability to make the product they imagined. Products could also be extensively customized by potentially increasing their desirability, pleasure and attachment and therefore their longevity. Evolution of additive manufacturing technologies and the development of new materials and multiple material technologies have the potential to change product design to a great extent.

2.2.5 Implementation and operational issues

Amrina and Yusof (2012) conducted a study in a Malaysian automotive industry. They highlighted the key benefits of sustainable manufacturing concept in the competitive global environment. They however concluded that its implementation on the shop floor is quite low. They studied towards the identification of various elements as sustainable manufacturing initiatives in automotive companies. ‘Establishing company’s image’ and ‘Enhancing market competitiveness’ were perceived as leading motivators for the implementation of sustainable manufacturing initiatives. On the contrary, ‘High cost’ and ‘Lack of understanding and knowledge’ were perceived as major bottlenecks towards the implementation of sustainable manufacturing initiatives.

Rosen and Kishawy (2012) discussed the key importance of integrating sustainability with manufacturing and design. They had presented various tools that might help in incorporating sustainability into design. Some of these are: design for environment, life cycle assessment, design for resources and energy efficiency etc.

Nidumolu et al. (2009) discussed that manufacturers on their journey to sustainability moves through five distinct stages of change. These are: (i) viewing compliance as opportunity (ii) making value chains sustainable (iii) designing sustainable products and services (iv) developing new business models and (v) creating next-practice platforms. They outlined the challenges that each stage entails and the capabilities needed to tackle them.

Kaebernick and Kara (2006) conducted an industry-oriented survey across the world by taking into consideration five key issues viz. product development, strategic issues, manufacturing practices, product recovery and legislation. They revealed the disparities of industries’ approaches towards implementing environmental regulations in their manufacturing operations.

Srinivasan (2011) cited that the European regulation namely restriction of the use of hazardous substances (ROHS) which was implemented in 2006 had profound impact on electrical and electronics industries across the world. They assessed that ROHS had inspired many businesses to adopt sustainable practices due to its several benefits.

2.3 IDENTIFICATION OF VARIOUS BARRIERS OF SMS

Literature review and experts’ opinion revealed various barriers towards the adoption of SMS. These are discussed below:

2.3.1 Poor education and environmental awareness of workmen

Kollmuss and Agyeman (2002) described environmental awareness as ‘knowing of the impact of human behavior on the environment’. All stakeholders need to realize the consequences of environmental damage emanating from uncontrollable manufacturing activities and strive towards development, that will be truly ‘sustainable’.

Lack of consciousness on environmental and sustainable issues can be treated as one of the most important barriers towards the implementation of sustainable manufacturing practices. Appropriate training and education should be imparted to the workmen so as to make them aware of undesirable environmental impacts caused by manufacturing operations. Together, they can play a very important role in developing long term sustainable work practices.

Society, due to lack of environmental awareness and sustainability perception, do not raise their concern to the policy makers for the formulation of stringent guidelines that would force manufacturers to adopt sustainability practices (Kulatunga et al., 2013).

2.3.2 Poor focus on conservation of natural resources

With the rise of population, there is an increasing demand for various goods that are ultimately manufactured using some kind of natural resources. An increasing demand for goods and products worldwide is causing fast depletion of natural resources. Shortage of resources will result in higher price for raw materials - the consumers have to spend more money for the finished goods as well. In long-term consideration, this shortage means life on this earth will be at stake. Under global competition, manufacturers are under constant pressure to deliver goods at the cheapest possible price. This might be possible if manufacturers across the globe innovate appropriate strategies for resource conservation (including energy resources).

According to Koltun (2010) management of natural resources and focus towards reducing the environmental impact as a result of manufacturing activities are crucial. This is so because current style of manufacturing is mostly unsustainable and reason behind many environmental problems.

2.3.3 Lack of top management support

For any kind of business, top management is essentially responsible for framing business policies, setting of goals, standards and for running ethical business. It is perceived that top management support and commitment is essential for implementing a successful business culture and sustainable work practice. An active participation of top management can ensure the implementation of SMS on the shop floor.

Hameed et al. (2014) provided empirical evidence on the influence of top management commitment and stakeholder pressure towards sustainable practices. They viewed that without active participation and commitment of the top management, implementation of SMS in the organization is not at all possible.

2.3.4 Poor motivation and teamwork of the employees

Carley et al. (2014) stated that many successful companies believe that their employees involved with day-to-day manufacturing operations have the finest idea about the incorporation of sustainable practices. A motivated workforce can help in promoting sustainability mission set by the management. Participatory teamwork can promote long-term sustainable development. Organizing various training and awareness programs on environmental issues, involving employees in decision making process and rewarding them for their achievements on sustainable practices are crucial for the promotion and implementation of sustainable goals.

2.3.5 Lack of capital to set up green projects

A majority of manufacturing practices are responsible for environmental degradation in terms of resource depletion, increased pollution or generation of waste. Technological innovation in manufacturing can help in the progress towards SMS. Manufacturers are required to invest huge capital for the adoption of green and sustainable technologies. For many manufacturers, financial constraint act as strong deterrent towards the adoption of sustainable technologies and eco-innovation. According to Ghisetti et al. (2015) 'Finance' is a key lever towards innovation that plays a critical role in defining green economy directions. Lack of capital is thus an important barrier towards the attainment of sustainability in manufacturing.

2.3.6 Improper business ethics/company policy

Business ethics are related to the policies, values or cultures within an organization. Business ethics are echoed through corporate social responsibility (CSR). Manufacturers striving towards sustainable practices must incorporate sustainability mission in their company policy. A sustainable business policy should reflect the strategy and commitment towards the business for long-term sustainable development. A well-defined sustainable policy will promote the environment management system (EMS), comply environmental legislations and administer business excellence through the setup of SMS. Kumar et al. (2014) expressed that moral values should be embedded in the business ethics of an organization. The moral values may encompass 'sustainability' as one of its basic tenets. Such a statement in the preamble of an organization would naturally navigate the company's policies and processes to adopt SMS.

2.3.7 Improper pollution and waste management practices

Manufacturing activities are generally accompanied with the generation of some kind of waste. In order to improve manufacturing sustainability, organizations must address the issues of emission, pollution, waste minimization, waste treatment, waste disposal and the like. Disposal of hazardous waste and e-waste in particular, are crucial from sustainability point of view. Carley et al. (2014) discussed that emission reduction is possible either through process efficiency improvement or through the change in input or technology. Improper pollution control and waste management acts as important bottleneck towards the accomplishment of sustainable manufacturing practices.

2.3.8 Lack of vision for long term sustainable development

Sustainable development through the adoption of sustainable manufacturing practices mandates that all stakeholders should have clear understanding about the environment and environmental issues. Government, non-government institutions, academic institutions may impart environment education for all - environment awareness has the highest potential for long term sustainable development. A well-educated society and well-informed customers can make responsible and informed decisions towards the acceptability and use of green products. The enunciation of a firm's vision statement on sustainability is the key for promoting sustainability management system. Moreover, in the present context, mere economic considerations bereft of sustainability considerations has revealed the hollowness of the management systems governing the manufacturing setup. Lack of vision and commitment of top management towards sustainable practices act as barrier for long term sustainable development.

2.3.9 Lack of appropriate technologies

Beder (1994) suggested that appropriate technology can solve many of the present-day environmental problems. Appropriate technologies realized through redesigning of existing technologies may change the resource consumption practices (from non-renewable to renewable one) and help in the progress towards sustainable manufacturing. Invention of non-polluting technologies are crucial in this direction. Inappropriate technologies are mostly responsible for the creation of unproductive waste, generation of uncontrollable emission and pollution.

Gunasekaran (2018) prescribed that newer technologies which are 'sustainability' sensitive help in automation, better process control, reduction of waste, saving of energy and the like, thus promoting sustainability in manufacturing. He referred to computer-aided engineering, micromanufacturing, IoT, smart logistics, life-cycle management as some of the important manufacturing technologies in this direction. Lack of appropriate technologies is important barrier towards the development of SMS.

2.3.10 Lack of eco innovation-oriented research

In order to compete in the market, the role of innovation and innovative technologies cannot be underrated. Lack of innovative technologies acts as deterrent towards the progress of SMS. Mulder (2007) discussed that in order to motivate the organizations towards innovation, the institutional arrangements of the market should be transformed through the participation of government agencies, tax laws, national laboratories, NGO's and all stakeholders.

2.3.11 Lack of standardized metrics or performance benchmarks

In order to sustain in today's competitive market, manufacturers need to consistently monitor their own progress and performance. Performance benchmarking through the use of sustainable indicators (metrics), can rate the organizations for their progress and performance. Organization for economic co-operation and development (OECD) discussed various sustainable development indicators (SDI's) generally used by industries for their manufacturing processes. SDI's help to measure performance with respect to set goals and help to take remedial measures in case of any deviations. Some common indicators widely followed are: Key performance indicators (KPIs), material flow analysis (MFA), environmental accounting, eco-efficiency indicators, life cycle analysis (LCA) indicators, sustainability reporting indicators, socially responsible investment indices (SRI), international organization for standardization (ISO 14031), global reporting initiative (GRI) etc. Manufacturers willing to develop SM practices must adopt some kind of standardized indicators that suits their specific requirements.

Faure (1995) discussed that emission standards are one of the common legal techniques towards environmental protection. Emission standards prescribe maximum limits of emission for various substances but generally do not prescribe the technology or method of production to be used to achieve that standard.

2.3.12 Inadequate focus on 4 R's Principles

Shirodkar and Terkar (2017) opined that waste recycling is a significant aspect towards sustainable manufacturing and e-waste is one of the most threatening and fastest growing waste problems throughout the globe.

Shi et al. (2005) highlighted that obsolete computers generate a lot of waste and causes environmental pollution. He suggested that through the use of disposal technologies, 80% components can be recycled and reused, remaining 20% can be remanufactured. Use of such practices therefore can help in the conservation of scarce resources and promote sustainable practices.

2.3.13 Poor compliance to environmental legislations

Faure (1995) discussed that manufacturers usually have the tendency of not complying with environmental regulations as they perceive it as something that adds cost to the production. Implementation of sustainable practices help to comply with environmental regulations through the adoption of advanced technologies and eco-innovations. Organizations opting for sustainable performance indicators have more chance to comply with environmental legislations.

Poor compliance of environmental legislations escalates environmental problems caused by manufacturing activities and is an important barrier towards achieving sustainability.

2.3.14 Poor focus on energy efficiency and energy efficient process

Poor focus on energy efficiency is an important barrier for the industries towards the adoption of sustainable manufacturing practices. According to Carley et al. (2014) energy reduction necessitates the installation of energy efficient appliances and making the manufacturing process more efficient.

United Nations department of economic and social affairs (2006) estimated that approximately one-third of the energy consumed globally is used by the industrial sector. As energy resources are depleting very fast, manufacturers must focus on ways to conserve energy. Adoption of innovative practices improve the machine as well as process efficiency. This results in the realization of economic efficiency apart from energy (resource) efficiency thus stimulating strong economic growth and sustainability.

2.3.15 Lack of government support towards developing new technologies

Government can offer various incentives, financial aids, subsidies or tax concessions to motivate the manufacturers in developing new technologies towards green initiatives and thus can initiate a significant role towards long term sustainable development. Apart from market competition, manufacturers are under constant pressure to comply with the norms and regulations set by the government from time to time. Manufacturers may face difficulty in developing new technologies unless they get requisite government support. A survey was conducted on the adoption of sustainable manufacturing practices in the Caribbean. It suggested four different roles that can be initiated by the government. These are (i) Fund provider (ii) Auditor (iii) Facilitator and (iv) Regulator. Lack of government support and funding acts as strong barrier for the manufacturers willing to adopt sustainable technologies (Millar and Russell, 2011).

2.3.16 Inappropriate environment management systems

Environment management system (EMS) aims towards reducing the environmental damages caused by manufacturing operations. Through the adoption of P-D-C-A (Plan, do, check, act) cycle, EMS can do continuous improvement in terms of environmental performance. Jayashree et al. (2015) cited that implementation of ISO 14000 environment management system can promote greater environmental performance and sustainability improvement through appropriate environment management. They also highlighted that its successful implementation necessitates the active participation of employees at various levels in the organization.

An inappropriate EMS is responsible for improper waste management, degradation of resources, increase of manufacturing cost, decrease of energy efficiency and non-compliance of environmental regulations. Inappropriate EMS is therefore an important barrier towards the development of SMS.

2.3.17 Poor monitoring and control

A modern manufacturing set up entails automated machines, sophisticated measuring tools and gauges, established system for monitoring and control, suitable techniques to convert raw materials into finished products etc. In order to improve the manufacturing efficiency, organizations are expected to impart knowledge and training to their personnel at every level. With the advent of highly automated machines with latest technologies, there is a strong need to adequately train the employees so that they attain the skill and competency to operate, monitor, control and repair the machines. Skilled workers will not only be able to monitor and control the process, but will also be able to optimize the process parameters.

The quality of sustainability criteria, its management, control and adherence are very crucial in achieving the prescribed goals. A proper regulatory framework elaborating on control, monitoring and corroboration should form essential components of the standards set for voluntary adoption (Pavlovskaia, 2014).

Poor monitoring and control inhibit the sustainability in manufacturing process. Process monitoring helps to determine the state of the process through various sensors, while process control aims in the regulation of process parameters. Both on-line and off-line process control are useful for regulating the process. Process control through adaptive control helps to optimize associated variables on-line (Stavropoulosa et al., 2013).

2.4 GAPS IN LITERATURES

A systematic review of literatures helps to find the trends and challenges in the study area. Moreover, it provides information about study parameters, important findings, range of study, gaps in literatures, summary of literatures etc., considered as crucial for future research. The conclusion and future research sections of the articles provide information about scope of investigation that can be taken up for future examination. The literatures on sustainable manufacturing outlines the practical applications of sustainable concepts in manufacturing. There exist a few case studies for mapping the sustainability approaches in manufacturing. Case studies and analysis found from related books, company websites, various environmental establishments, conference articles, project reports etc. also supplement the literatures.

Research gap is a 'research question or problem' that helps in clear understanding of the status of knowledge in the research area. It is therefore very much essential to identify the gaps in existing literatures to further the research. This also helps with a pool of knowledge in the study area. The present analysis is aimed towards the compilation of existing theories and knowledge from the review of literatures. The research questions obtained from the study can promote the development of more motivating and persuasive theories for future research. The gaps in some selected literatures have been presented in Table 2.1.

Table 2.1: Identified gaps in some literatures

S. No.	Title	Authors	Identified gaps
1	Sustainable Manufacturing: Integrating lean and green	Nagi et al. (2017)	An in-depth analysis using MCDM techniques might further help for the progress towards sustainability
2	Human-robot collaboration in disassembly for sustainable manufacturing	Liu et al. (2019)	The case study analysis may be extended in various manufacturing systems for improving their sustainability
3	Key performance indicators of steel re-rolling mills for sustainable manufacturing	Jani et al. (2017)	More key performance indicators (KPI's) should have been included; Some MCDM technique could have

S. No.	Title	Authors	Identified gaps
			been used to obtain their ranking and to model them for meaningful results
4	An analysis of enablers and barriers of sustainable manufacturing in southern Africa	Mutingi et al. (2017)	Although some enablers and barriers have been identified, their causal relationships could have been studied by using some MCDM techniques. This would have given important insights for the progress towards sustainability
5	Drivers and barriers in sustainable manufacturing implementation in Malaysian manufacturing firms	Nordin et al. (2014)	Some Analytic tools might have been used in the study to get meaningful insights for the business managers in improving manufacturing sustainability
6	Sustainable reverse logistics network design for household plastic waste	Bing et al. (2014)	Future research may include other parameters such as quality and separation rate in the model
7	Innovation for sustainability: toward a sustainable urban future in industrialized cities	Han et al. (2012)	Among various challenges of urban sustainability only three factors have been discussed. More issues could have been investigated
8	Establishing greener products and manufacturing processes	Linke et al. (2012)	Research has taken into consideration only energy and GHG emissions. More parameters could have been analyzed in the study. Detailed analysis using MCDM techniques are missing
9	Compromise ranking approach for sustainable concept selection in an Indian modular switches manufacturing organization	Vinodh et al. (2013)	The case study was conducted in a modular switch manufacturing organization located in Tamil Nadu, south India. Similar studies can be conducted in other industries in future
10	Recent advances on key technologies for innovative manufacturing	Brousseau and Eldukhri (2011)	The research focused on four main research areas and was limited within Europe. The study can be extended in other geographic locations
11	Product category rules and environmental product	Fet et al. (2009)	Data-assisted tool for sustainable product can be specifically designed

S. No.	Title	Authors	Identified gaps
	declarations as tools to promote sustainable products: experiences from a case study of furniture production		for other industries as well for the progress towards sustainable manufacturing
12	Sustainable manufacturing for obsolete computers based on 3R engineering	Shi et al. (2005)	Similar studies can be conducted for other products. 6R's principle may also be used in future research

2.5 METHODOLOGIES USED FOR ANALYSIS OF SMS

Multi criteria decision making (MCDM) techniques namely ISM, GTA and AHP have been used for the analysis of various enablers and barriers towards the successful implementation of sustainable manufacturing system. These are explained below:

2.5.1 Interpretive structural modeling (ISM)

ISM was first proposed by Warfield in 1973. ISM is a MCDM technique that is often used for the understanding and analysis of complex situations. It helps to solve complex decision problems by developing relationships among selected elements followed by the development of a hierarchical model. Followings are important steps in ISM methodology:

- Development of structural self-interaction matrix (SSIM) among selected elements
- Construction of reachability matrix
- Level partitioning
- Formulation of conical matrix
- Structuring of ISM Model
- MICMAC analysis

The following section gives a brief description of ISM procedure (Thakkar et al., 2008; Raj et al., 2009; Faisal, 2006). This is summarized below.

i Identification of various elements related to the problem/ system under consideration by means of literature review and questionnaire survey

ii Establishment of contextual relationships among these elements by SSIM involving a panel of experts in the subject area. SSIM represents the pair-wise relationships among the identified elements of the system. Four symbols V, A, X and O are used to denote the relationships between two elements (i, j).

- Symbol V is used if element i influences j
- Symbol A is used if element i is influenced by j
- Symbol X is used if both i and j influences each other
- Symbol O is used if i and j have no relation

An initial reachability matrix is developed from SSIM by substituting the symbols (V, A, X and O) with 1's or 0' s based on substitution rule:

- If (i, j) entry in the SSIM is V, then put 1 in the (i, j) entry and 0 in (j, i) entry
- If (i, j) entry in the SSIM is A, then (i, j) entry in initial reachability matrix becomes 0 and (j, i) entry becomes 1
- If (i, j) entry in the SSIM is X, then put 1 in both (i, j) and (j, i) entry
- If (i, j) entry in the SSIM is O, then both (i, j) and (j, i) entry becomes 0

iii The initial reachability matrix is checked for transitivity to develop final reachability matrix. Transitivity concept states that if an element P is related to Q and Q is related to element R, then element P is inevitably related to element R

iv The final reachability matrix is partitioned into different levels. This is done through iterations where reachability set, antecedent set and intersection set are calculated.

v Conical matrix is formed from the reachability matrix. It contains most zero (0) elements in the upper diagonal half of the matrix and most unitary (1) elements in the lower half.

vi The digraph is converted into an ISM model by replacing nodes of the elements with their descriptions

vii The ISM model is checked for conceptual inconsistency and necessary amendments are done.

Literatures reveal various applications of ISM methodologies. Table 2.2 gives a brief review of the same.

Table 2.2: Applications of ISM in literatures

S. No.	Title of literature	Author(s)	Brief description
1	Knowledge management (KM) barriers: An interpretive	Singh and Kant (2008)	The paper identifies eleven enablers for the success of KM. ISM methodology has been used to evolve mutual relationships among these enablers. It is observed that three enablers, namely internet, electronic-mail, and intranet have strong driving power and weak dependence power among selected enablers. Selected

S. No.	Title of literature	Author(s)	Brief description
	structural modeling approach		KM enablers are classified to analyze their driving power and dependence power.
2	Interpretive structural modeling for E-electricity utility service.	Satapathy et al. (2012)	Service quality is recognized as one of the important aspects towards organization's sustainability. The paper discusses important aspects of customer's satisfaction in service quality. ISM has been used to analyze E-electricity utility service in this regard.
3	Interpretive structural modeling of supply chain risks	Pfohl et al. (2011)	The paper analyzes potential supply chain risks. It demonstrates how ISM modeling supports risk managers in identifying and understanding interdependencies among supply chain risks at various levels. Interdependencies among risks are derived and structured into a hierarchy.
4	An analysis of the drivers affecting the implementation of green supply chain management	Diabat and Govindan (2011)	An ISM framework is used to develop a model of the drivers affecting the implementation of green supply chain management. Various drivers of green supply chain management are identified based on the related literatures and in consultations with experts. The model is validated using a case study involving a manufacturing firm in southern India.
5	Analysis of interaction among the barriers to total quality management implementation using interpretive structural modeling approach	Talib (2011)	The paper identifies 12 TQM barriers. An ISM-based model has been utilized to understand the mutual influences among these barriers of TQM. The ISM analysis helps to categorize them into driver and dependent clusters.
6	Interpretive structural modeling (ISM) of IT-enablers for Indian manufacturing SMEs.	Thakkar et al. (2008)	This paper investigates the issue of IT adoption and implementation in Indian manufacturing enterprise (SMEs) towards enhancing the capabilities of their supply chain. Key managerial insights are obtained by developing an ISM model for the set of factors. These factors are classified into autonomous, driver, dependent and linkage categories. It helps

S. No.	Title of literature	Author(s)	Brief description
			in understanding their relative impact towards the implementation of IT in Indian context.
7	Supply chain risk mitigation: Modeling the enablers	Faisal (2006)	The paper presents an ISM approach for effective supply chain risk mitigation. By using interpretive structural modeling, the research presents a hierarchy-based model that establishes the mutual relationships among the various enablers of risk mitigation.
8	Interpretive structural modeling approach for development of electric vehicle market in India	Digalwar and Giridhar (2015)	There exist many factors that affect the growth of electric vehicles (EV) market in India. The present paper uses ISM method to analyze critical success factors towards the promotion and development of EV market in India.
9	Lean, green and resilient practices influence on supply chain performance: Interpretive structural modeling approach	Govindan et al. (2015)	This paper uses ISM methodology to identify the inter-relationships among lean, green, resilient practices and supply chain performance and to classify them according to their driving or dependence power. The study analyses Just-in-time (lean practice), flexible transportation (resilient practice) and environmentally friendly packaging (green practice) as the main driving power. Customer satisfaction is perceived as strong dependence and weak driving power.
10	Analysis of barriers to implement solar power installations in India using interpretive structural modeling technique	Ansari et al. (2013)	This study develops a structural model of the barriers to implement solar power installations in India. ISM technique is used to develop a structural model of barriers to implement solar power installations in India. The paper suggests various ways of mitigating these barriers. The study can provide guidance so that maximum number of solar power projects can be installed in India.
11	Modelling the factors affecting flexibility in FMS	Raj et al. (2012)	The research identifies various factors that affect the flexibility of FMS. Interpretive structural modeling is used to segregate the driving and dependent factors. An ISM model of these factors helps to identify key factors and their implications.

S. No.	Title of literature	Author(s)	Brief description
12	Risk mitigation in the implementation of AMTs: A guiding framework for future.	Nagar and Raj (2012)	The research focuses towards the identification of various risks towards the implementation of AMT. An ISM framework is developed to mitigate them. ISM depicts the relationship and priority among various risks. The analysis indicates dominant risks based on high driving power.
13	Identification and modelling of the various factors affecting the productivity of FMS.	Dixit and Raj (2016)	The paper enlists the factors affecting the productivity of FMS installation. Modeling has been done incorporating various factors using ISM. The model is further reinforced using MICMAC analysis by evaluating driving power and dependencies of these factors.
14	An ISM approach to analyze interaction among the barriers for the transition towards flexible manufacturing system.	Raj et al. (2009)	The purpose of this paper is to identify and analyze various barriers that prevents the transition towards flexible manufacturing system. ISM approach is used for modeling of these barriers. The analysis gives important managerial implications.
15	An ISM approach for modelling the variables affecting the selection of material handling equipment in advance manufacturing system (AHMS)	Kumar and Raj (2015).	This paper presents the application of ISM for modelling the variables of AMHS. Several variables help in the implementation of material handling systems in advance manufacturing systems. The ISM approach analyzes their mutual interaction and a model is developed. The model enables the smooth transition towards the implementation of AMHS.

2.5.2 Graph theoretic approach (GTA)

Graph theory is a powerful MCDM methodology for the modeling and analysis of complex engineering systems. It analyzes various elements or sub-systems, their mutual relationships and their effects on the whole system. GTA reflects graphical (digraph representation) as well as numerical scoring obtained through permanent matrix. GTA methodology primarily consists of three steps. These are:

a. Digraph representation
b. Matrix representation
c. Permanent function representation

Various steps followed in GTA are enlisted below (Attri et al., 2013; Wani and Gandhi, 1999; Venkata and Gandhi, 2002). These are:

i. Identification of sub-systems that affect the main system
ii. Development of digraph for the system elements based on their mutual interactions
iii. Development of variable permanent function (VPF) matrix at the system/sub-system level based on digraphs
iv. Evaluation of permanent value for the system/sub-system
v. Analysis of results and meaningful conclusions.

Digraph represents the structure of system in terms of nodes and edges. Nodes correspond to a set of characteristics (sub-systems) within the system, whereas edges represent their dependence using directed lines. The one-to-one depiction in the digraph is replicated by matrix representation. Permanent representation gives mathematical expression for the characteristics and their mutual interdependence. The salient features of GTA methodology are:

- GTA reflects inheritance, interdependence and directional relationships among the selected characteristics
- Graphic analysis through digraph helps in visualization and better understanding
- It helps to convert qualitative data into quantitative scores
- Ranking the alternatives are possible through numerical scores
- It can be useful for selecting best alternatives through permanent function values.

Various GTA applications found in literatures is presented in Table 2.3.

Table 2.3: GTA applications found in literatures

S. No.	Title of literature	Author(s)	Brief description
1	Crowd behavior analysis and classification using graph theoretic approach	Zerdi et al. (2014)	A graph theoretic approach is used for the analysis of crowd behavior analysis and classification system. The analysis addresses the issue of automation in surveillance

S. No.	Title of literature	Author(s)	Brief description
			systems. The crowd behavior is reflected by the motion trajectories of the personnel in the crowd.
2	An optimal graph theoretic approach to data clustering: Theory and its application to image segmentation	Leahy (1993)	The paper demonstrates the application of graph theoretic approach for data clustering and its application to the image segmentation problem. This method accurately locates region boundaries as well as guarantees the formation of closed edge contours.
3	Development of maintainability index for mechanical systems	Wani and Gandhi (1999)	A procedure based on digraph and matrix method is used for the evaluation of maintainability index of mechanical systems. Maintainability attributes and their inter-relations are used to present digraph for the system. The digraph is converted by matrix that gives maintainability expression and is representative of the system.
4	Failure cause analysis of machine tools using digraph and matrix methods	Rao and Gandhi (2002)	This paper presents a methodology to analyze the failure causes of machine tools using digraph and matrix methods. The machine tool failure causality digraph takes into consideration the failure contributing events and their interaction in terms of cause-effect relationship. The matrix obtained from the digraph characterizes the failure cause.
5	Quantification of risk mitigation environment of supply chains using graph theory and matrix methods	Faisal et al. (2007)	The paper uses graph theory and matrix methods to quantify the risk mitigation environment (RME). The proposed model can integrate new variables that can impact the overall supply chain risk mitigation environment along-with the potential to benchmark supply chains on risk mitigation dimension.
6	Graph theory-based approach to optimize single-product flow-line configurations of RMS	Dou et al. (2009)	The paper presents a graph model to optimize capital cost of single- product flow-line (SPFL) configurations of RMS. The parameters of SPFL includes a number of workstations, machines and assigned operations for each workstation.
7	A graph-theoretic approach to evaluate the intensity of barriers in the implementation of FMSs	Raj et al. (2010)	The paper uses a graph-theoretic approach (GTA) to find the intensity of FMS barriers. This is done through an index that is calculated by a permanent function obtained from the digraph of FMS barriers.

S. No.	Title of literature	Author(s)	Brief description
8	Selection, identification and comparison of industrial robots using digraph and matrix methods	Rao and Padmanabhan (2006)	A robot selection index is proposed in this paper. It evaluates and ranks robots for a specific industrial application. A methodology based on digraph and matrix method has been used for the evaluation of alternative industrial robots. The index is obtained from a robot selection attributes function obtained from the robot selection attributes digraph.
9	A digraph approach to TQM evaluation of an industry	Grover et al. (2004)	This paper identifies factors responsible for the development of a TQM environment. A mathematical model for the TQM environment is developed by various interacting factors using a graph theoretic approach. The method is flexible enough to accommodate new factors and market dynamics in global business.
10	Role of human factors in TQM: a graph theoretic approach	Grover et al. (2006)	The paper represents the effect of 'human factors' in TQM environment' in terms of a single numerical index by considering their inheritances and interactions. The overall effect of human factors is quantified through a mathematical model using GTA. The approach uses digraph, matrix model and a multinomial to represent the interactions among identified human factors.
11	GTA modeling of combined cycle power plant efficiency analysis	Dev et al. (2015)	The paper uses a methodology based on graph theory and matrix method for the efficiency analysis of a combined cycle power plant (CCPP). Sub-systems of CCPP and their interdependencies are used to develop system structure digraph. The methodology is extended to sub-system level and the performance parameter digraph is developed by the inheritance and interdependencies of parameters. Permanent function is developed by converting digraph into matrix form. Relative efficiency index (REI) at sub-system level is obtained by comparing the value of permanent function in real time situation to that of design condition.
12	Critical factors of website performance: a graph theoretic approach	Saha and Grover (2011)	The paper represents the overall effect of key website performance attributes quantitatively using GTA. The interactions among identified key website performance attributes are represented through digraph, matrix model

S. No.	Title of literature	Author(s)	Brief description
			and a multinomial. 'Website performance index' provides an insight into the website performance parameters both at the system and subsystem levels.

2.5.3 Analytic hierarchy process (AHP)

AHP is a system analysis technique that was developed by T. L. Saaty (1980). AHP transmutes complex decision problems into a hierarchy of criteria and alternatives. It generates a hierarchical model in which the overall goal is placed at the highest level and various decision alternatives are positioned at the lower levels (Tung and Tang, 1998). AHP is one of the preferred MCDM techniques that can be used for the selection of best alternatives out of a number of available choices. AHP has several benefits like wider acceptability, adaptability in many situations, user-friendliness etc. AHP is also capable of solving objective as well as subjective characteristics. Ranking of alternatives are done using pairwise comparison of attributes by using a scale of relative importance. Important steps in AHP methodology are:

- Structuring the problem
- Formation of pairwise comparison matrix
- Normalization and consistency analysis

The important steps in AHP methodology are given below (Patra et al., 2019; Sharma et al., 2008; Ramanathan, 2001).

a. Structuring of problem is done by developing a hierarchy structure consisting of main criteria, sub- criteria, sub sub-criteria and so on.
b. Pairwise comparison matrix is made based on relative importance of one element over the other. A panel of experts are involved for pairwise comparison using a questionnaire. A table of relative importance (1- 9) is used for this purpose.
c. Normalization and consistency analysis is done. The consistency index (CI) and consistency ratio (CR) are evaluated. CR is the ratio of CI and RI, where RI is obtained from random index table of Saaty (1980). The CR value should be less than 0.10 for judgmental consistency. The priority weight of each element is obtained and ranking are done.

Table 2.4 gives a summary of various applications of AHP found in literatures.

Table 2.4: Applications of AHP found in literatures

Sl. No.	Title of literature	Author(s)	Brief description
1	A review of applications of analytic hierarchy process in operations management.	Subramanian and Ramanathan (2012)	The paper reviews the literature on the applications of analytic hierarchy process (AHP) in operations management. It also suggests possible gaps from researchers and practitioners' point of view. This paper systematically categorizes the published literatures from 1990 to 2009 and then reviews and analyzes them methodologically.
2	Marketing applications of the AHP Process	Wind and Saaty (1980)	The paper reviews several marketing applications of the AHP process. The paper discusses a number of illustrative applications of AHP covering the following areas: i. Portfolio decisions of a firm concerned with the determination of the desired target portfolio and allocation of resources ii. Determination of the directions for new product development iii. Generation and evaluation of marketing mix strategies. iv. Various suggestions for additional research on AHP and its marketing applications are also highlighted.
3	Measuring project complexity using analytic hierarchy process.	Vidal et al. (2011)	The paper is dedicated towards defining a measure of project complexity in order to assist decision-making. AHP process has been used to evaluate the project complexity.
4	Analytic hierarchy process applied to maintenance strategy selection	Bevilacqua and Braglia (2000)	This paper describes an application of AHP for selecting the best maintenance strategy for an Italian oil refinery. Five possible alternatives considered are: preventive, predictive, condition-based, corrective and opportunistic maintenance. Using AHP technique, several aspects that characterize each of the maintenance strategies are arranged in a hierarchic structure and evaluated using a series of pairwise judgements.
5	Project risk assessment using the analytic hierarchy process.	Mustafa and Al-Bahar (1991)	This paper uses AHP to analyze and assess project risks during the bidding stage of a construction project and to overcome the limitations of the approaches currently used by

Sl. No.	Title of literature	Author(s)	Brief description
			contractors. AHP assists the decision-maker in formulating the problem in a logical and rational manner. An analysis of the risk involved in constructing the Jamuna multipurpose bridge in Bangladesh is carried out using AHP methodology.
6	A note on the use of the analytic hierarchy process for environmental impact assessment	Ramanathan (2001)	This paper uses AHP for the analysis of environmental impact assessment (EIA). AHP has the flexibility to combine quantitative and qualitative factors, to handle different groups of factors, to combine the opinions expressed by many experts and can help in stakeholder analysis. The use of AHP is illustrated for a case study involving socio-economic impact assessment.
7	Evaluation of services using a fuzzy analytic hierarchy process.	Mikhailov and Tsvetinov (2004)	This paper proposes a new fuzzy modification of the AHP process approach for tackling the uncertainty and imprecision of the service evaluation process. The proposed fuzzy prioritization method uses fuzzy pairwise comparison judgements rather than exact numerical values of the comparison ratios.
8	Determining key capabilities of a firm using analytic hierarchy process	Hafeez et al. (2002)	This paper provides a structured framework to determine key capabilities of manufacturing companies using AHP process. Both quantitative (financial) as well as qualitative (non-financial) measures have been employed for capability evaluation. The results obtained from the analysis can help the company to undertake strategic investment decisions (capability development, outsourcing, focusing or diversification) with regard to new products, services or markets.
9	Analytic hierarchy process to assess and optimize distribution network	Sharma et al. (2008)	This paper relates product characteristics to optimize supply chain delivery network design. The cost and service factor performance metrics are considered as the decision criteria. AHP methodology is developed to take into account both qualitative and quantitative factors in the best delivery network design selection.
10	Quantifying the complexity of transportation projects using the fuzzy	Nguyen et al. (2015)	This study deduced six components of project complexity namely sociopolitical, environmental, organizational, infrastructural, technological and scope complexity. Fuzzy analytic hierarchy process (Fuzzy AHP) method is employed

Sl. No.	Title of literature	Author(s)	Brief description
	analytic hierarchy process		to determine the weights of the components and parameters of project complexity. Sociopolitical complexity is found as the most defining component of complexity in transportation construction.

2.6 CONCLUSION

In an increasingly competitive business environment, manufacturers have to adopt advanced technologies, innovate new products, renovate their manufacturing systems etc. to improve their performance. Integration of resource conservation, manufacturing efficiency, use of alternate energy in manufacturing are vital for the progress towards SMS. A well-established SMS can improve the efficiency, productivity and profitability of firms. However, incorporation of several changes for the development of SMS has high risk of failure. Therefore, there is a need for systematic and in-depth analysis of associated elements towards the implementation of SMS. Literature survey enables to identify various approaches for this purpose. MCDM analysis helps to develop models and yield optimized solutions towards the implementation of SMS.

The present work is aimed at the analysis of energy efficient sustainable manufacturing system. The study draws inputs from academia and industry in order to frame strategic framework for SMS. The present work focusses on various issues of manufacturing with the aim to enhance the manufacturing sustainability. Section 2.3 illustrates various barriers towards the progress of SMS. An ISM based hierarchy model for SMS has been developed by incorporating these barriers. Moreover, an analysis of critical success factors towards the success of SMS has been carried out using AHP and R^3I methodology. The present work will be helpful towards the implementation of sustainability in manufacturing systems.

CHAPTER III

DEVELOPMENT AND ADMINISTRATION OF QUESTIONNAIRE

3.1 INTRODUCTION

Sir Francis Galton, an English polymath had introduced the concept of questionnaires in survey research. Questionnaires are a set of questions that are used to seek the opinion of participants in a survey. A survey is used to collect, analyze and infer the opinions of selected people from a target population. Survey is widely used in various fields of research like sociology, politics, psychology, marketing, industry etc. Survey is an important tool that can be used to collect industrial data for the advancement of technology.

A questionnaire-based survey is an established method to know the respondent's perception related to research problems. This approach has been used in present work to get broad insights towards the development of SMS. The questionnaire has been prepared in consultation with a panel of experts consisting of academicians and industry experts. The questionnaire gives due weightage to environmental, social, economic, technological and other issues. Responses obtained from the survey are collected and compiled for further analysis.

Surveys are extensively used to gather information on a designated issue. Surveys use a set of questions to seek data from the respondents. Questionnaire and survey differ in the sense that a survey represents the views or opinions of a target group of people through their response of questions; whereas the questionnaire is defined as a set of printed questions devised for the purpose of a survey or statistical study.

Surveys are broadly categorized according to instrumentation and according to the span of time involved. Instrumentation survey includes questionnaire and interview survey. Survey according to the span of time comprises of cross-sectional survey and longitudinal survey.

Questionnaires administered to the respondents may either be closed-ended or open-ended questions. Closed-ended questions typically have response options to be filled in. Open-ended questions are used to explore the answers of the respondents. Questionnaires utilized in various surveys are self-administered or group-administered. Self-administered questionnaires are commonly known as mail survey method. Mail surveys are supplemented by web surveys to improve the response rates. Various steps in self-administered questionnaire survey are mail distribution and return, monitoring returns, follow-up mailings. These surveys are cheaper and quicker, incurs same cost for national and local survey and can offer anonymity. In case of group administered questionnaire survey, a sample of respondents are brought together and inquired about their response to a structured sequence of questions.

3.2 DEVELOPMENT OF QUESTIONNAIRE

A survey-based research has been used towards the identification of various issues, enablers and barriers for the development of SMS. Both primary and secondary data are used in the current research. Primary data has been gathered from survey research through the participation of industry experts and academicians in the field. Secondary data are obtained from literature survey on various issues of sustainable manufacturing. Keywords used for this search are “sustainable manufacturing” and “sustainable manufacturing system”. These keywords were used in combination with descriptive words namely “barriers”, “inhibitors”, “enablers”, “drivers”, “parameters”, “factors”, “elements”, “metrics”, “issues”, “energy efficient”, “energy efficiency”, “sustainability”, “sustainable development” etc. It helped in the identification of possible range of enablers, barriers and important issues of sustainable manufacturing.

A closed-ended questionnaire was developed based on various issues, critical success factors (enablers) and barriers of sustainable manufacturing. Respondents were asked to rate the questions in a scale of 1 to 5, where 1 represent very low influence and 5 for very high influence. A panel of industry professionals, consultants and academicians were involved to review the questionnaire before it was administered to the respondents. Respondents were carefully selected from the field of manufacturing industry. Participants were contacted through postal survey as well as through e-mail. Their independent views on enabler and barrier elements associated with sustainable manufacturing practices were sought. Respondents were motivated to share their experience with regard to environmental, economic, social and other sustainability issues. The following section gives a brief summary on the questionnaire development, its administration and findings obtained from questionnaire survey.

The questionnaire-based survey was conducted to reveal various enablers and barriers that are crucial towards the establishment of SMS from Indian manufacturing context. Academicians and industry experts in the field of manufacturing/sustainable manufacturing were consulted to refine the questionnaire. In order to check the suitability of the questionnaire, a pilot survey was conducted. It is a preliminary survey that is used to gather information prior to the conduct of main survey. Pilot survey helps in the following ways:

- To determine the efficiency of the questionnaire for future survey
- To judge the need for revision
- To reduce worries and difficulties before administering the main survey
- To improve the survey response rate

It has mostly been perceived that respondents are reluctant to spare their valuable time in replying to such questionnaires. Keeping this in mind, the questionnaire was suitably modified so that it requires minimum time and effort to fill in.

3.3 QUESTIONNAIRE ADMINISTRATION

This questionnaire survey is arranged in two sections. Section 1 presents the organizational profile such as number of employees, total turnover, products manufactured, company policy etc. Section 2 includes responses related to technical aspects in sustainable manufacturing. It includes the significance of various issues, barriers and enablers towards SMS. A five-point 'Likert scale' has been used to indicate the responses in a scale of 1- 5. Respondents were asked to rate the questions where, rating 5 stands for very high and 1 for very low rating.

3.3.1 Target Industries for questionnaire organization

The target industries for the survey were steel, automobile, fabrication, manufacturing sectors in India. Primarily industries based in north India were targeted for the survey. Most of the questionnaires were distributed in-person. Some of the questionnaires were e-mailed and uploaded in google form to improve the survey response. A few were sent to various organizations by post along-with self-addressed envelope.

3.4 SURVEY RESPONSE AND RESPONDENTS PROFILE

The questionnaire-based survey is targeted for the evaluation of various enablers and barriers towards the development of SMS. A total of 400 questionnaires were circulated in various organizations. Out of these, 149 questionnaires were received back while 11 questionnaires were found to be incompletely filled and were therefore rejected for further analysis. Thus, 138 questionnaires have been considered valuable for the present analysis. This gives a response rate of 34.50% which is considered as fair for such surveys (Malhotra and Grover, 1998).

The survey response enlightens the number of employees, annual turnover of the companies, type of industries (small, medium or large scale), variety of products manufactured, in-house components produced, company policy etc.

3.5 ANALYSIS OF SURVEY RESPONSES

Table 3.1 depicts the following observations based on the responses obtained from the survey of industries.

Table 3.1: Data obtained from survey responses

S. No.	Description	Range of data	No. of industries
1	Total number of employees	< 100	43
		101-500	52
		501-1000	25
		>1000	18
2	Turnover of the organization (Rupees in Cr.)	< 10	38
		10-50	48
		50-100	24
		100-500	19
		>500	9
3	No. of different production shops in the organization	1	34
		2-4	58
		5-8	36
		>8	10
4	Varieties of components manufactured	1-5	71
		6-10	33
		11-20	23
		>20	11
5	Components being manufactured in-house	<25	45
		25- 50	29
		50- 75	38
		75- 100	26

3.5.1 Number of employees in the organization

Out of 138 responses concluded for the analysis, it has been observed that 31% companies have less than 100 employees, 38% have employees between 101-500, 18% have between 501-1000 employees and 13% have more than 1000 employees. This is represented in Figure 3.1.

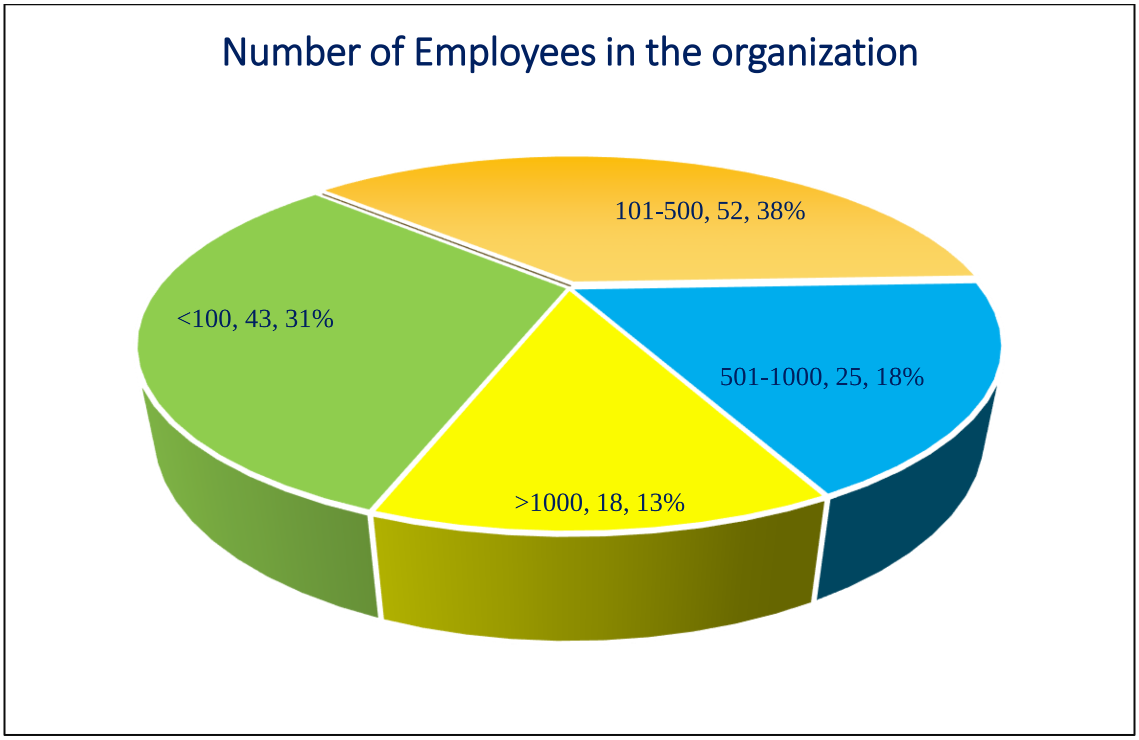

Figure 3.1: Number of employees in the organization

3.5.2 Turnover of organization

With respect to turnover of 138 respondent industries, it is observed that 38 industries or 28% industries have less than 10 cr. annual turnover, 48 industries or 35% industries have turnover between 10-50 Cr., 24 industries or 17% have between 50-100 Cr. turnover, 19 industries or 14% are in 100-500 cr. range while 9 industries or 6% lie in more than 500 cr. range. Turnover profile of the organizations is shown in Figure 3.2.

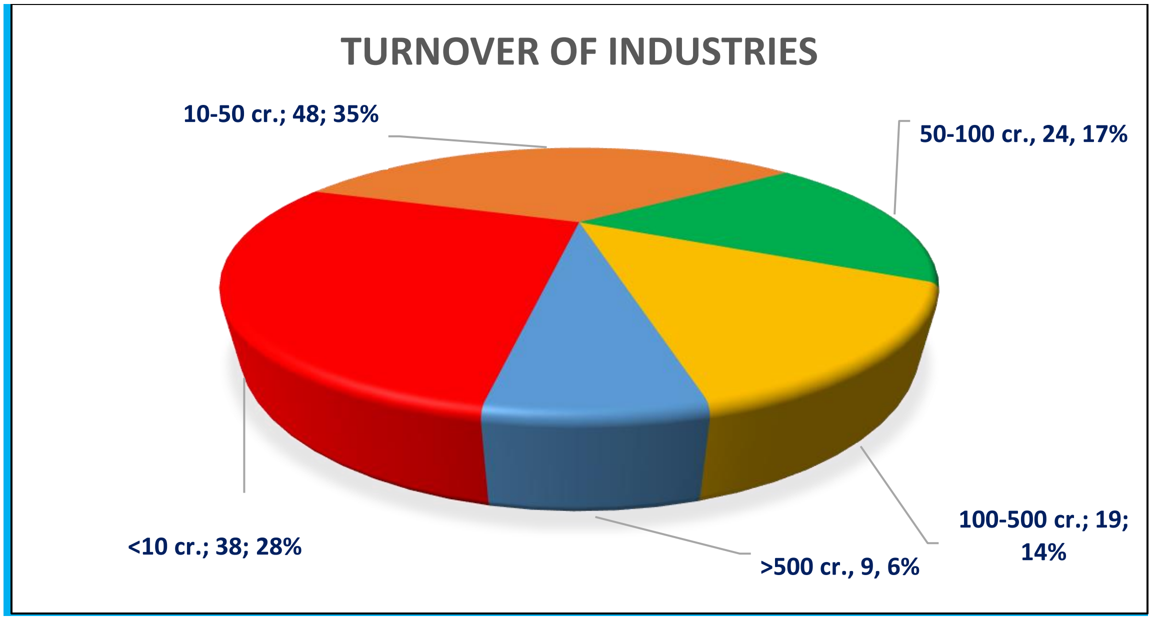

Figure 3.2: Turnover of industries (Rs. in Cr.)

3.5.3 Number of production shops in the organizations

It is observed that out of 138 industries, 34 industries i.e., around 25% industries have single production shop, 58 industries or about 42% have 2-4 shops, 36 industries or 26 % have 5-8 shops and 10% industries or 7% have more than 8 shops. This is shown in Figure 3.3.

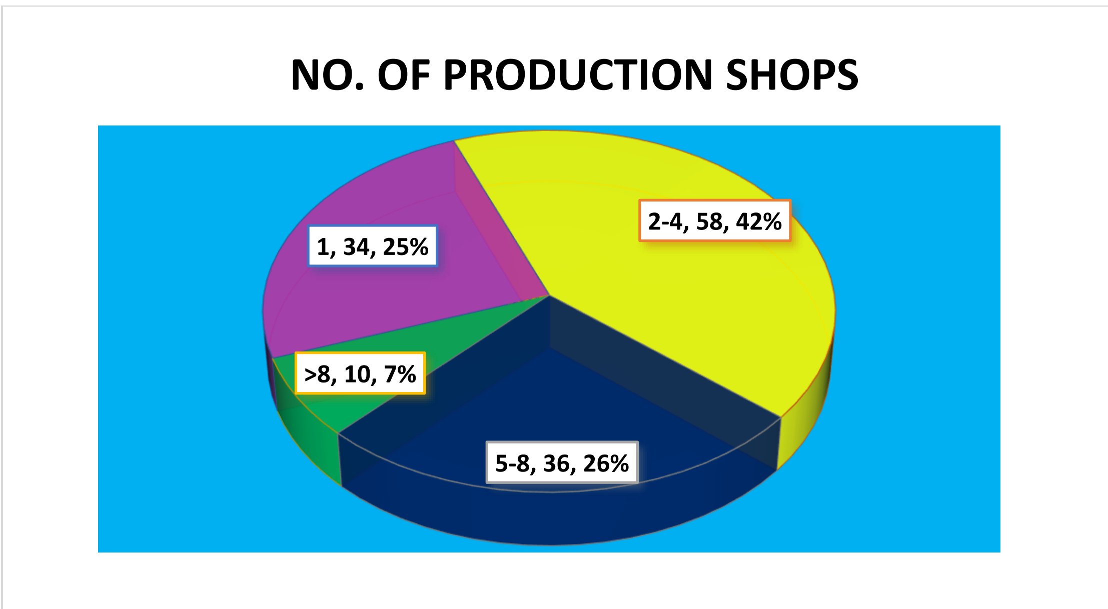

Figure 3.3: Number of production shops in the organizations

3.5.4 Variety of components manufactured

With respect to the number of components produced in the organization, 71 industries or 51.44% produce between 1-5 components, 33 industries or 23.91% produce 6-10 numbers of components, 23 industries or 16.66% produce between 11-20 numbers of components, 11 industries or 7.97% produce more than 20 components. This is depicted in Figure 3.4.

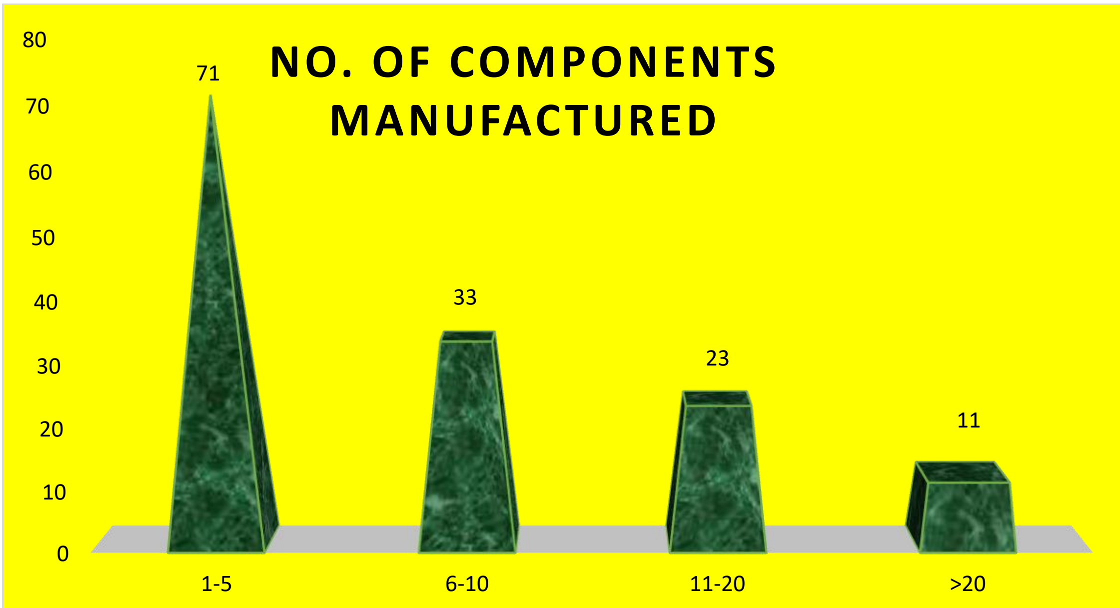

Figure 3.4: Number of components manufactured

3.5.5 Components being manufactured in-house

It is observed that 45 manufacturers produce less than 25% components inside their plant, 29 industries produce 25-50% components inhouse, 38 industries produce 50-75% components inhouse, while 26 industries produce 75-100% components within their plant boundary. This is shown in Figure 3.5.

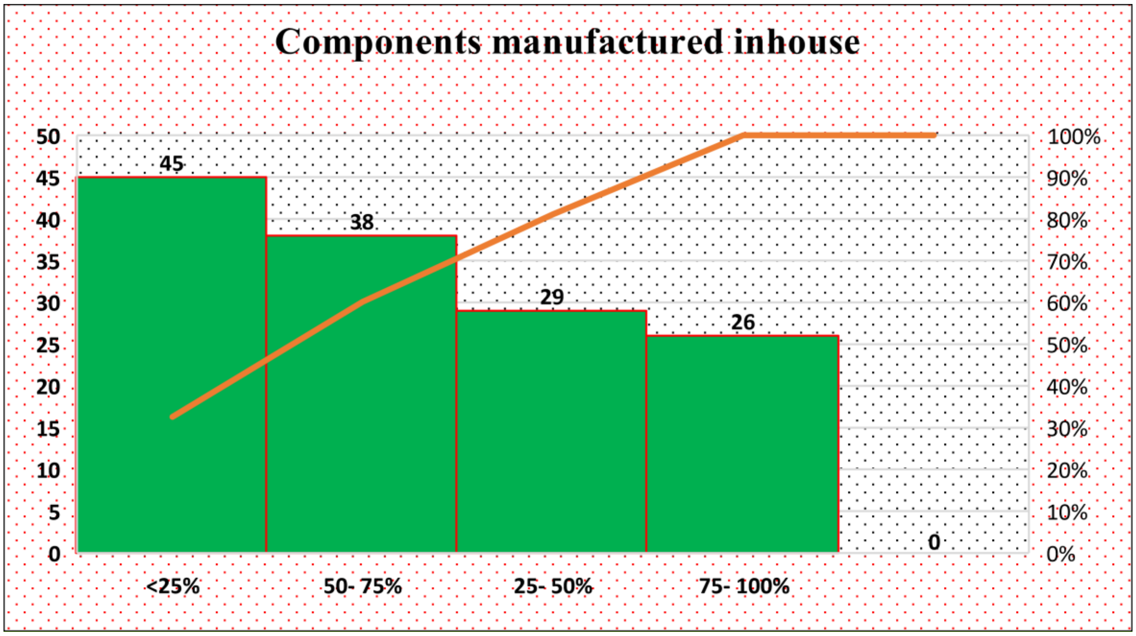

Figure 3.5: Number of components manufactured inhouse

3.5.6 Analysis of survey responses on identified barriers for SMS

The responses of questionnaire survey give the ratings of each barriers towards SMS. Based on individual responses, each barrier scores are calculated by totaling individual ratings. Figure 3.6 displays the scoring of each identified barriers.

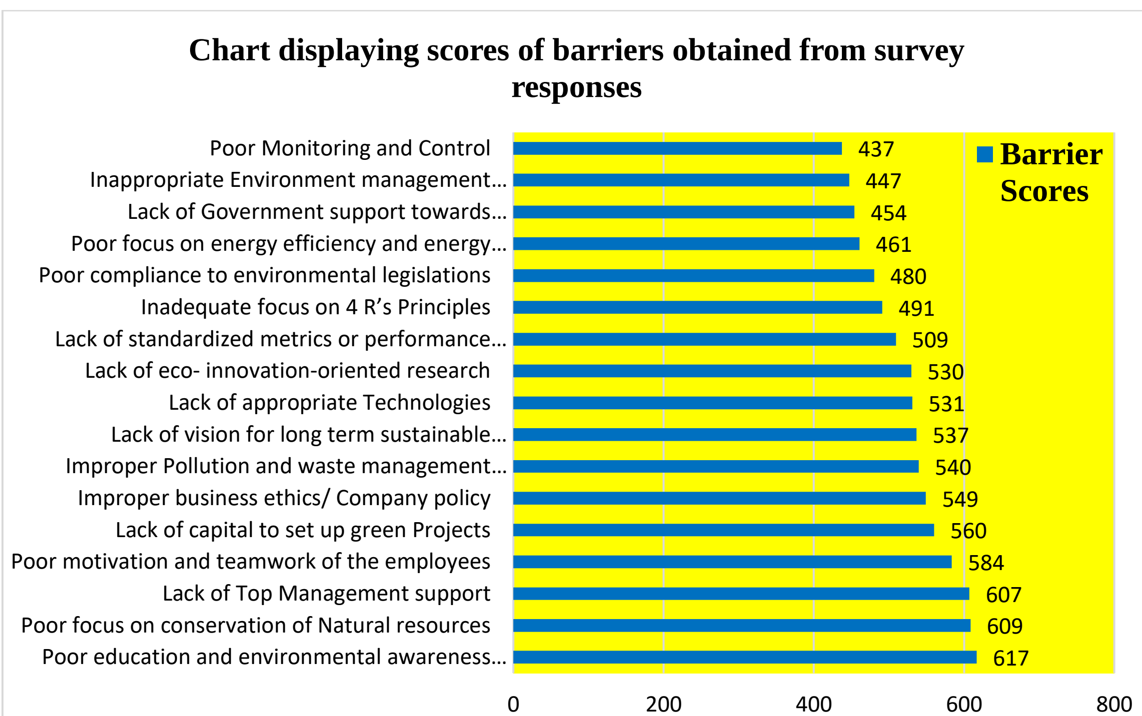

Figure 3.6: Bar chart displaying barrier scores obtained from survey responses

The mean score of each barrier has been calculated and barriers have been ranked. Table 3.2 represents the same.

Table 3.2: Barriers' ranking based on questionnaire survey

Sl. No.	Identified barriers of sustainable manufacturing	Mean score	Rank
1	Poor education and environmental awareness of workmen	4.47	I
2	Poor focus on conservation of natural resources	4.41	II
3	Lack of top management support	4.40	III
4	Poor motivation and teamwork of the employees	4.23	IV
5	Lack of capital to set up green projects	4.06	V
6	Improper business ethics/ company policy	3.98	VI
7	Improper pollution and waste management practices	3.91	VII
8	Lack of vision for long term sustainable development	3.89	VIII
9	Lack of appropriate Technologies	3.85	IX
10	Lack of eco- innovation-oriented research	3.84	X
11	Lack of standardized metrics or performance benchmarks	3.69	XI
12	Inadequate focus on 4 R's principles	3.56	XII
13	Poor compliance to environmental legislations	3.48	XIII
14	Poor focus on energy efficiency and energy efficient process	3.34	XIV
15	Lack of government support towards developing new technologies	3.29	XV
16	Inappropriate environment management systems	3.24	XVI
17	Poor monitoring and control	3.17	XVII

The chart reflects that the top three barriers indicated by the survey response are: Poor education and environmental awareness of workmen (mean score= 4.47), poor focus on conservation of natural resources (mean score= 4.41) and lack of top management support (mean score= 4.40).

3.5.7 Analysis of critical success factors towards SMS from survey responses

Based on survey responses, the scores of each critical success factors are evaluated. Figure 3.7 displays total scoring of each enablers from survey responses.

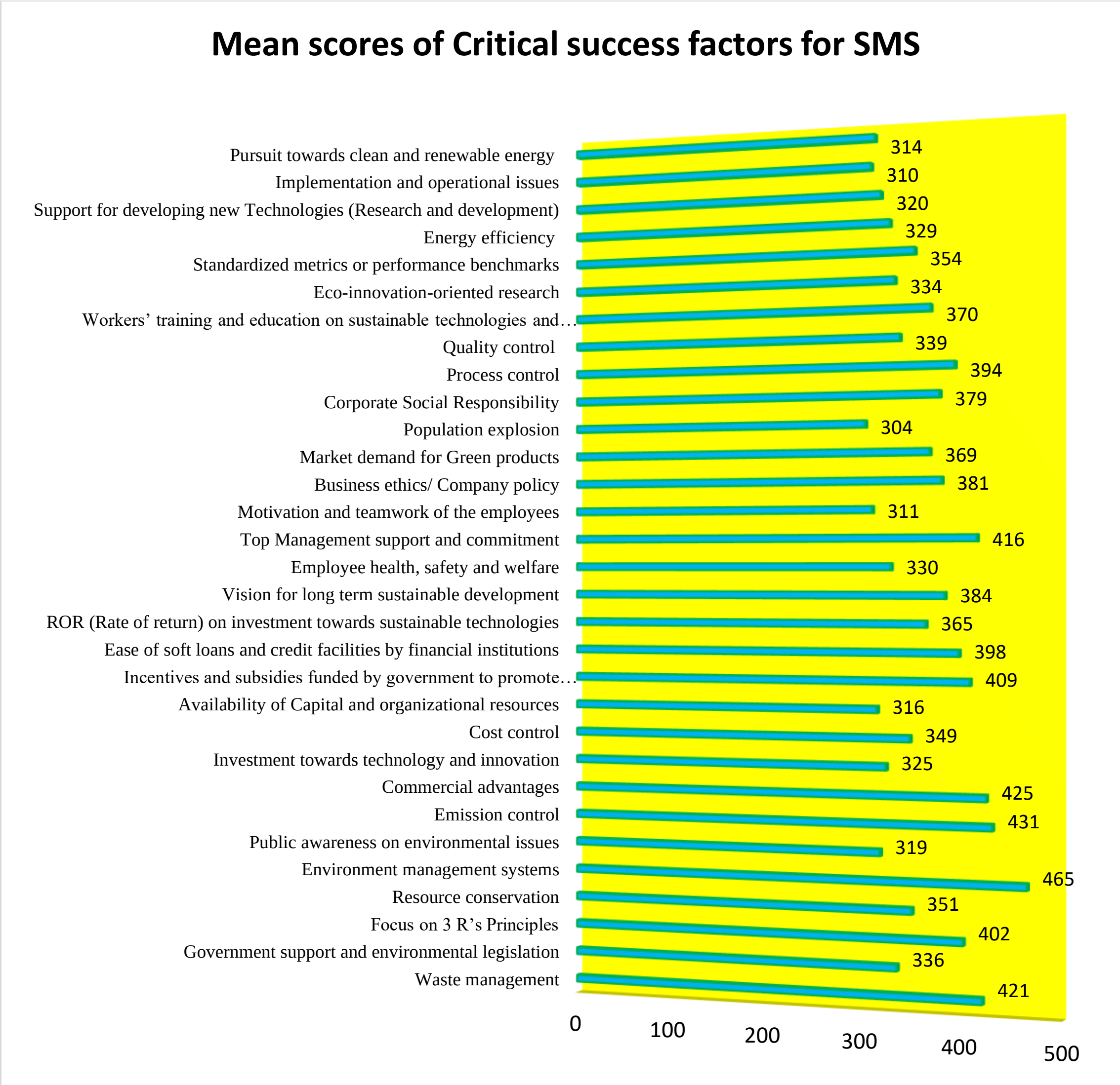

Figure 3.7: Bar chart displaying critical success factors from survey responses

Figure 3.7 shows that environment management systems (total score= 465), emission control (total score= 432) and commercial advantages (total score= 425) are the top three critical success factors towards the implementation of SMS based on survey responses.

3.6 VALIDATION THROUGH ANOVA

ANOVA stands for analysis of variance. ANOVA was developed by statistician and evolutionary biologist Ronald Fisher in 1918. ANOVA analysis has been used for validating the data in the present study. It is a statistical method to test the differences between two or more means in a sample through statistical models and the associated estimation procedure namely the variation among and between groups. ANOVA is based on the principle of law of total variance in which the observed variance in a particular variable is subdivided into components attributable to different sources of variation. It also provides a statistical test of whether two or more population means are equal, and therefore generalizes the t-test beyond two means. It assesses the significance of one or more factors by comparing the response variable means at different factor levels.

Various assumptions in ANOVA are:

- The variances of all the errors are equal to each other
- The errors are independent
- They are normally distributed

Various types of ANOVA analysis are: (i) One-way ANOVA (ii) Multivariate ANOVA (iii) Repeated measures ANOVA (iv) Mixed design ANOVA

One-way ANOVA is used to check whether there is any significant difference between the means of three or more unrelated groups. It mainly tests the null hypothesis which states that all population means are equal.

H_0: $\mu_1 = \mu_2 = \mu_3 = \ldots\ldots = \mu_x$, where μ means group mean and x means group number.

3.6.1 Outline of ANOVA analysis

Based on questionnaire survey, responses obtained from 138 Indian manufacturers have been validated using ANOVA. The one-way analysis of variance (ANOVA), also known as one-factor ANOVA, is an extension of independent two-samples t-test for comparing means in a situation where there are more than two groups. In one-way ANOVA, the data is organized into several groups based on one single grouping variable (also called factor variable). ANOVA test hypothesis are of two types:

- Null hypothesis: It implies that the means of different groups are the same and the population have the same normal distribution
- Alternative hypothesis: It implies that at least one sample mean is not equal to the others. This indicates that at least two of the sample groups come from the population with different normal distributions.

One factor analysis of variance also known as ANOVA makes multiple comparisons of several population means. It does simultaneous comparisons of the means under consideration rather than pairwise comparison. ANOVA test compares two kinds of variation namely the variation between the sample means and the variation within each sample. All these variations are combined into a single statistic, called the 'F statistic' because it uses the F-distribution. This is done by dividing the variation between samples by the variation within each sample. The following steps have been used for the present analysis.

1. Calculate the sample mean for each sample and the mean for all of the sample means.

   Let the samples be: X1, X2, X3, ………, Xk

   The mean of each sample is: $\overline{X1}$, $\overline{X}2$, $\overline{X3}$, …….., $\overline{Xk}$

   Mean of '*all samples mean*' is: $\overline{\overline{X}} = (\overline{X1} + \overline{X}2 + \overline{X3} + \ldots\ldots.. + \overline{Xk})/k$ …………(i)

2. Calculate the sum of squares of variance between the samples ($SS_{between}$)

   This is done by squaring the deviation of each sample mean from $\overline{\overline{X}}$ (Mean of sample means) and multiplying them with the number of items in the respective sample and then adding their sum. This is represented as:

   $SS_{between} = n_1(\overline{X1} - \overline{\overline{X}})^2 + n_2(\overline{X2} - \overline{\overline{X}})^2 + n_3(\overline{X3} - \overline{\overline{X}})^2 + \cdots\cdots + n_k(\overline{Xk} - \overline{\overline{X}})^2$ …….(ii)

3.Calculate the variance or mean square ($MS_{between}$) between samples

   This is done by dividing the result obtained from equation (ii) by the degree of freedom between the samples. This is represented as:

   $MS_{between} = SS_{between} /(k-1)$ …………(iii)

   where (k-1) is the degree of freedom (d.f) between samples

4.Calculate the sum of squares for variance within samples (SS_{within})

   This is done by squaring the deviations of the values of the sample elements for all samples from respective means of the samples and then adding them together. This is represented as:

   $SS_{within} = \sum(X1i - \overline{X1})^2 + \sum(X2i - \overline{X2})^2 + \sum(X3i - \overline{X3})^2 + \cdots\cdots + \sum(Xki - \overline{Xk})^2$……(iv)

   (i= 1, 2, 3,……………k)

5. Calculate the variance or mean square within samples (MS_{within})

   This is done by dividing the result obtained from (iv) by the degree of freedom within samples. This is represented as:

   $MS_{within} = SS_{within} /(n-k)$…………………(v)

   where (n-k) represents degree of freedom within samples.

n= Total number of items in all the samples i.e. $n_1 + n_2 + n_3 + \ldots\ldots\ldots.. + n_k$, k= Number of samples

6. The sum of squares of deviations for total variance ($SS_{total\ variance}$) is equal to the squares of deviations for individual items from the mean of all sample means. This is represented as:

$SS_{total\ variance} = \sum(Xij - \bar{\bar{X}})^2$……………(vi)

i= 1, 2, 3,……..,   j= 1,2,3,………

$SS_{total\ variance}$ is equal to the sum of $SS_{between}$ and SS_{within}

($SS_{total\ variance} = SS_{between} + SS_{within}$)

7. The F- ratio in ANOVA is used to test the hypothesis and to judge whether the difference between several means is significant or has a sampling fluctuation.

F-ratio = $\frac{MSbetween}{MSwithin}$ …………(vii)

F-test is used to compare two population variances and F distribution is a right-skewed distribution. In F distribution, the numerator degrees of freedom are always given first because switching the order of degrees of freedom changes the distribution. To determine the 0.10 critical value for an F distribution with 5 and 6 degrees of freedom, the column 5 (numerator) is considered first and then row 6 (denominator) in the F table for ∞= 0.10.

It is observed that $F_{(0.10, 5, 6)} = 3.1075$ while $F_{(0.10, 6, 5)}$ is found to be 3.40451.

Hence $F_{(0.10, 5, 6)} \neq F_{(0.10, 6, 5)}$.

If the F value is less than the prescribed value (F-critical value) in the table then the difference is taken as insignificant and the null hypothesis between sample stands. When the value of F is greater than or equal to the F- critical value, then the difference is considered as significant. It implies that the samples could have come from different universe.

3.6.2 Methodology adopted for validation

Based on survey responses, the data obtained from 138 Indian industries are placed for validation using ANOVA analysis. The calculation steps are explained below:

Step 1: Calculate sample mean

Data collected from survey are used to calculate the sample mean using equation (i)

Step 2: Calculate the $SS_{between}$ and $MS_{between}$

Calculate the sum of squares between the samples by using equation (ii) and then mean of squares between the samples by using equation (iii)

Step 3: Calculate the SS_{within} and MS_{within}

Calculate the sum of squares within samples by using equation (iv) and mean of squares within samples using equation (v)

Step 4: Calculate F-ratio

F- ratio is calculated by dividing $MS_{between}$ and MS_{within} (obtained from step 3)

Step 5: Compare F-ratio with F-critical value

In this step, F- ratio obtained from step 4 is compared with F- critical value. This is done for different significant levels (∞= 0.01, 0.05 and 0.10).

The ANOVA analysis using above steps are shown in Table 3.3.

Table 3.3: ANOVA analysis at 0.01, 0.05, 0.1 significant factors

Source of variation	SS	DF	MS	F-ratio	F- critical value for different significant factors		
					∞= 0.01	∞= 0.05	∞= 0.10
Between groups	12.6554	2	6.3277	1.756	2.340	3.920	2.347
Within groups	41.1803	70	0.5883				
Total	53.8356	72					

Table 3.3 depicts the calculation steps for F-ratio and also gives the F-critical values. It reflects that F-ratio is 1.756, which is smaller than F- critical value for different values of ∞= 0.01, 0.05 and 0.10. The analysis therefore signifies that the data collected from questionnaire survey is significant and the null hypothesis stands i.e., all sample means are equal.

3.7 SUMMARY

The followings are important observations from the survey analysis.

i On the basis of responses obtained, the organizations can be classified as below:

- Based on number of employees
- Based on turnover of the organizations
- Based on number of production shops
- Based on number of products manufactured by the industries
- Based on components manufactured in-house.

ii Out of 138 respondent industries, the following observations are obtained:

- 31% industries have less than 100 employees
- 6% industries have more than 500Cr. turnovers

- 25% industries have single production shops while 7% industries have more than 8 shops
- 51.44% industries produce 1-5 components while 7.97% produce more than 20 components.

Data obtained through survey questionnaire were analyzed using ANOVA analysis and verified at different significant levels. ANOVA analysis reflects that the data obtained from survey of Indian industries are significant. The F-value of 1.756 is found to be lower than F-critical value of 2.34 (at 0.01 significant factor), 3.920 (at 0.05 significant factor) and 2.347 (at 0.10 significant factor). The analysis therefore validates that the collected data from questionnaire survey is significant.

CHAPTER IV

INTERPRETIVE STRUCTURAL MODELING FOR MITIGATING BARRIERS TOWARDS SMS

4.1 INTRODUCTION

Industrial revolution played key roles towards the society's restructuring by creating new products using new manufacturing technologies and processes. Increased manufacturing activities to fulfil the demand of the society has however escalated environmental problems, resource depletion, generation of pollution and several other issues (Young et al., 2012).

Modern age customers desire products of high-quality, improved design and aesthetics, environment-friendliness and that too at the lowest possible price. Traditional manufacturing practices have strong economic concerns, but are responsible for environmental degradation, ecological imbalance and several negative implications to the society. Manufacturers are expected to address these challenges through the adoption of manufacturing practices amenable to sustainable manufacturing system (SMS).

Shankar et al. (2017) viewed that manufacturers have to reassess and redesign their existing manufacturing systems to cope with the challenges of globalization and environmental concerns. They discussed the benefits of sustainable manufacturing from triple bottom line (environmental, social and financial pillars of sustainability) and viewed that the majority of manufacturing strategies are limited to one or two of these factors.

In view of the existence of multifaceted barriers integral to manufacturing systems, transitioning to SMS is a real challenge. There is no reliable procedure or guidelines that can guarantee the successful implementation of SMS- the existing literatures can't adequately support the organizations in this direction. The gap in literatures has forced the researchers to investigate towards the development of SMS. Review of literatures and aptly complimented by experts' opinion helped to identify critical barriers from sustainability perspective. The present study takes the opportunity to identify various barriers from current manufacturing practices and to mitigate them. An ISM modeling framework for SMS is developed linking important barriers in Indian manufacturing context. The model reveals important insights to formulate strategies to overcome these barriers.

4.2 IDENTIFICATION OF BARRIERS FOR THE DEVELOPMENT OF SMS

Various barriers identified for the development of SMS is deliberated in Table 4.1.

Table 4.1: Identification of barriers for SMS

S. No.	Barriers of Sustainable manufacturing	Reference/ Sources
1	Poor education and environmental awareness of workmen	Bhanot et al. (2015), Mutingi et al. (2017), Kollmuss and Agyeman (2002), Kulatunga et al. (2013)
2	Poor focus on conservation of natural resources	Koltun (2010), United Nations department of economic and social affairs (2006), Gungor and Gupta (1999)
3	Lack of top management support	Hameed et al. (2014), Bhanot et al. (2015), Mutingi et al. (2017)
4	Poor motivation and teamwork of the employees	Carley et al. (2014)
5	Lack of capital to set up green projects	Bhanot et al. (2015), Mutingi et al. (2017), Geir (1994)
6	Improper business ethics/ company policy	Kumar et al. (2014)
7	Improper pollution and waste management practices	Carley et al. (2014), Kaebernick and Kara (2006), Mohanty (2011), Gungor and Gupta (1999)
8	Lack of vision for long term sustainable development	Bhanot et al. (2015), Mutingi et al. (2017), Kulatunga et al. (2013), Strandberg consulting (2012), McDonach and Yaneske (2002)
9	Lack of appropriate technologies	Gunasekaran et al. (2018), Beder (1994), Herdman (1994), Shan et al. (2012)
10	Lack of eco- innovation-oriented research	OECD (2009), Mulder (2007)
11	Lack of standardized metrics or performance benchmarks	OECD (2009), Bhanot et al. (2015), Mutingi et al. (2017), Faure (1995), Feng and Joung (2009)
12	Inadequate focus on 4 R's principles	Shirodkar and Terkar (2017), Shi et al. (2005), Chen (2006), Mohanty (2011)
13	Poor compliance to environmental legislations	Faure (1995), Gungor and Gupta (1999)
14	Poor focus on energy efficiency and energy efficient process	United Nations department of economic and social affairs (2006), Carley et al. (2014)
15	Lack of government support towards developing new technologies	Millar and Russell (2011)

16	Inappropriate environment management systems	McDonach and Yaneske (2002), Jayashree et al. (2015)
17	Poor monitoring and control	Pavlovskaia (2014), Stavropoulosa et al. (2013)

4.3 ANALYSIS OF BARRIERS FOR SMS USING ISM AND MICMAC

Interpretive structural modeling is a MCDM technique first proposed by J. Warfield in 1973 for the analysis of complex socio-economic systems. ISM methodology enables to develop mutual relationships among a set of elements in a complex system. Experts' judgment was sought to develop the relationships among the identified barriers and to obtain a SSIM matrix. A reachability matrix is formed incorporating transitivity concept. Other steps in ISM are level partitioning, conical matrix formation, development of digraph and hierarchy model. The developed model reflects the relationships among the barriers that provide meaningful understanding for the success towards SMS. The various stages towards the expansion of analysis are described below.

4.3.1 Stages of ISM methodology

ISM develops a contextual relationship among the identified barriers. The important steps in ISM methodology are the followings:

- To develop the contextual relationships among the barriers and to establish structural- self interaction matrix (SSIM)
- Establishment of reachability matrix (RM) by incorporating transitivity
- Level partitioning and formation of conical matrix
- Structuring of digraphs using nodes
- Development of ISM model from the digraph with nodes replaced by statements
- MICMAC analysis
- Review of ISM model for conceptual inconsistency and carry out necessary changes, if required.

The above steps are explained below.

4.3.1.1 Development of structural self-interaction matrix

A panel of experts were involved in the development of SSIM linking 17 identified barriers. Their contextual relationship is developed through an organized decision-making process by a team of experts to systematically arrive at the decision solution. Four notations namely V, A, X and O has been used to denote their mutual relationships in the (i, j) matrix. Symbol V is used if i helps to achieve j; A is used if j helps to achieve i; X is used if both i and j help to achieve each other; O is used if i and j has no relation. The SSIM for the barriers is represented in Table 4.2.

Table 4.2: SSIM for barriers in sustainable manufacturing

Sl. No.	Barriers for Sustainable manufacturing	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2
1	Poor education, environmental awareness of workmen	V	V	O	V	V	V	A	X	V	V	V	A	O	V	A	V
2	Poor focus on conservation of natural resources	A	A	A	X	X	X	A	A	A	A	V	A	A	A	A	
3	Lack of top management support	V	V	A	V	V	V	V	V	V	V	V	A	V	V		
4	Poor motivation, teamwork of the employees	V	V	O	V	V	V	X	V	V	V	V	A	O			
5	Lack of capital to set up green projects	O	V	A	V	V	V	O	V	O	O	V	O				
6	Improper business ethics/ company policy	V	V	A	V	V	V	V	V	V	V	V					
7	Improper pollution and waste management practices	A	A	A	X	X	X	A	A	A	A						
8	Lack of vision for long term sustainable development	V	V	A	V	V	V	V	V	V							
9	Lack of appropriate technologies	V	V	A	V	V	V	A	A								
10	Lack of eco- innovation-oriented research	V	V	A	V	V	V	A									
11	Lack of standardized metrics or performance benchmark	V	V	A	V	V	O										
12	Inadequate focus on 4 R’s principles	A	A	A	X	X											
13	Poor compliance to environmental legislations	A	A	A	X												
14	Poor focus on energy efficiency and energy efficient process	A	A	A													
15	Lack of government support towards developing new technologies	V	V														
16	Inappropriate environment management systems	V															
17	Poor monitoring and control																

4.3.1.2 Development of reachability matrix

Initial reachability matrix is formed by the following substitution rule:

i. If (i, j) cell in SSIM is V: replace V with 1 in (i, j) and place 0 in (j, i)
ii. If (i, j) cell in SSIM is A: replace A with 0 in (i, j) and place 1 in (j, i)
iii. If (i, j) cell in SSIM is X: replace X with 1 in (i, j) and place 1 in (j, i)
iv. If (i, j) cell in SSIM is O: replace O with 0 in (i, j) as well as place 0 in (j, i)

This is represented in Table 4.3.

Table 4.3: Initial reachability matrix

S. No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	1	1	0	1	0	0	1	1	1	1	0	1	1	1	0	1	1
2	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
3	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1
4	0	1	0	1	0	0	1	1	1	1	1	1	1	1	0	1	1
5	0	1	0	0	1	0	1	0	0	1	0	1	1	1	0	1	0
6	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1
7	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
8	0	1	0	0	0	0	1	1	1	1	1	1	1	1	0	1	1
9	0	1	0	0	0	0	1	0	1	0	0	1	1	1	0	1	1
10	1	1	0	0	0	0	1	0	1	1	0	1	1	1	0	1	1
11	1	1	0	1	0	0	1	0	1	1	1	0	1	1	0	1	1
12	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
13	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
14	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
15	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
16	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	1	1
17	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	1

The concept of transitivity is applied for developing the final reachability matrix. If a barrier ‘p’ affects ‘q’ and ‘q’ affects ‘r’, then as per transitivity concept ‘p’ will also affect ‘r’. Figure 4.1 represents the same.

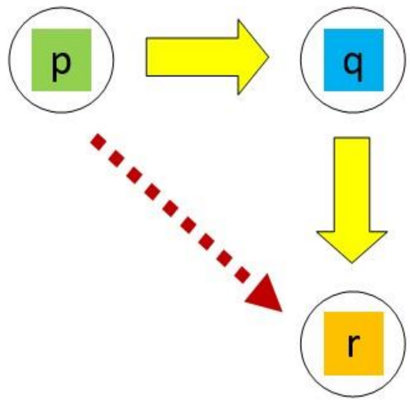

Figure 4.1: Concept of transitivity

The concept of transitivity is applied to obtain the final reachability matrix. Symbol (*) denotes the transitivity applied. Table 4.4 represents the same.

Table 4.4: Final reachability matrix

S. No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	1	1	0	1	0	0	1	1	1	1	0	1	1	1	0	1	1
2	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
3	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1
4	1*	1	0	1	0	0	1	1	1	1	1	1	1	1	0	1	1
5	1*	1	0	0	1	0	1	0	1*	1	0	1	1	1	0	1	0
6	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1
7	0	1*	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
8	1*	1	0	1*	0	0	1	1	1	1	1	1	1	1	0	1	1
9	0	1	0	0	0	0	1	0	1	0	0	1	1	1	0	1	1
10	1	1	0	0	0	0	1	0	1	1	0	1	1	1	0	1	1
11	1	1	0	1	0	0	1	0	1	1	1	1*	1	1	0	1	1
12	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
13	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
14	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0
15	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
16	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	1	1
17	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	1

4.3.1.3 Level partitioning

Level partitioning helps to arrange the barriers in a hierarchical manner. This is done by using the final reachability matrix to find the reachability set, antecedent set and intersection set. Reachability set encompasses the barrier itself and all other barriers that are influenced by it. The antecedent set contains the barrier itself and all other barriers that can influence it. Intersection set includes common barriers of reachability and antecedent set. Top-level barrier corresponds to the one where reachability set matches with the intersection set. Top-level barrier is removed from the iteration and the procedure is repeated for next level of barriers. The final iteration table reflects iteration (Level I- X) and is shown in Table 4.5.

Table 4.5: Final iteration table (i to x)

Barrier No.	Reachability Set	Antecedent Set	Intersection Set	Level
2	2,7,12,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15, 16,17	2,7,12,13,14	**I**
7	2,7,12,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15, 16,17	2,7,12,13,14	
12	2,7,12,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15, 16,17	2,7,12,13,14	
13	2,7,12,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15, 16,17	2,7,12,13,14	
14	2,7,12,13,14	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15, 16,17	2,7,12,13,14	
17	17	1,3,4,6,8,9,10,11,15, 16,17	17	**II**
16	16	1,3,4,5,6,8,9,10,11, 15,16	16	**III**
9	9	1,3,4,5,6,8,9,10,11,15	9	**IV**
1	1,4,8,10	1,3,4,5,6,8,10,11	1,4,8,10	**V**
10	1,10	1,3,4,5,6,8,10,11,15	1,10	
4	4,8,11	3,4,6,8,11	4,8,11	**VI**
5	5	3,5,15	5	
11	4,11	3,4,6,8,11,15	4,11	
8	8	3,6,8,15	8	**VII**
3	3	3,6,15	3	**VIII**
6	6	6,15	6	**IX**
15	15	15	15	**X**

4.3.1.4 Development of conical matrix

Conical matrix is formed by clubbing the barriers of the same level. The driving power of a barrier is the sum of 1's in the rows and its dependence power is that in the columns. This is shown in Table 4.6.

Table 4.6: Conical matrix representing drive and dependence power of barriers

Barrier No.	2	7	12	13	14	17	16	9	1	10	4	5	11	8	3	6	15	Drive Power
2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	**5**
7	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	**5**
12	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	**5**
13	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	**5**
14	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	**5**
17	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	**6**
16	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	**7**
9	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	**8**
1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	**12**
10	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	**10**
4	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	**13**
5	1	1	1	1	1	0	1	1	1	1	0	1	0	0	0	0	0	**10**
11	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	**12**
8	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	**13**
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	**15**
6	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	**15**
15	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	**15**
Dependence Power	**17**	**17**	**17**	**17**	**17**	**11**	**11**	**10**	**8**	**9**	**6**	**3**	**6**	**6**	**3**	**2**	**1**	

4.3.1.5 Development of digraph

Based on conical matrix, a digraph is developed using nodes and directed edges. The top-level barrier is placed at the top of the digraph. Second level barrier is placed at second position and so on until all the barriers are placed in the digraph. The digraph is shown in Figure 4.2.

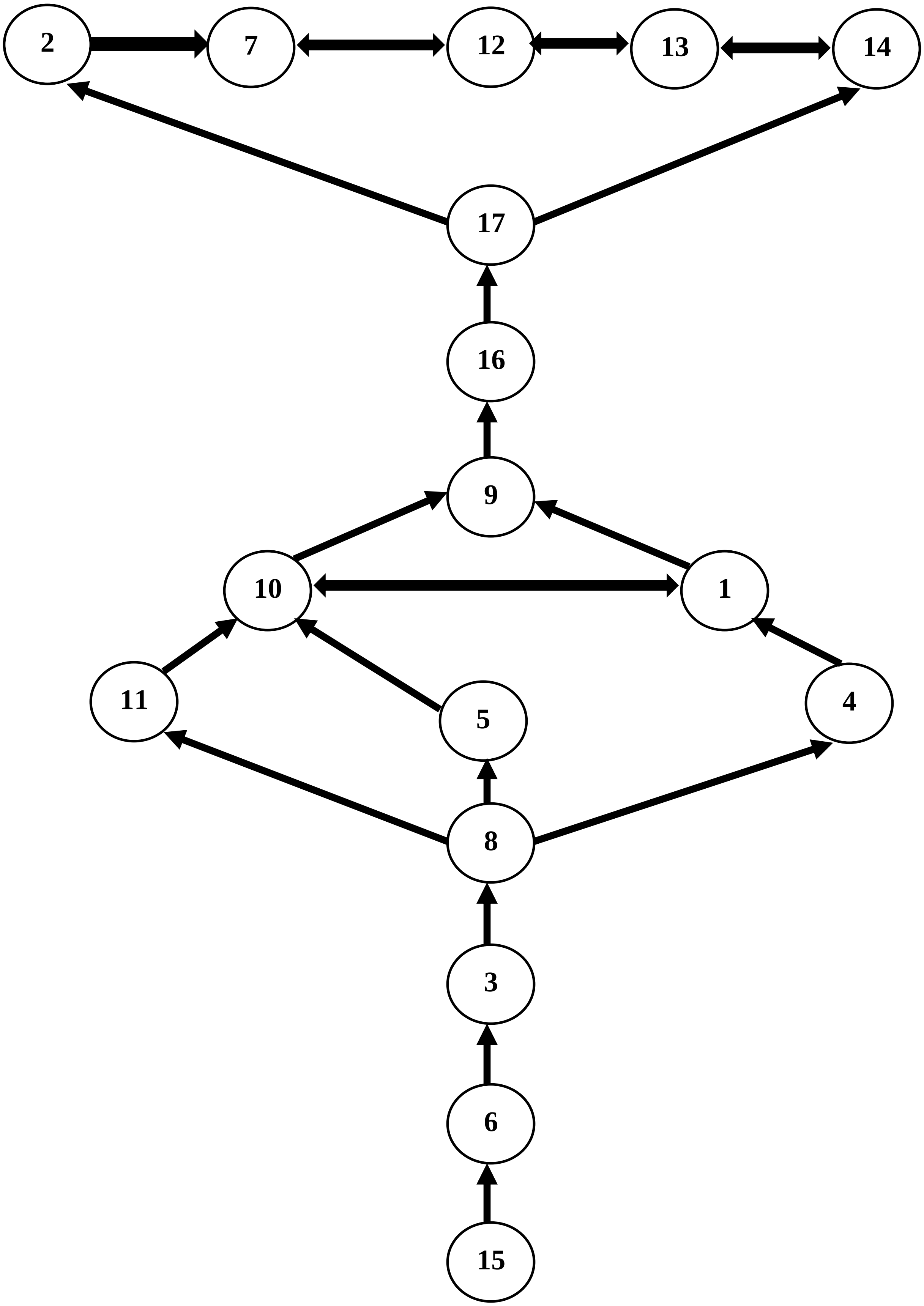

Figure 4.2: Digraph for the development of SMS

4.3.1.6 Development of ISM-based model

The digraph is converted into an ISM based model by replacing the nodes with barrier descriptions. This is shown in Figure 4.3 (page 70). The model reflects that the most important barrier towards the implementation of SMS in Indian manufacturing context is lack of government support towards developing new technologies (barrier 15) and is placed at the bottom of the ISM hierarchy. Barriers namely (2), (7), (12), (13) and (14) are top level barriers. ISM model shows the hierarchical structure incorporating identified barriers. The model explains the followings:

- Five barriers (2), (7), (12), (13), (14) are positioned at the top of the hierarchy. These 'Top-level barriers' are: Poor focus on conservation of natural resources, improper pollution and waste management practices, inadequate focus on 4 R's principles, poor compliance to environmental legislations and poor focus on energy efficiency and energy efficient process. The effectiveness of SMS implementation depends on these top-level barriers to a great extent. These are influenced by lower-level barriers. Top level barriers (L-I) are designated as level-I barrier
- Barrier namely poor monitoring and control (17) is at level- II. It is to note that inadequate monitoring and control will influence each of the level-I barriers
- Inappropriate environment management system (16) is level- III barrier. This is affected by lack of appropriate technologies (9), a level- IV barrier
- Poor education and environmental awareness of workmen (1) and lack of eco-innovation-oriented research (10) are level V- barriers. These barriers have influence on each other as reflected from the hierarchy model. It is evident that lack of education and awareness and eco-innovative research (level- V barriers) can adversely impact the level- IV barrier
- Poor motivation and teamwork of the employees (4), lack of capital to set up green projects (5) and lack of standardized metrics or performance benchmarks (11) are level- VI barriers. It is observed that both the barriers (11) and (5) influence the barrier (10) of level- V
- Lack of vision for long term sustainable development (8) is at level-VII. This barrier influences the barriers (4), (5) and (11) of level- VI
- Lack of top management support (3) is placed at level-VIII. Lack of sensitivity by top management can blur the organization's vision towards long term sustainable development. This barrier is one the most important pillars for the development of SMS
- Improper business ethics/ company policy (6) is a level- IX barrier.

- Lack of government support towards developing new technologies (15) is at the bottom of the ISM hierarchy and is placed at level- X. This barrier has highest drive power and lowest dependence and is vital towards the initiation as well as implementation of SMS.

All stakeholders must take appropriate remedial measures to overcome these barriers. Based on the hierarchy and mutual interactions of these barriers, remedial measures must be taken for successful implementation of SMS.

4.3.1.7 MICMAC analysis

Cross-impact matrix multiplication applied to classification is abbreviated as MICMAC. It is based on multiplication properties of matrices and is used to analyze the driving/dependence power of elements in a system (Gorane and Kant, 2013; Dubey et al., 2015).

In the present analysis the identified barriers are classified into four clusters. The first cluster contains 'autonomous barriers' that have weak driving as well as weak dependence power. These barriers have weak links with the system and are relatively disconnected from the system. Second cluster consists of 'dependent barriers' that have strong dependence power but weak driving power. Third cluster contains barriers that have strong driving as well as strong dependence power and are called 'linkage' barriers. The fourth cluster contains 'independent barriers' that have strong driving but weak dependence power. The key barriers with high degree of driving power generally lie in independent or linkage category.

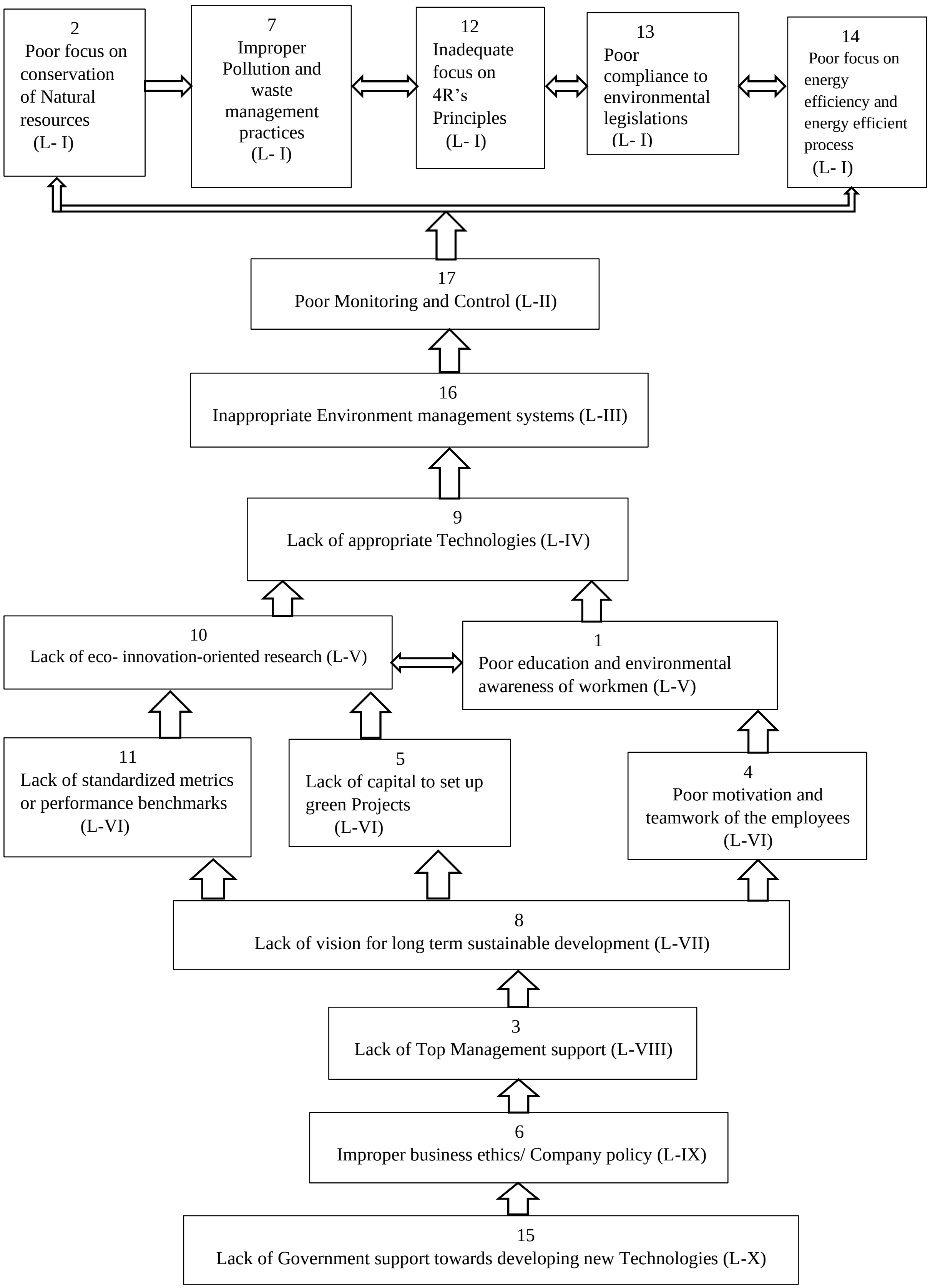

Figure 4.3: ISM-based hierarchical model for mitigating barriers in SMS

The driving- dependence power diagram is depicted in Figure 4.4.

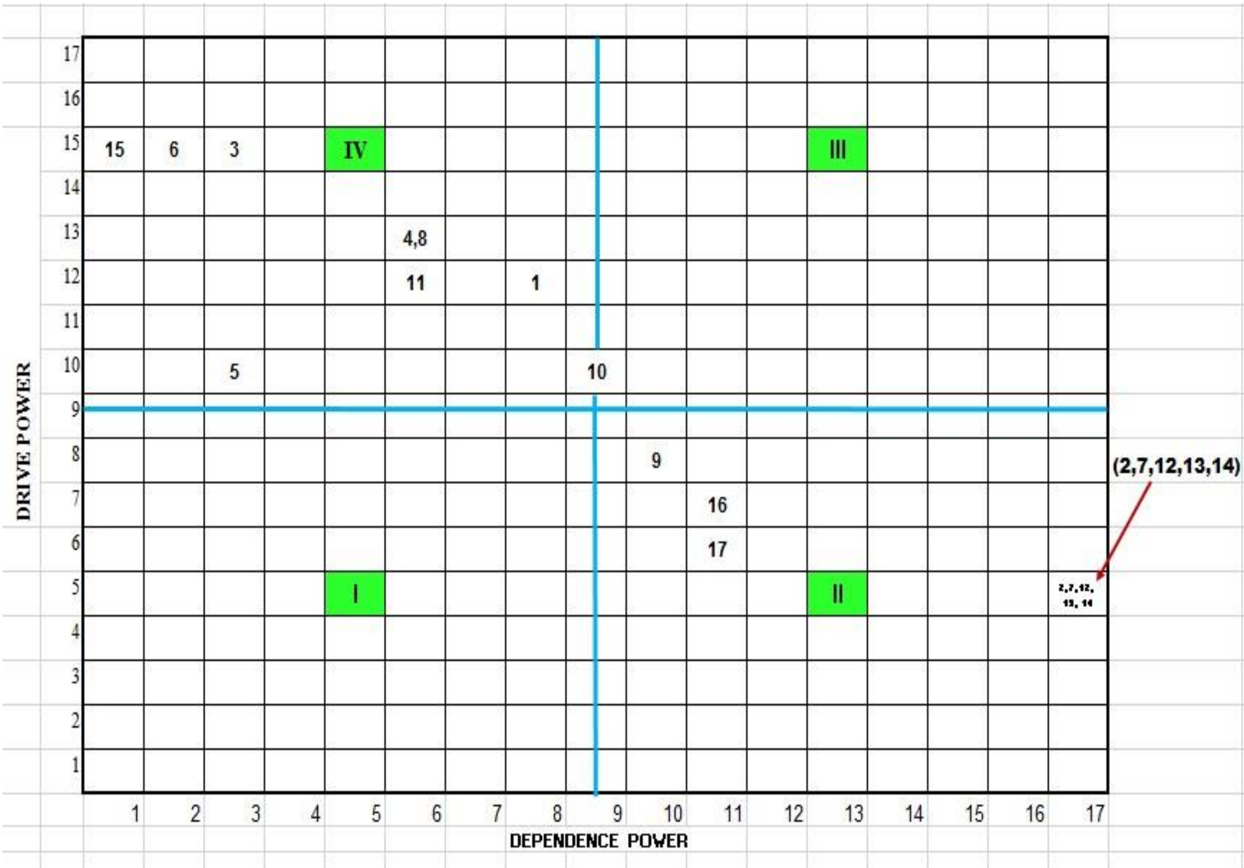

Figure 4.4: Driving- dependence power diagram (MICMAC analysis)

MICMAC analysis represents the driving-dependence relationships of the barriers. Following inferences are drawn from the MICMAC analysis:

- Autonomous barriers are characteristically disconnected from the system because of weak driving and dependence power. There is no autonomous barrier in the driving-dependence diagram implying that all the identified barriers are of critical importance from sustainability viewpoint.
- Dependent barriers have weak driving power but strong dependence power. These barriers are therefore influenced by other barriers. A total of 8 barriers that lie in this category are: Poor focus on conservation of natural resources (2), improper pollution and waste management practices (7), inadequate focus on 4 R's principles (12), poor compliance to environmental legislations (13), poor focus on energy efficiency and energy efficient

process (14), lack of appropriate technologies (9), inappropriate environment management systems (16) and poor monitoring and control (17).

Dependent barriers have little or insignificant effect on other barriers. They are however influenced by other low-level barriers. Management must attribute a benchmark index representing the impact level of such barriers. It is also observed that out of these, barriers (2), (7), (12), (13) and (14) occupy exactly the same cell (same driving and dependence power).

- Linkage barriers (marked as III) have strong drive, as well as, strong dependence power. These barriers can influence higher level barriers. For example, lack of eco-innovation-oriented research (10) can influence the technological upgradation. Lower-level barriers also influence this barrier. It may be noted that barrier (10) lies in both the linkage and independent barrier category.
- Independent barriers can be considered as *key-barriers*. They have strong driving but weak dependence power. These are: Lack of Government support towards developing new technologies (15), improper business ethics/ company policy (6), lack of top management support (3), poor motivation and teamwork of the employees (4), lack of vision for long term sustainable development (8), lack of standardized metrics or performance benchmarks (11), poor education and environmental awareness of workmen (1) and lack of capital to set up green projects (5). These barriers by virtue of high driving power can greatly influence all other barriers. Management should implement pro-active interventions in alleviating these key barriers.

4.4 CONCLUSION

This chapter analyzes barriers that hinder the promotion of sustainable manufacturing system. The ISM based model is developed to analyze the interaction among these barriers. MICMAC analysis, through driving - dependence analysis helps in classifying these barriers. Analysis of ISM indicates that there is no barrier in the Autonomous barrier category. Therefore, all the selected barriers have an impact towards the progress of SMS. Dependent barriers, by virtue of weak driving and strong dependence power, are influenced by other barriers. Government support and commitment of top management together form the pillars for the promotion of SMS by mitigating the effects of other barriers. Eco-innovative research is a linkage barrier. This barrier, by virtue of strong drive and dependence power can influence, and be influenced, by other barriers. The management should invest in research and development activities and impart training to all employees in order to moderate this barrier. Independent barriers have strong driving but weak dependence power and are the key barriers. Due to their high driving power, these barriers can significantly influence other barriers. These barriers have a dissimilar driving power. For example, lack of government support towards developing new technologies poses the highest barrier. Lack of business ethics/company policy and lack of top management support are also important bottlenecks towards the evolution of SMS in any organization. Focus on alleviating the effects of the remaining independent barriers can further the cause of SMS.

The analysis reveals that barriers like lack of government support towards new technologies, lack of commitment from top management, poor motivation of the employees and all such barriers are detrimental towards the promotion of SMS. It is concluded from the analysis that support of government and top management through pro-active interventions are essential for alleviating all allied barriers of manufacturing and therefore will encourage the implementation of sustainable manufacturing systems.

CHAPTER V

QUANTITATIVE ANALYSIS OF VARIOUS BARRIERS USING GTA METHODOLOGY

5.1 INTRODUCTION

The challenges of environmental degradation, sinking natural resources and various other issues caused by existing manufacturing practices pursuit for newer manufacturing techniques to address such issues. Sustainable manufacturing practices can address increasing social, economic and environmental challenges typically associated with traditional manufacturing systems. Because of the existence of a variety of barriers in an industrial setup, the advancement towards sustainable manufacturing system is a formidable task. A holistic study of manufacturing systems is the indispensable need to formulate strategies to overcome these barriers.

5.2 ORGANIZATION OF BARRIERS FOR SMS

Based on literature review related to sustainable manufacturing practices and understandings from academicians and industry experts, it has been perceived that SMS is a complex and multifaceted system. Implementation of SMS on the shop floor therefore is a challenging mission. A holistic study of various barriers that inhibits the progress towards SMS is essential for the meaningful implementation of sustainable practices in a manufacturing setup.

Literature review and expert’s opinion helped to recognize important barriers that hinder the implementation of SMS to a great extent. In order to analyze the barriers appropriately, they are clustered in five categories (B_1 to B_5) as listed in Table 5.1.

Table 5.1: Main barrier categories towards SMS

Barrier No.	Description of Barriers
B_1	Environmental barriers
B_2	Social and behavioral barriers
B_3	Financial barriers
B_4	Technological barriers
B_5	Implementation and operational barriers

The following section gives a brief review of each barrier categories.

5.2.1 Environmental barriers (B_1)

Rapid industrialization is the primary reason behind environmental problems like increase of pollution, global warming, climate change, acid rain, ozone layer depletion, rise of emission etc. Manufacturers across the globe can mitigate these global challenges to a great extent through the adoption of sustainable manufacturing practices.

The average growth rate of manufacturing industries in China between 1990 to 2015 was 24%. Various manufacturing activities were primarily responsible for depletion of resources and environmental degradation to a great extent (Lin and Xu, 2017; Orji, 2019).

Feng et al. (2018) cited that China's metal industries consume approximately 36.65% of the total energy and may be put under high emission and high energy consumption category – these poses serious threat to sustainability. Zhu et al. (2010) noted that environmental regulatory policies in China has latterly focused on organizational restructuring through the adoption of sustainable practices.

5.2.2 Social and behavioral barriers (B_2)

Social and behavioral barriers reflect human perceptions and responses towards the changes of their surroundings and work areas. These barriers are related to their values, habits, conducts, philosophies or cultures within the societal framework and plays a significant role towards the adoption of SMS. These barriers might include employees' resistance towards organizational changes, lack of public perception towards environment and environmental issues, poor CSR initiatives by the management, lack of workers' motivation, lack of participatory teamwork of all stakeholders and the like. Employees' resistance largely arises due to their fear and anxiety towards loss of jobs during the execution and development of new projects.

Lack of societal awareness towards sustainability concepts do not compel manufacturers in promoting sustainable manufacturing practices. Neither, the policy makers are being forced by the ignorant community to frame stringent regulations or guidelines that might address sustainability issues in manufacturing sectors. It has also been highlighted that some manufacturers with foreign business partnerships improved their manufacturing operations by incorporating sustainability concepts in their manufacturing practices. Some other organizations adopted the same due to market pressure stimulated from environmentally conscious customers (Kulatunga et al., 2013).

5.2.3 Financial barriers (B_3)

To cope-up with the rising competitions, manufacturers need to periodically invest in new equipment and sustainable technologies. In early businesses, it was perceived that incorporation of sustainability concepts in manufacturing would incur a lot of capital without much return on investment. Many organizations therefore were not willing to invest towards technological upgradation. Moreover, it was difficult to accurately forecast the returns that could have been achieved by investing huge sum of capital. Gradually the earlier perception has changed and sustainable practices have become a preferred choice due to its perceived benefits. Government and financial institutions are expected to offer incentives and subsidies to the manufacturers who are willing to develop sustainable technologies and practices. In contrary to the general perception that sustainability increases the cost of business, it can actually result in financial gain for the business. Mutingi et al. (2017) recommended that high costs and inadequate funding are the most inhibiting barriers towards SMS.

Ghisetti et al. (2017) carried out an empirical analysis which showed that financial barriers have negative effects on environmental innovation investment decisions. The research further studied various influential factors of financial barriers towards cleaner production choices.

5.2.4 Technological barriers (B_4)

Technological barriers are linked with the non-availability of advanced machines and technologies that could enhance the productivity or efficiency. By enlightening skills and competencies to the employees with latest technologies and sustainability concepts, some issues in technological barriers can be addressed. Role of research and development and technological innovations are indispensable towards the eradication of technological barriers.

Mutingi et al. (2017) noted that proper management of manufacturing processes might help in reduction of overall cost and thereby aid in the implementation of sustainable manufacturing technologies and practices. Herdman (1994) observed that availability of appropriate technologies is vital to promote sustainable development in United States.

5.2.5 Implementation and operational barriers (B_5)

Implementation and operational barriers are important bottleneck towards the development of SMS. These barriers might arise due to unfavorable government support and policies, lack of capital and appropriate technologies, lack of top management support and similar reasons. In order to mitigate inadequate funding or financial barriers it is expected that organizations must invest and work towards innovation and sustainable technologies (Mutingi et al., 2017).

Herdman (1994) suggested that partnerships and mutual cooperation among industrial and developing countries might help to address various technological and implementational issues through appropriate innovative solutions.

5.3 ANALYSIS OF BARRIERS FOR SMS USING GTA

The current work is directed towards the analysis of identified barriers and to appraise them in numerical values using graph theoretic approach (GTA). GTA being an important MCDM technique towards the modeling and analysis of a variety of scientific and engineering problems has been chosen for the present analysis. Literature review divulges a wide- ranging applications of GTA. Some of these are presented in literature review section.

Swiss mathematician Leonhard Euler invented the graph theory in the 18^{th} century. It does not represent any kind of graph or chart like line graph, area graph, bar graph, pie graph etc. Rather it represents to a set of nodes (points or vertices) connected by edges. Directed graphs or digraphs have directions for each edge.

GTA methodology has the following characters, distinctiveness and advantages as compared to other similar MCDM techniques. These are highlighted below:

i. It is a systematic technique and a convenient decision-making tool
ii. It is a mathematical modelling technique
iii. The methodology follows three distinct steps namely: (a) Digraph representation (b) Matrix representation and (c) Permanent function representation
iv. GTA reflects directional relationships, inheritance and interdependence among a set of selected criteria and sub-criteria
v. It helps in the conversion of qualitative data into quantitative one
vi. Digraph representation aids in visual analysis; computerized processing is also possible
vii. It is possible to obtain single numerical value for the system under study
viii. It helps in the selection of best alternatives through permanent function values
ix. The numerical score helps in ranking of alternatives.

The permanent function encompasses all barrier categories and sub-barriers in manufacturing systems, thus portraying a true picture of the whole system. The outcome of the analysis will help business managers to derive strategies to overcome the barriers. This will enable smooth transition towards SMS in the organization.

5.3.1 Structuring of digraph involving various barriers

A detail theory of directed graphs was presented by Bangjensen and Gutin (2008). Digraphs are extensively used by researchers for various studies and analysis. It has been successfully used in the field of mathematics, operations research, physics, computer science among others.

A digraph (directed graph) depicts a visual representation displaying inter-relationships among various elements linked to the system under consideration. The digraph consists of nodes and directed edges. The nodes represent the barriers/sub-barriers that have been taken into consideration in the present analysis. The edges characterize the interdependence among the barriers or sub-barriers. Directed arrows display how the barriers affect or are being affected by one another. In the SMS barriers' digraph (Figure 5.1), five nodes represent the barrier categories and the directed edges reflect their mutual relationships.

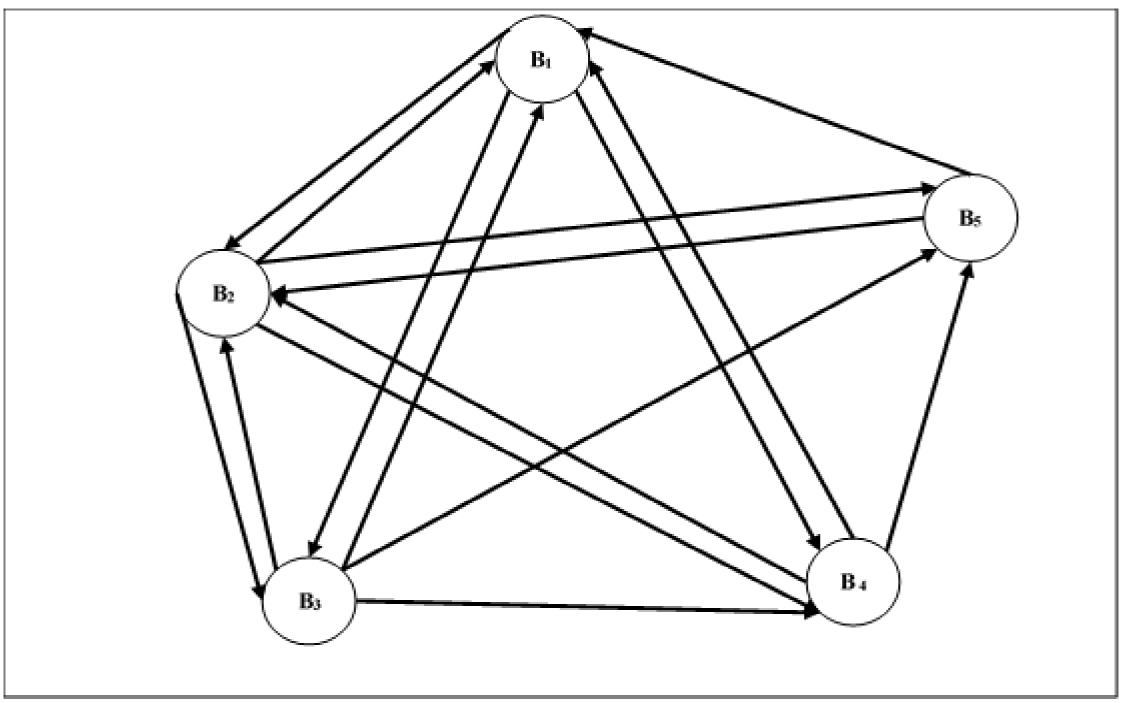

Figure 5.1: Digraph representing various categories of barriers

The mutual relationships among barriers are derived from the inferences of academicians and industry experts. Figure 5.1 reflects that financial barriers (B_3) affects all other barriers namely environmental barriers (B_1), social and behavioral barriers (B_2), technological barriers (B_4) and implementation and operational barriers (B_5). However, financial barriers (B_3) are affected by environmental barriers (B_1) and social and behavioral barriers (B_2) as dictated by experts. The sub-barriers under each barrier categories (B_1 to B_5) are denoted in Table 5.2 to 5.6. Digraphs in Figure 5.2 to 5.6 characterizes the relationships among sub-barriers based on expert's opinion.

Table 5.2: Sub-elements to environmental barriers (B_1)

Environmental barriers (B_1)		
Sub-barriers	**Description of sub-barriers**	**Reference/ sources**
B_{11}	Lack of societies consciousness on environmental issues and sustainable development	Bhanot et al. (2015), Mutingi et al. (2017), Kollmuss and Agyeman (2002), Kulatunga et al. (2013)
B_{12}	Lack of initiatives towards resource conservation by stakeholders	Koltun (2010), UNDESA (2006), Gavrilescu (2004), Lin and Xu (2017), Orji (2019), Herdman (1994)
B_{13}	Lack of sensitivity of policy designers towards eco-friendly products and practices	Hameed et al. (2014), Bhanot et al. (2015), Mutingi et al. (2017), Zhu et al. (2010), Chen (2006), Faure (1995), Gungor (1999)
B_{14}	Poor monitoring and control of EMS (Environment management system) by the concerned regulatory agencies	McDonach et al. (2002), IIED, Gavrilescu (2004), Chen (2006), Jayashree et al. (2015)
B_{15}	Inefficient pollution control systems and waste management practices	Carley et al. (2014), Gavrilescu (2004), Mohanty (2011)

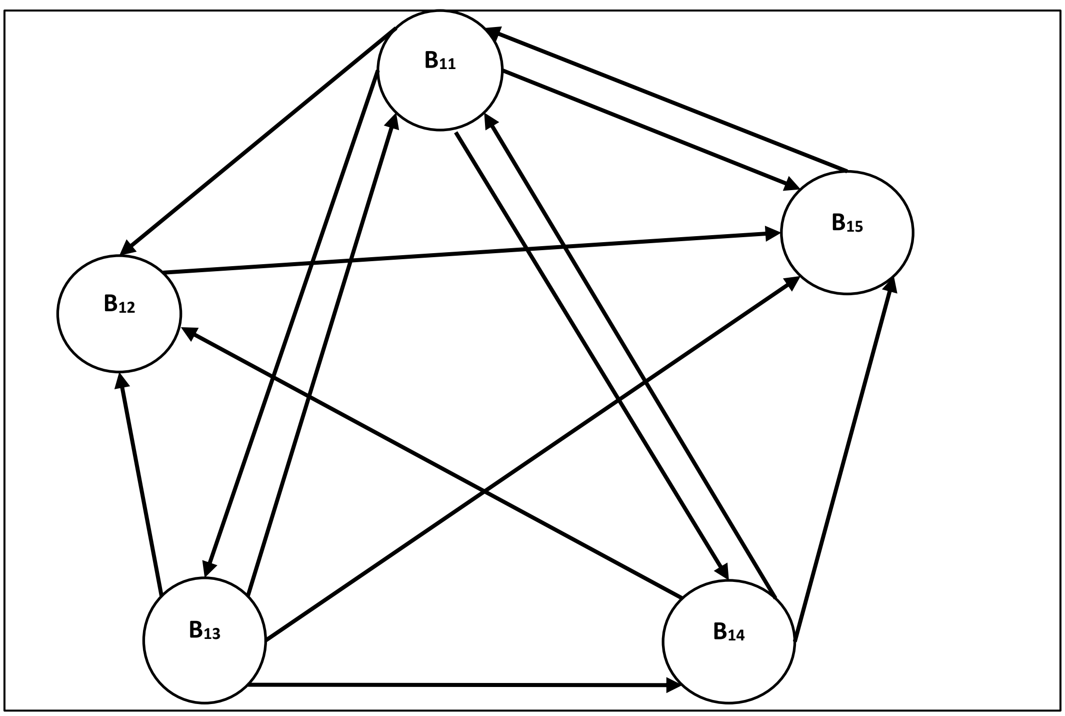

Figure 5.2: Digraph representing environmental barriers

Table 5.3: Sub-elements to social and behavioral barriers (B_2)

Social and behavioral barriers (B_2)		
Sub-barriers	**Description of sub-barriers**	**Reference/ sources**
B_{21}	Employee resistance to organizational change	Bhanot et al. (2015), Mutingi et al. (2017), Kulatunga et al. (2013)
B_{22}	Lack of public awareness and societal pressure on sustainability related issues	Bhanot et al. (2015), Mutingi et al. (2017), Kulatunga et al. (2013), Enshassi and Mayer (2005), Garg et al. (2014)
B_{23}	Lack of internal motivation influenced by values, attitude and emotions	Gavrilescu (2004), Safiullah (2015)
B_{24}	Demographic barriers including income, education level, culture, location of home	Buzuku and Kraslawski (2017), Enshassi and Mayer (2005)
B_{25}	Poor corporate social responsibility culture	Lixin et al. (2015), Valiente et al. (2012)

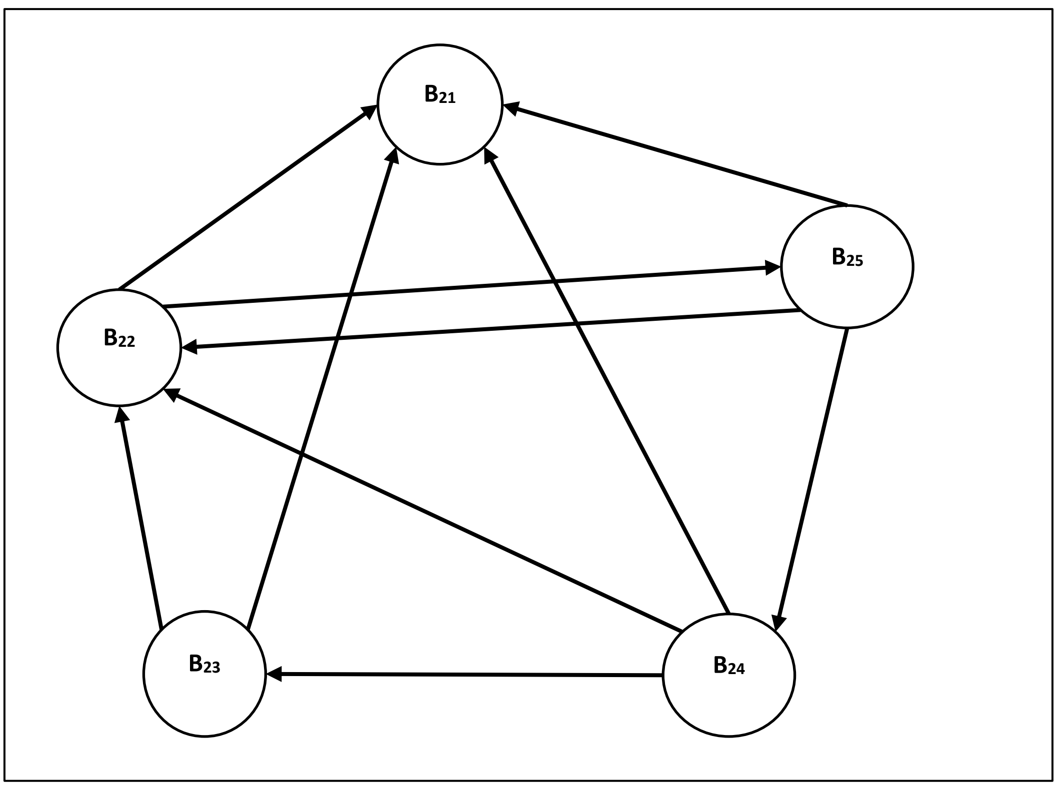

Figure 5.3: Digraph representing social and behavioral barriers

Table 5.4: Sub-elements to financial barriers (B_3)

Financial barriers (B_3)		
Sub-barriers	**Description of sub-barriers**	**Reference/ sources**
B_{31}	Lack of financial resources	Ametepey et al. (2015), Enshassi and Mayer (2005), Ghisetti (2015)
B_{32}	Deficit towards high investment cost towards implementing SMS	Bhanot et al. (2015), Mittal et al. (2012), Mutingi et al. (2017), Ghisetti et al. (2017)
B_{33}	Inadequate government support in the form of incentives and subsidies towards promoting sustainable manufacturing practices	Bhanot et al. (2015), Oguntoye and Evans (2017), Gavrilescu (2004)
B_{34}	Hurdles for releasing soft loans and credit facilities by financial institutions	Bhanot et al. (2015), Enshassi and Mayer (2005)
B_{35}	Protection and safeguarding manufacturers or service providers against possible financial losses	Gavrilescu (2004)

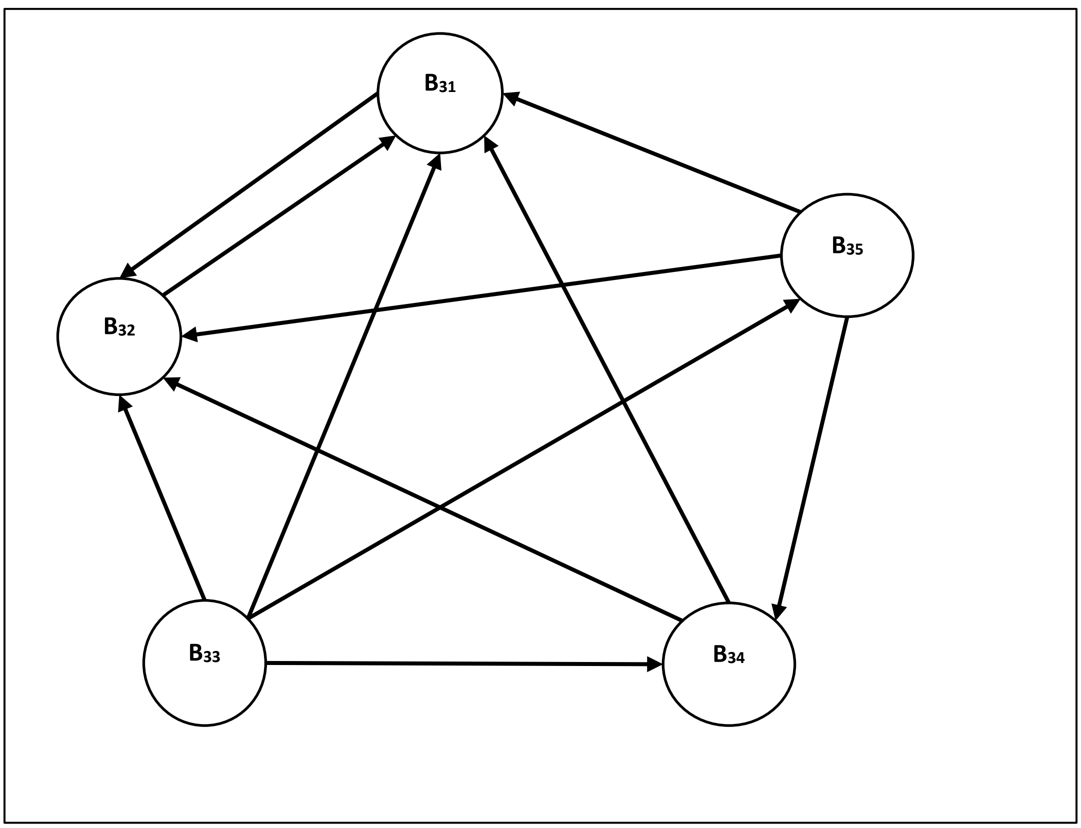

Figure 5.4: Digraph representing financial barriers

Table 5.5: Sub-elements to technological barriers (B_4)

Technological barriers (B_4)		
Sub-barriers	**Description of sub-barriers**	**Reference/ sources**
B_{41}	Lack of standardized metrics or performance benchmarks	Bhanot et al. (2015), Mutingi et al. (2017), Huang and Badurdeen (2016), Feng (2009)
B_{42}	Poor focus on energy efficiency and energy efficient process	Herdman (1994), UNDESA (2006), Carley et al. (2014), Gavrilescu (2004), Chen (2006)
B_{43}	Poor focus on employees' training on sustainable technologies and practices	Moldavska and Welo (2017), Herdman (1994)
B_{44}	Lack of support towards eco-innovation-oriented research	OECD (2009), Mulder (2007), Gavrilescu (2004), Enshassi and Mayer (2005), Abdullah (2015)
B_{45}	Lack of research and development initiatives	Enshassi and Mayer (2005)

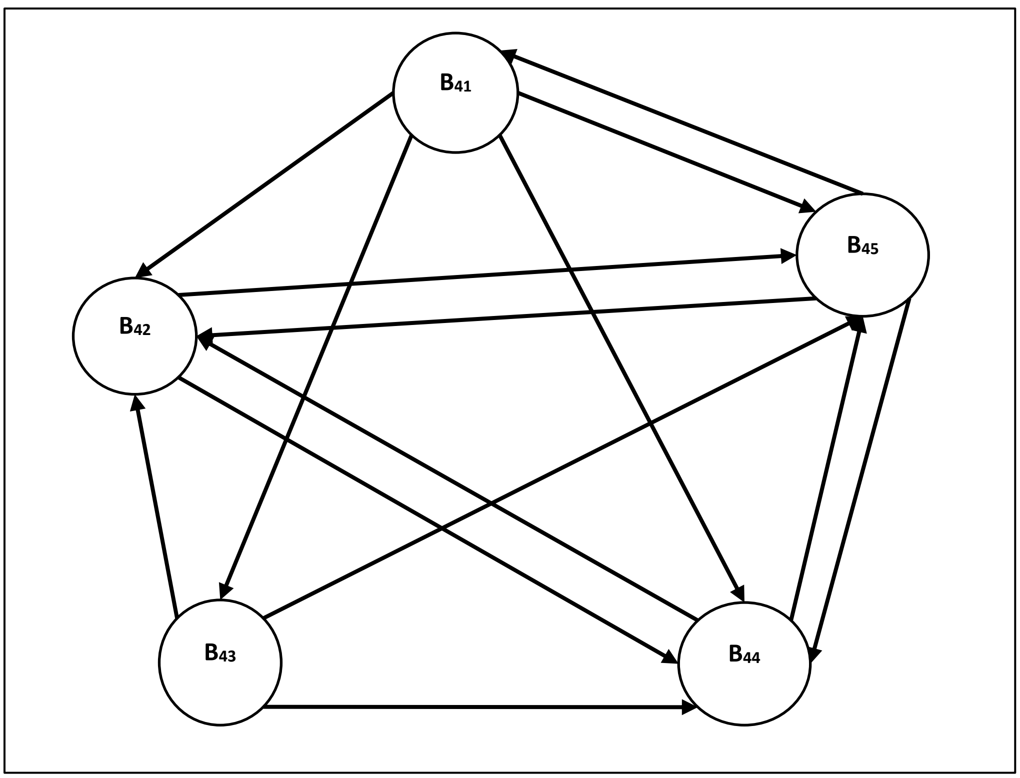

Figure 5.5: Digraph representing technological barriers

Table 5.6: Sub-elements to implementation and operational barriers (B_5)

Implementation and operational barriers (B_5)		
Sub-barriers	**Description of sub-barriers**	**Reference/ sources**
B_{51}	Lack of top management support and commitment	Hameed et al. (2014), Bhanot et al. (2015), Mutingi et al. (2017), Jayashree (2015)
B_{52}	Ignorance towards sustainability concepts	Bhanot et al. (2015), Mutingi et al. (2017), Enshassi and Mayer (2005), Kulatunga et al. (2013)
B_{53}	Absence of appropriate skills and relevant competencies	Beder (1994), Herdman (1994)
B_{54}	Logistical barriers	Parmar et al. (2016), Roso et al. (2013)
B_{55}	Lack of clear vision regarding ROI and payback	Enshassi and Mayer (2005)

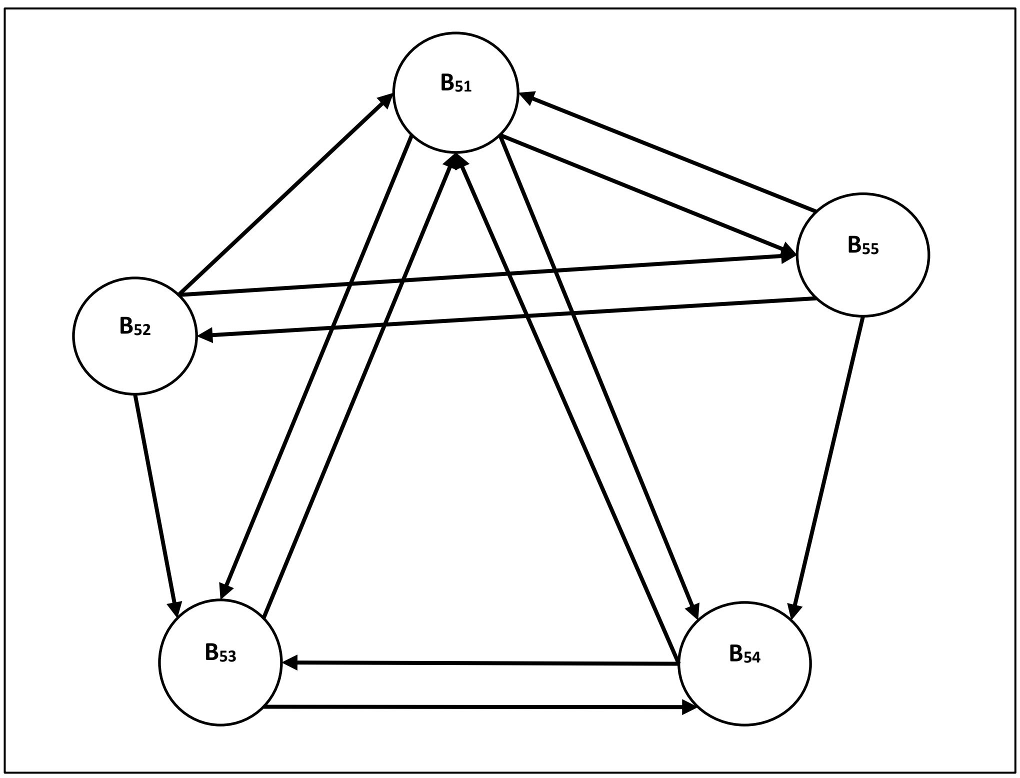

Figure 5.6: Digraph representing implementation and operational barriers

The following section describes the methodology adopted in the present analysis.

5.4 APPLICATION OF GTA METHODOLOGY

Various barriers were identified based on literature review followed by experts' opinion. Based on the inheritance and interdependence of various barriers and sub-barriers, numerical values are assigned to them through the judgement of a panel of experts. The various steps in GTA methodology are as follows:

i. Identification of various barriers that dissuade the progress towards SMS
ii. Classification of sub-barriers in five categories (classes)
iii. Development of '*system-digraph*' linking all category of barriers on the basis of their interdependence
iv. Development of '*sub-system digraph*' for each barrier category involving sub-barriers
v. Development of variable permanent matrix for system and sub-system level based on logical values for inheritances and interdependencies as per experts' opinion
vi. Evaluation of permanent values for each sub-system level
vii. Evaluation of permanent value at the system level through the incorporation of sub-system permanent values in the matrix
viii. Computation of intensity of barriers (IOB's) for the system as well as for each sub-system

GTA analyzes the intensity of each barrier categories as well as for the whole system. The following section describes the systematic steps followed in GTA analysis.

5.4.1 Formulation of matrix representation

Along with the expansion and complexity of the system, digraph becomes complicated and makes its' visual analysis more difficult. This necessitates the need for modeling it mathematically. Mathematical modeling using matrix representation is also convenient to process using computer (Attri et al., 2013).

To establish a mathematical expression for SMS barriers, a matrix representation is established which signifies the digraph. Assuming 'n' number of barriers with interdependencies among all of them and no self-loops, the SMS barrier matrix for the SMS barriers' digraph is represented as:

$$
E = \begin{array}{c} \text{Barriers} \\ B_1 \\ B_2 \\ B_3 \\ B_4 \\ \cdots \\ \cdots \\ B_n \end{array}
\begin{array}{c} \begin{array}{cccccccc} B_1 & B_2 & B_3 & B_4 & \cdots & \cdots & \cdots & B_n \end{array} \\
\begin{Bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & \cdots & \cdots & \cdots & B_{1n} \\ B_{21} & B_{22} & B_{23} & B_{24} & \cdots & \cdots & \cdots & B_{2n} \\ B_{31} & B_{32} & B_{33} & B_{34} & \cdots & \cdots & \cdots & B_{3n} \\ B_{41} & B_{42} & B_{43} & B_{44} & \cdots & \cdots & \cdots & B_{4n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ B_{n1} & B_{n2} & B_{n3} & B_{n4} & \cdots & \cdots & \cdots & B_{nn} \end{Bmatrix} \end{array}
$$

In the above matrix, element B_{ij} represent the inter-relationship between barrier B_i and Bj. Diagonal elements (B_{11}, B_{22}, B_{33}, B_{44}, ……, B_{nn}) represent the inheritance of these barriers towards SMS.

A study was carried out on TQM evaluation in an industry using digraph approach. The study pinpointed that in matrix representation some coefficients in the determinant carry negative signs, hence information is lost during matrix analysis. The study therefore proposed to use variable permanent function (VPF) that would give a correct representation of the system. Many other literatures also compliment the same (Grover et al., 2004).

5.4.2 Variable permanent function representation

Based on the digraph (Figure 5.1) linking barrier classes, the VPF is obtained. This is signified below:

$$
VPF_E = \begin{array}{c} \text{Barriers} \\ B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{array}
\begin{array}{c} \begin{array}{ccccc} B_1 & B_2 & B_3 & B_4 & B_5 \end{array} \\
\begin{Bmatrix} B_{11} & B_{12} & B_{13} & B_{14} & 0 \\ B_{21} & B_{22} & B_{23} & B_{24} & B_{25} \\ B_{31} & B_{32} & B_{33} & B_{34} & B_{35} \\ B_{41} & B_{42} & 0 & B_{44} & B_{45} \\ B_{51} & B_{52} & 0 & 0 & B_{55} \end{Bmatrix} \end{array}
$$

All the coefficients in the matrix have relative importance towards the attainment of SMS. Based on the response of experts, numerical values are assigned. This is done based on the linguistic scale as shown in Table 5.7 and 5.8.

Table 5.7: Linguistic scale for the inheritance of SMS barriers

S. No.	Intensity of inheritance	Value to assign
1	Exceptionally low	1
2	Extremely low	2
3	Very low	3
4	Below average	4
5	Average	5
6	Above average	6
7	High	7
8	Very high	8
9	Extremely high	9
10	Exceptionally high	10

Table 5.8: Linguistic scale for the interdependence of SMS barriers

S. No.	Intensity of interdependence	Value to assign
1	Very low	1
2	Low	2
3	Medium	3
4	Strong	4
5	Very strong	5

Quantitative estimation of SMS in an organization can be obtained from variable permanent function (VPF_{sms}) by substituting the numerical values from above tables. Computation of VPF_{sms} consisting of five barriers is expressed by the following multinomial equation.

$$VPF_{sms} = \text{per}(E) = \prod_1^5 B_i + \sum_1^5 (b_{12}b_{21}) B_3 B_4 B_5 + \sum_1^5 (b_{12}b_{23}b_{31} + b_{13}b_{32}b_{21}) B_4 B_5$$
$$+ \left\{ \sum_1^5 (b_{12}b_{21})(b_{34}b_{43}) B_5 + \sum_1^5 \left((b_{12}b_{23}b_{34}b_{41}) + (b_{14}b_{43}b_{32}b_{21}) \right) B_5 \right\}$$
$$+ \left\{ \sum_1^5 (b_{12}b_{21})(b_{34}b_{45}b_{53} + b_{35}b_{54}b_{43}) + \sum_1^5 (b_{12}b_{23}b_{34}b_{45}b_{51}) + (b_{15}b_{54}b_{43}b_{32}b_{21}) \right\}$$

5.4.3 Determination of intensity of barriers (IOB)

It has been perceived that the development of SMS is a complex task. This is so because some barriers are inevitably associated with manufacturing systems that tend to make it unsustainable. In order to transform a non-sustainable system into sustainable one, it is essential to evaluate the system in quantitative terms. An assessment of intensity of barriers (IOB) for the system under consideration can give an indication about the problems that might occur during the development of SMS. IOB for each barrier category is calculated by the permanent value of VPF; IOB of the system is calculated by the permanent value of VPF for the system. Higher values of IOB_{sms} will indicate more challenges towards the realization of SMS. Judgement can be made from IOB_{sms} values for different organizations using GTA methodology. The IOB_{sms} thus characterizes organization's ability for the transition towards sustainable manufacturing environment. The following steps are used to evaluate the Intensity of barriers. These are:

a. Structuring of digraph linking SMS barriers

b. Formulation of matrix representation towards SMS

c. Formulation of permanent function representation towards SMS

d. Evaluation of intensity of barrier for the system by calculating permanent value.

These are further illustrated in the following section.

5.5 RESULT AND DISCUSSION

VPF has been developed for each barrier category. These are represented below.

$$
\begin{array}{r|ccccc|}
\text{Sub-barriers} & B_{11} & B_{12} & B_{13} & B_{14} & B_{15} \\
B_{11} & 5 & 4 & 2 & 2 & 1 \\
B_{12} & 0 & 7 & 0 & 0 & 2 \\
VPF_{E1} = B_{13} & 4 & 3 & 6 & 2 & 2 \\
B_{14} & 4 & 3 & 0 & 7 & 1 \\
B_{15} & 4 & 0 & 0 & 0 & 9
\end{array}
$$

$$
\begin{array}{r|ccccc|}
\text{Sub-barriers} & B_{21} & B_{22} & B_{23} & B_{24} & B_{25} \\
B_{21} & 7 & 0 & 0 & 0 & 0 \\
B_{22} & 2 & 7 & 0 & 0 & 3 \\
VPF_{E2} = B_{23} & 4 & 2 & 6 & 0 & 0 \\
B_{24} & 3 & 2 & 2 & 4 & 0 \\
B_{25} & 4 & 3 & 0 & 4 & 8
\end{array}
$$

$$
\begin{array}{rccccc}
\text{Sub-barriers} & B_{31} & B_{32} & B_{33} & B_{34} & B_{35} \\
B_{31} & 9 & 5 & 0 & 0 & 0 \\
B_{32} & 2 & 8 & 0 & 0 & 0 \\
VPF_{E3} = B_{33} & 4 & 4 & 8 & 3 & 3 \\
B_{34} & 5 & 4 & 0 & 7 & 0 \\
B_{35} & 4 & 3 & 0 & 4 & 7
\end{array}
$$

$$
\begin{array}{rccccc}
\text{Sub-barriers} & B_{41} & B_{42} & B_{43} & B_{44} & B_{45} \\
B_{41} & 8 & 5 & 3 & 3 & 3 \\
B_{42} & 0 & 7 & 0 & 3 & 4 \\
VPF_{E4} = B_{43} & 0 & 4 & 9 & 4 & 3 \\
B_{44} & 0 & 4 & 0 & 7 & 3 \\
B_{45} & 3 & 4 & 0 & 3 & 7
\end{array}
$$

$$
\begin{array}{rccccc}
\text{Sub-barriers} & B_{51} & B_{52} & B_{53} & B_{54} & B_{55} \\
B_{51} & 8 & 0 & 3 & 4 & 3 \\
B_{52} & 1 & 6 & 1 & 0 & 2 \\
VPF_{E5} = B_{53} & 1 & 0 & 8 & 4 & 0 \\
B_{54} & 2 & 1 & 0 & 4 & 0 \\
B_{55} & 2 & 2 & 0 & 4 & 6
\end{array}
$$

The permanent matrix of each barrier category has been calculated. This is given below:

$IOB_{E1} =$ Per (VPF_{E1}) = 24926

$IOB_{E2} =$ Per (VPF_{E2}) = 12264

$IOB_{E3} =$ Per (VPF_{E3}) =32144

$IOB_{E4} =$ Per (VPF_{E4}) = 66636

$IOB_{E5} =$ Per (VPF_{E5}) =18488

Barrier matrix for the system level is obtained by putting the above permanent values in the diagonal elements of system barrier matrix. This is given below.

$$\begin{array}{c} \text{Barriers} \quad B_1 \quad B_2 \quad B_3 \quad B_4 \quad B_5 \\ VPF_E = \begin{array}{c} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{array} \left\{ \begin{array}{ccccc} 24926 & 4 & 2 & 1 & 0 \\ 1 & 12264 & 2 & 2 & 3 \\ 3 & 4 & 32144 & 2 & 4 \\ 3 & 4 & 0 & 66636 & 4 \\ 1 & 2 & 0 & 0 & 18488 \end{array} \right\} \end{array}$$

The value of permanent matrix for the system i.e., per (VPF_E) is calculated from the above matrix to obtain IOB_{sms}. The value obtained for IOB_{sms} is 1.21055 x 10^{22}. This numerical value represents the cumulative inhibiting power of all barriers towards the implementation of SMS. In order to draw meaningful conclusions from the analysis, the range (maximum and minimum values) of IOB_{sms} must be determined. IOB_{sms} will be maximum or minimum when the inheritance of all its barriers is maximum or minimum respectively. The IOB value for the system will be maximum if the inheritance of all barriers is maximum i.e., 10 and will be minimum for values corresponding to 1. Based on this logic, the maximum and minimum values for the system are evaluated. This is given in Table 5.9.

Table 5.9: Range of IOB's

Sl. No.	Permanent function	Maximum value	Minimum value	Present value
1	Per E_1	127616	293	24926
2	Per E_2	111880	82	12264
3	Per E_3	110000	11	32144
4	Per E_4	173414	2108	66636
5	Per E_5	132004	370	18488
6	Per E	3.59518 x10^{25}	2.08469 x10^{11}	1.21055 x 10^{22}

It is observed that IOB values in order of preference are $E_4 > E_3 > E_1 > E_5 > E_2$. This signifies that technological barrier (B_4) is the predominant barrier towards the progress of sustainability. This can be justified from the fact that the efficiency of manufacturing system greatly depends on the available technology. Financial barrier (B_3) is the second major barrier. Financial barrier is important for any investment decisions concerning new technology, new process or any decision involving capital towards sustainability. Other barriers also hinder the development towards SMS based on their relative IOB's.

The range of IOB values can guide managers regarding the scope for improvement. Various barriers should be aptly addressed so as to attain minimum possible values for IOB's. This will help in fast-tracking towards the implementation of SMS. Based on IOB_{sms} values, different organizations can be compared for their achievement towards SMS. With the changes in manufacturing practices this methodology will be able to appraise the variations in sustainability performances.

5.6 CONCLUSION

The analysis obtained from GTA highlights that technological barrier (B_4) is crucial towards the evolution of sustainability in manufacturing systems. This is virtually acceptable as substandard technologies can significantly hamper the efficiency of manufacturing as well as promotion towards the sustainability in manufacturing systems. Sub-technological barriers like lack of performance benchmark, lack of energy efficient process and practices, lack of research initiatives etc. seek critical examination in order to improve the IOB rating of this critical barrier category. Financial barrier (B_3) is the second most important barrier and is critical towards new investment decisions towards sustainability enhancement. Similarly, other barrier categories based on their relative IOB's, can deter the development towards achieving sustainability in manufacturing systems.

Graph theoretic approach has been carefully employed in the present analysis to systematically analyze and then rank the selected barriers from sustainable manufacturing viewpoint. The GTA technique was reasonably chosen keeping in mind that it facilitates in mapping qualitative data into quantitative entities and therefore was fairly appropriate in this study. The results obtained from mathematical analysis suggests meaningful contributions to formulate appropriate strategies for the transition towards SMS. The adopted methodology can be expanded to include 'n' number of barriers and also encompass the entire gamut of industries. This methodology can be used to formulate generalized strategies to overcome barriers for the smooth transition towards sustainable manufacturing systems.

CHAPTER VI

ANALYSIS OF CRITICAL SUCCESS FACTORS FOR SMS USING AHP AND R^3I BASED METHODOLOGY

6.1 INTRODUCTION

To cope-up with global business challenges and to comply with environmental regulations, manufacturers are shifting their focus towards sustainable practices. Promotion of sustainable manufacturing technology and practices are the need of the hour. This is so because sustainable practices will help in the conservation of natural resources and will also assist for long-term economic gain for the business. Various initiatives like product redesign, reorganization of processes, renovation of system, enhancement of energy efficiency, adoption of clean and renewable energy, reduction of waste, emission, pollution, devotion towards resource conservation and recycling practices etc. with the active participation of all stakeholders, can help to realize the same. A critical examination of various enabler elements in current manufacturing systems can provide significant acumens that would be supportive towards the development of SMS.

6.2 OVERVIEW OF METHODOLOGY ADOPTED

The current research is aimed at identifying various enablers towards the success of SMS. An extensive survey of literatures followed by expert opinion helped to identify these enablers. The identified enablers have been analyzed using multi criteria decision making (MCDM) techniques namely AHP and R^3I. Ranking of these enabler elements are done based on their weightages. The analysis provides decision supports to the managers willing to implement SMS.

From this chapter, following paper has been published:

Patra, S. K., Raj, T., and Arora, B. B. (2019). Identification of elements towards establishing Sustainable manufacturing system: an analysis using AHP and R^3I combined methodology. *Industrial Engineering Journal, 12(5),* 1–17.

The main objectives of this analysis are:

- Identification of enablers towards the development of SMS in a manufacturing setup
- Judgmental analysis to formulate the relationships among them
- Ranking of these enablers using AHP
- Authentication and validation of the result using relative reliability risk index (R^3I) technique
- Result and discussion

6.2.1 Identification of critical success factors and their categorization

A comprehensive literature review on various manufacturing practices and associated issues helped in identifying an initial list of elements that might be helpful towards the establishment of SMS. Academicians and industry experts helped to identify these enablers through brainstorming. A total of 31enabler elements were agreed upon as reasonable and significant. These are segregated into four groups on the basis of their attributes and features. These are:

i. Environment related issues (E1)
ii. Economic related issues (E2)
iii. Social and behavioral issues (E3)
iv. Technology and allied issues (E4)

Table 6.1 shows these issues and linked enabler elements.

Table 6.1: Various issues and linked enablers for SMS

Issues and elements of SMS				Reference/ Sources
E_1	**Environment related issues**	E_{11}	Waste management	Haapala et al. (2011), Bhanot et al. (2015), Paulraj (2009), Gilbert (2000)
		E_{12}	Government support and environmental legislation	Mutingi et al. (2017), Bhanot et al. (2015), Chen (2006), Paulraj (2009), Luthra et al. (2011)
		E_{13}	Focus on 3 R's principles	Bhanot et al. (2015), Molamohamadi and Ismail (2013), Chen (2006), Gilbert (2000)
		E_{14}	Resource conservation	Gilbert (2000), Bhanot et al. (2015)
		E_{15}	Environment management systems	Paulraj (2009), Gilbert (2000), Sarkis (2010)
		E_{16}	Public awareness on environmental issues	Bhanot et al. (2015), Paulraj (2009)

Issues and elements of SMS				Reference/ Sources
		E_{17}	Emission control	Haapala et al. (2011), Gilbert (2000), Chen (2006), Han et al. (2012)
E_2	**Economic related issues**	E_{21}	Commercial advantages	Bhanot et al. (2015), Gilbert (2000), Srinivasan (2011)
		E_{22}	Investment towards technology and innovation	Mutingi et al. (2017), Bhanot et al. (2015), Ravi and Shankar (2005)
		E_{23}	Cost control	Haapala et al. (2011), Gilbert (2000), Bhanot et al. (2015), Srinivasan (2011)
		E_{24}	Availability of capital and organizational resources	Mutingi et al. (2017), Bhanot et al. (2015)
		E_{25}	Incentives and subsidies funded by government to promote sustainable technologies	Bhanot et al. (2015)
		E_{26}	Ease of soft loans and credit facilities by financial institutions	Bhanot et al. (2015), S. Gilbert (2000)
		E_{27}	Rate of return (ROR) on investment towards sustainable technologies	Gilbert (2000), Srinivasan (2011)
E_3	**Social and behavioral issues**	E_{31}	Vision for long term sustainable development	Gilbert (2000), Bhanot et al. (2015)
		E_{32}	Employee health, safety and welfare	Haapala et al. (2011)
		E_{33}	Top management support and commitment	Molamohamadi and Ismail (2013), Bhanot et al. (2015), Ravi and Shankar (2005)
		E_{34}	Motivation and teamwork of the employees	Lin and Ho (2008), Ravi and Shankar (2005)
		E_{35}	Business ethics/ company policy	Molamohamadi and Ismail (2013), Sarkis (2010)
		E_{36}	Market demand for green products	Mutingi (2017), Bhanot et al. (2015), Reijonen (2011), Gilbert (2000)
		E_{37}	Population explosion	Han et al. (2012)
		E_{38}	Corporate social responsibility	Jawahir et al. (2006), Srinivasan (2011), Valiente et al. (2017)
E_4	**Technology and allied issues**	E_{41}	Process control	Bhanot et al. (2015)
		E_{42}	Quality control	Mutingi et al. (2017), Bhanot et al. (2015)
		E_{43}	Workers' training and education on sustainable technologies and practices	Mutingi et al. (2017), Bhanot et al. (2015)

Issues and elements of SMS				Reference/ Sources
		E_{44}	Eco-innovation-oriented research	Tornatzky and Fleischer (1990), Van Bommel (2011), Srinivasan (2011), Johansson and Magnusson (1998)
		E_{45}	Standardized metrics or performance benchmarks	Mutingi et al. (2017), Bhanot et al. (2015), Sarkis (2010), Petrie et al. (2007)
		E_{46}	Energy efficiency	Haapala et al. (2011), Chen (2006)
		E_{47}	Support for developing new technologies (Research and development)	Jawahir et al. (2006)
		E_{48}	Implementation and operational issues	Jawahir et al. (2006), Sarkis (1998), Van Bommel (2011)
		E_{49}	Pursuit towards clean and renewable energy	Han et al., 2012

6.3 APPLICATION OF AHP METHODOLOGY

Literature review in chapter 2 provides a detail description of various applications of analytic hierarchy process. AHP is a multi-criteria decision- making tool, typically used for solving decision problems involving multi-objectives. This methodology has been used to analyze various enabler elements towards the development of SMS. Expert opinion was sought to assign weightages to these elements in order to evaluate their ranking (relative importance) over one another. The following steps have been used in the AHP analysis.

- Structuring the problem

  This is done by developing a two-level hierarchy structure. The four main issues E_1 - E_4 are placed at the criteria level. All the sub- elements (E_{11} - E_{17}, E_{21} - E_{27}, E_{31} - E_{38}, E_{41} - E_{49}) are placed at the sub-criteria level.

- Formation of pair-wise comparison matrix

  A pairwise comparison of the criteria and sub-criteria is done using Saaty’s scale. Based on the relative importance of one element over the other, weightage is assigned (in a judgmental scale of 1-9) based on overall goal of enhancing the sustainability and the contribution of each element towards the development of SMS.

- Normalization and consistency analysis

  The matrix is normalized by customary calculations. The value of consistency index (CI) and consistency ratio (CR) are evaluated. CR is the ratio of CI and RI (CR = CI/RI), where RI is obtained from the random index table of Saaty (1980). The value of CR should be less than 0.10 for judgmental consistency.
- Ranking of elements

  The normalized weight of each element reflects their importance and priorities towards the development of SMS. Based on relative priority weights, elements are ranked. Table 6.2 reflects the pair-wise comparison matrix among the primary issues.

Table 6.2: Pair-wise comparison matrix among various issues

Issues in SMS	**E_1**	**E_2**	**E_3**	**E_4**
Environment related issues (E_1)	1	2	4	2
Economic related issues (E_2)	1/2	1	3	2
Social and behavioral issues (E_3)	1/4	1/3	1	1/4
Technology and allied issues (E_4)	1/2	1/2	4	1

The various steps of AHP methodology are represented in subsequent sections. Table 6.3 indicates the values of CI and CR as shown below.

Table 6.3: Tabulation of results for SMS issues

CI	**RI for n=4**	**CR= CI/RI**	**Consistency**
0.050104	0.9	0.05567111	5.56%

The value of CR obtained from analysis is 0.0556, which is well below the acceptable limit of 0.10. This reflects that there is significant judgmental consistency in this analysis. Table 6.4 displays the priority weights for each issue and are ranked based on their priority weights.

Table 6.4: Priority weights and ranking of SMS issues

SMS Issues	**Priority weights**	**Rank**
E_1	0.42	I
E_2	0.279	II
E_3	0.082	IV
E_4	0.219	III

Figure 6.1 demonstrates the priority weights of these issues.

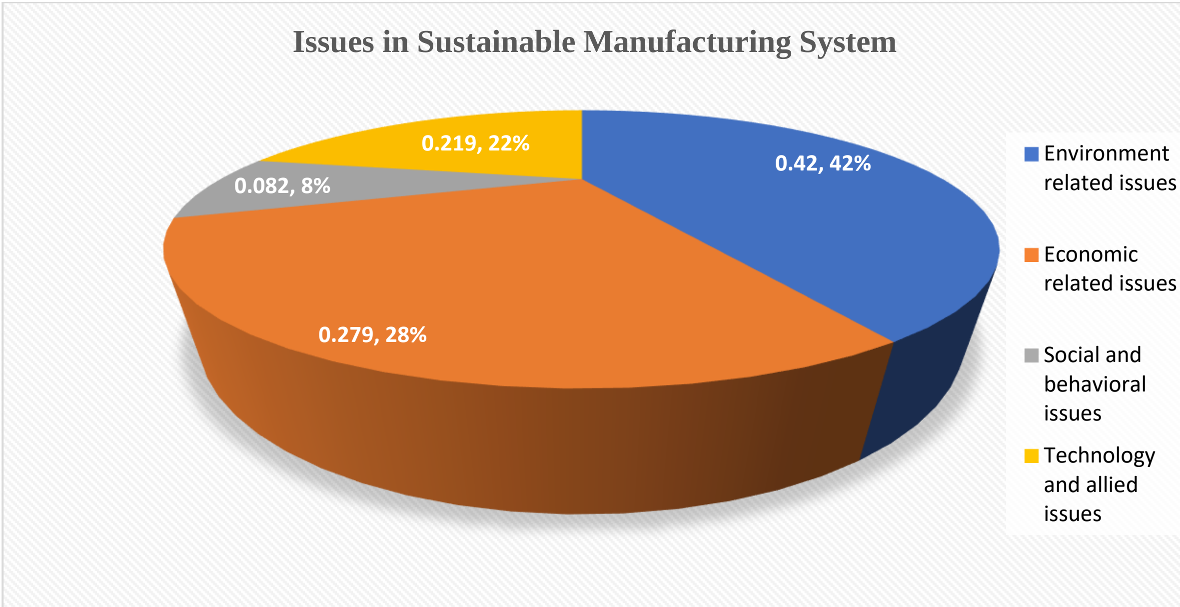

Figure 6.1: Priority weights of various SMS issues

Figure 6.1 shows that environment related issues are ranked I. This indicates that there is an urgent need for managing waste, emission, pollution and other environment related issues. Economic related issues (Ranked II) signify its importance towards developing SMS. Availability of funds, credit, subsidies and other economic resources are thus vital for the implementation of SMS. Technology and allied issues are ranked III. It signifies that relevant technologies are essential towards improving the manufacturing efficiency. Technological upgradation through R&D and innovation will be supportive towards promoting eco-friendly practices that are vital towards SMS. Social and behavioral issues are ranked IV. This however does not mean that this issue is less critical considering the fact that all manufacturing activities takes place in close vicinity to our societal framework. With the increasing public awareness on environment and sustainable issues, business firms have to be more practical, responsible, careful and sensible in carrying out their manufacturing processes. The subsequent article computes the priorities for each sub-enabler elements linked with the main issues. Table 6.5 illustrates the pair-wise comparison among the environment related elements.

Table 6.5: Pair-wise comparison matrix for environment related elements

Environment related elements	E_{11}	E_{12}	E_{13}	E_{14}	E_{15}	E_{16}	E_{17}
E_{11}	1	4	2	3	1/3	6	1
E_{12}		1	1/3	1/2	1/4	2	1/5
E_{13}			1	3	1/4	7	1/3
E_{14}				1	1/5	4	1/3
E_{15}					1	7	2
E_{16}						1	1/5
E_{17}							1

Table 6.6 represents the results obtained by AHP methodology.

Table 6.6: Tabulation of results for environment related elements

CI	RI for n=7	CR= CI/RI	Consistency
0.08403	1.32	0.063657	6.36%

The following priority weights are obtained for each of the environment related elements. They are further multiplied by the priority weight of main criteria (Environment related issues) to obtain the global priority index. This is represented in Table 6.7.

Table 6.7: Global priority index for environment related elements

Environment related elements	Priority weights (x)	Global priority index (x*0.42)
E_{11}	0.179	0.07518
E_{12}	0.050	0.021
E_{13}	0.128	0.05376
E_{14}	0.074	0.03108
E_{15}	0.337	0.14154
E_{16}	0.029	0.01218
E_{17}	0.204	0.08568

Similarly, the results obtained for other elements are depicted below:

Table 6.8: Tabulation of results for economic related elements

CI	RI for n=7	CR= CI/RI	Consistency
0.09483	1.32	0.07184	7.184 %

Table 6.9: Global priority index for economic related elements

Economic related elements	Priority weights (y)	Global priority index (y*0.279)
E_{21}	0.305	0.085095
E_{22}	0.054	0.015066
E_{23}	0.093	0.025947
E_{24}	0.044	0.012276
E_{25}	0.197	0.054963
E_{26}	0.180	0.05022
E_{27}	0.126	0.035154

Table 6.10: Tabulation of results for social and behavioral related elements

CI	RI for n=8	CR= CI/RI	Consistency
0.06287	1.41	0.04458	4.458 %

Table 6.11: Global priority index for social and behavioral related elements

Social and behavioral related elements	Priority weights (z)	Global priority index (z*0.082)
E_{31}	0.166	0.046314
E_{32}	0.061	0.017019
E_{33}	0.263	0.073377
E_{34}	0.036	0.010044
E_{35}	0.160	0.04464
E_{36}	0.129	0.035991
E_{37}	0.030	0.00837
E_{38}	0.154	0.042966

Table 6.12: Tabulation of results for technology and allied elements

CI	RI for n=9	CR= CI/RI	Consistency
0.115622	1.45	0.07973	7.973 %

Table 6.13: Global priority index for technology and allied elements

Technology and allied elements	Priority weights (a)	Global priority index (a*0.219)
E_{41}	0.217	0.047523
E_{42}	0.116	0.025404
E_{43}	0.177	0.038763
E_{44}	0.095	0.020805
E_{45}	0.158	0.034602
E_{46}	0.076	0.016644
E_{47}	0.068	0.014892
E_{48}	0.044	0.009636
E_{49}	0.050	0.01095

Based on the above analysis, all the 31 elements have been ranked based on their global priority index. This is represented in Table 6.14.

Table 6.14: Ranking of SMS elements

Elements	Weightage	Ranking
E_{15}	0.14154	1
E_{17}	0.08568	2
E_{21}	0.085095	3
E_{11}	0.07518	4
E_{33}	0.073377	5
E_{25}	0.054963	6
E_{13}	0.05376	7
E_{26}	0.05022	8
E_{41}	0.047523	9
E_{31}	0.046314	10
E_{35}	0.04464	11

Elements	Weightage	Ranking
E_{38}	0.042966	12
E_{43}	0.038763	13
E_{36}	0.035991	14
E_{27}	0.035154	15
E_{45}	0.034602	16
E_{14}	0.031080	17
E_{23}	0.025947	18
E_{42}	0.025404	19
E_{12}	0.02100	20
E_{44}	0.020805	21
E_{32}	0.017019	22
E_{46}	0.016644	23
E_{22}	0.015066	24
E_{47}	0.014892	25
E_{24}	0.012276	26
E_{16}	0.01218	27
E_{49}	0.01095	28
E_{34}	0.010044	29
E_{48}	0.009636	30
E_{37}	0.00837	31

Ranking of various elements are further epitomized in chart shown in Figure 6.2.

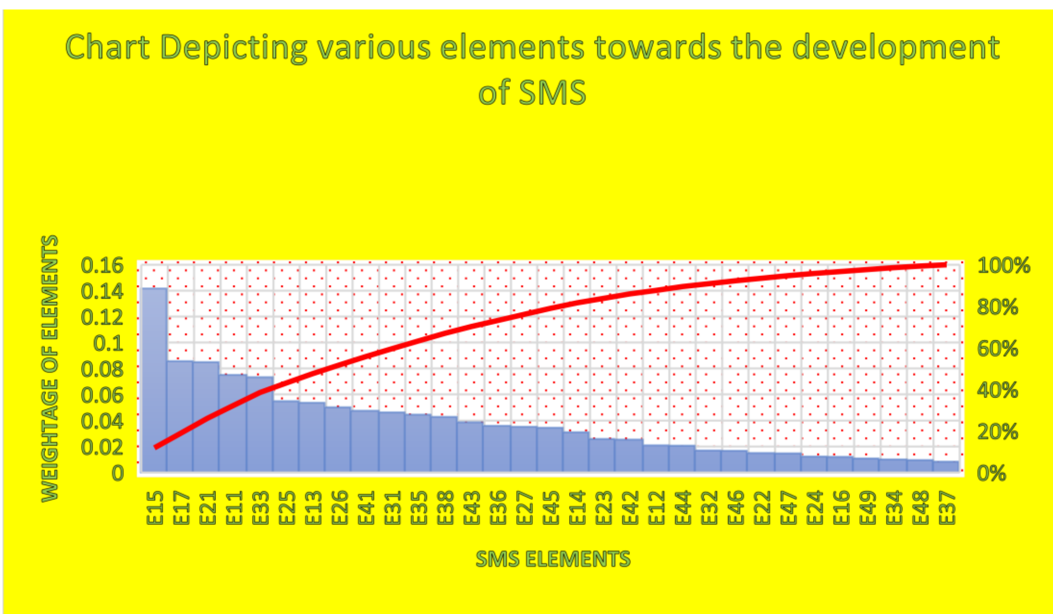

Figure 6.2: Chart depicting various elements towards the development of SMS

Figure 6.2 displays all 31 elements based on their rankings. Among these elements, top 10 elements are E_{15}, E_{17}, E_{21}, E_{11}, E_{33}, E_{25}, E_{13}, E_{26}, E_{41} and E_{31}.

Out of these, 04 elements namely E_{15} (Environment management systems), E_{17} (Emission control), E_{11} (Waste management) and E_{13} (Focus on 3 R's principles) are linked with environment and related issues.

03 elements namely E_{21} (Commercial advantages), E_{25} (Incentives and subsidies funded by government to promote sustainable technologies), E_{26} (Ease of soft loans and credit facilities by financial institutions) are linked with economic and related issues.

02 elements namely E_{33} (Top Management support and commitment) and E_{31} (Vision for long term sustainable development) are linked with social and behavioral issues.

Element E_{41} (Process control) is linked to technology and related issues.

The result obtained from AHP analysis need to be established for its authenticity and correctness. This necessitates the use of some other MCDM technique. The current study proposes to use R^3I technique which is a well-known MCDM technique for this purpose. The succeeding section illustrates the same.

6.4 RELATIVE RELIABILITY RISK INDEX (R^3I) METHODOLOGY

R^3I analysis has been used to calculate the intensity of the four primary issues. Entropy method has been used to carry out the analysis. The intensity assessment system concerning all issues and sub-elements are represented in Figure 6.3.

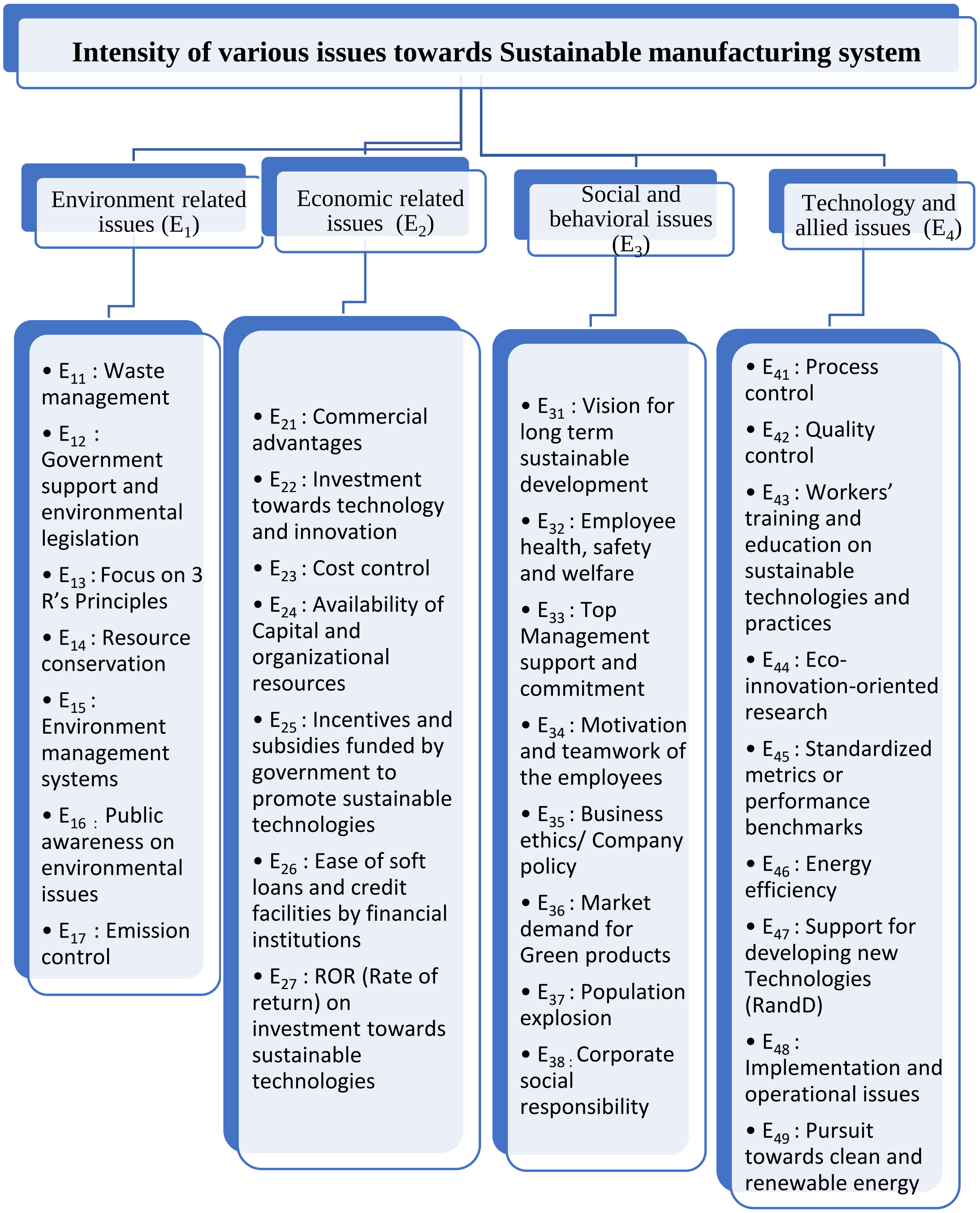

Figure 6.3: The intensity assessment system towards the development of SMS

6.4.1 Entropy method

Entropy method has been used to carry out the R^3I analysis. Five experts were involved to rate each element associated with the primary issues. The intensity evaluation matrix for each issue is obtained using Delphi method (in a scale of 1-5). For each issue the entropy values (e), entropy weights (w) and the intensity values (R) are calculated by adopting the following steps.

Step- I: Formulation of intensity evaluation matrix (M)

$$M=\begin{bmatrix} m_{11} & m_{12} & m_{13} & & m_{1j} \\ m_{21} & m_{22} & m_{23} & & m_{2j} \\ m_{31} & m_{32} & m_{33} & & m_{3j} \\ & & & & \\ m_{i1} & m_{i2} & m_{i3} & & m_{ij} \end{bmatrix} \quad \ldots\ldots\ldots(i)$$

where j = 1, 2, 3, 4, 5 (Serial no. of experts)

i = Serial no. of elements under each SMS issue

(i = 1- 7 for E_1, 1-7 for E_2, 1- 8 for E_3 and 1- 9 for E_4)

Step- II: Normalization of matrix (M^*)

$$M^*=\begin{bmatrix} m'_{11} & m'_{12} & m'_{13} & & m'_{1j} \\ m'_{21} & m'_{22} & m'_{23} & & m'_{2j} \\ m'_{31} & m'_{32} & m'_{33} & & m'_{3j} \\ & & & & \\ m'_{i1} & m'_{i2} & m'_{i3} & & m'_{ij} \end{bmatrix} \quad \ldots\ldots\ldots(ii)$$

where $m'_{ij} = \frac{m_{ij} - \min(m_{ij})}{\max(m_{ij}) - \min(m_{ij})}$

Step- III: Entropy calculation

Entropy $e_i = - K \sum f_{ij} . \ln f_{ij}$ ($f_{ij}. \ln = 0$ for $f_{ij} = 0$) ………(iii)

where K= 1/ (ln n), (n =No. of experts =5)

$$f_{ij} = \frac{m'_{ij}}{\sum m'_{ij}}$$

Entropy weight $w_i = \frac{1 - e_i}{m - \sum e_i}$, ($m = i_{max}$ for each issue) ……(iv)

Total intensity (risk) of each issue is calculated as $R = \sum w_i . e_i$ …….(v)

The intensity of each issue based on the values assigned by experts to each sub-element are calculated using the equations (i) to (v). These are tabulated below.

Table 6.15: Intensity evaluation for environment related issues (E_1)

$$M_1=\begin{bmatrix}4 & 3 & 4 & 5 & 3\\ 3 & 2 & 3 & 2 & 2\\ 3 & 3 & 2 & 2 & 2\\ 3 & 2 & 2 & 2 & 2\\ 4 & 3 & 3 & 3 & 3\\ 3 & 2 & 3 & 2 & 4\\ 3 & 3 & 4 & 4 & 5\end{bmatrix} \qquad M_1^*=\begin{bmatrix}0.5 & 0 & 0.5 & 1 & 0\\ 1 & 0 & 1 & 0 & 0\\ 1 & 1 & 0 & 0 & 0\\ 1 & 0 & 0 & 0 & 0\\ 1 & 0 & 0 & 0 & 0\\ 0.5 & 0 & 0.5 & 0 & 1\\ 0 & 0 & 0.5 & 0.5 & 1\end{bmatrix}$$

e_1 = (0.64601, 0.43068, 0.43068, 0, 0, 0.64601, 0.64601)

w_1 = (0.08427, 0.13553, 0.13553, 0.23806, 0.23806, 0.08427, 0.08427)

$R_{environment}$ = 0.28006

Table 6.16: Intensity evaluation for economic related issues (E_2)

$$M_2=\begin{bmatrix}2 & 3 & 2 & 2 & 2\\ 2 & 3 & 3 & 2 & 4\\ 2 & 2 & 2 & 3 & 2\\ 4 & 3 & 3 & 4 & 3\\ 3 & 3 & 2 & 3 & 2\\ 3 & 2 & 2 & 3 & 2\\ 3 & 2 & 3 & 3 & 4\end{bmatrix} \qquad M_2^*=\begin{bmatrix}0 & 1 & 0 & 0 & 0\\ 0 & 0.5 & 0.5 & 0 & 1\\ 0 & 0 & 0 & 1 & 0\\ 1 & 0 & 0 & 1 & 0\\ 1 & 1 & 0 & 1 & 0\\ 1 & 0 & 0 & 1 & 0\\ 0.5 & 0 & 0.5 & 0.5 & 1\end{bmatrix}$$

e_2 = (0, 0.64601, 0, 0.43068, 0.68261, 0.43068, 0.82773)

w_2 = (0.25111, 0.08889, 0.25111, 0.14296, 0.0797, 0.14296, 0.04326)

$R_{economic}$ = 0.27078

Table 6.17: Intensity evaluation for social and behavioral issues (E_3)

$$M_3=\begin{bmatrix}3 & 2 & 3 & 2 & 2\\ 2 & 2 & 3 & 2 & 2\\ 4 & 4 & 4 & 5 & 4\\ 2 & 2 & 3 & 2 & 2\\ 2 & 2 & 3 & 3 & 3\\ 3 & 2 & 2 & 2 & 2\\ 2 & 2 & 1 & 1 & 2\\ 3 & 3 & 2 & 2 & 2\end{bmatrix} \qquad M_3^*=\begin{bmatrix}1 & 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 1 & 1\\ 1 & 0 & 0 & 0 & 0\\ 1 & 1 & 0 & 0 & 1\\ 1 & 1 & 0 & 0 & 0\end{bmatrix}$$

e_3 = (0.43068, 0, 0, 0, 0.68261, 0, 0.68261, 0.43068)

w_3 = (0.09861, 0.17321, 0.17321, 0.17321, 0.05497, 0.17321, 0.05497, 0.09861)

R_{social} = 0.15999

Table 6.18: Intensity evaluation for technology and allied issues (E_4)

$$M_4 = \begin{bmatrix} 4 & 3 & 3 & 3 & 3 \\ 2 & 3 & 2 & 2 & 3 \\ 3 & 2 & 3 & 4 & 3 \\ 3 & 2 & 2 & 3 & 2 \\ 2 & 2 & 2 & 2 & 1 \\ 2 & 2 & 3 & 2 & 3 \\ 2 & 2 & 2 & 2 & 3 \\ 3 & 2 & 3 & 3 & 3 \\ 2 & 2 & 2 & 2 & 3 \end{bmatrix} \qquad M_4^* = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 \\ 0.5 & 0 & 0.5 & 1 & 0.5 \\ 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

e_4 = (0, 0.43068, 0.82773, 0.43068, 0.86135, 0.43068, 0, 0.86135, 0)

w_4 = (0.19389, 0.11039, 0.0334, 0.11039, 0.02688, 0.11039, 0.19389, 0.02688, 0.19389)

$R_{technology}$ = 0.21658

Based on the above calculation tables, the various SMS issues have been ranked. This is given in Table 6.19.

Table 6.19: Ranking of various SMS issues

S. No.	SMS Issues	Intensity value (R)	Ranking based on intensity
1	Environment related issues (E_1)	0.28006	I
2	Economic related issues (E_2)	0.27078	II
3	Social and behavioral issues (E_3)	0.15999	IV
4	Technology and allied issues (E_4)	0.21658	III

Based on R^3I analysis, the ranking of various enabler issues towards SMS are:

$E_1 \rightarrow E_2 \rightarrow E_4 \rightarrow E_3$

6.5 COMPARATIVE ANALYSIS OF AHP AND R^3I METHODOLOGY

Both the above analysis facilitated in ranking the identified enablers towards SMS. The ranking obtained from both the analysis in order of importance are environment related issues (E_1), economic related issues (E_2), technology and allied issues (E_4) and social and behavioral issues (E_3).

The result highlights that environment and related issues (ranked I) are paramount towards adopting SMS. Enablers related to environmental issues like waste management, emission control, recycling practices, resource conservation and others need to be suitably addressed. Necessary actions towards eco-friendly manufacturing practices are essential for the progress towards sustainable manufacturing system.

Economic related issues are ranked II. It signifies that without adequate capital and resources, progress towards SMS is not viable. Support and funding by the government and other agencies might be beneficial towards addressing economic hardships considered as crucial towards the development of SMS.

Technology and allied issues are ranked III. It is pertinent to highlight that many of the environmental issues can be suitably addressed through technological means. Technological barriers can be addressed through technological innovations, research and development initiatives, incorporating suitable training to the workmen and by focusing on sub- elements of technological issues.

The importance of social and behavioral issues (ranked IV) towards SMS are crucial. This is so because the vision, motivation, commitment and cooperation of the society can give immense impetus towards the attainment of SMS.

6.6 CONCLUSION

This chapter has come out with a comprehensive methodology towards the analysis of critical success factors for the development of sustainable manufacturing environment. By using analytic hierarchy process, priorities of various issues and the associated enablers are obtained. The result obtained through AHP analysis is further correlated using R^3I analysis. The analysis reveals that environment related issues (ranked I) is the enabler of highest importance towards the success of SMS. Key environmental elements like waste management, emission control, recycling practices, resource conservation etc. are of paramount importance towards the success of SMS. Economic related issue is ranked II. Commercial advantages and incentives, subsidies funded by government to promote sustainable technologies are important elements that can significantly contribute towards the success of SMS. Technology and allied issues (ranked III) is gaining rapid importance in this modern era and is a significant driver towards the success of SMS.

The result obtained from R^3I analysis validates that obtained from AHP analysis. The study establishes the relative merits of various issues and their sub- elements towards SMS. Managers can focus on various issues and their sub-elements (based on their relative weightages) which will be supportive in developing SMS. The investigation obtained through the analysis may thus be appreciated by the plant managers willing to adopt SMS in their organization.

CHAPTER VII

AN AHP BASED METHODOLOGY FOR THE SELECTION OF BEST MANUFACTURING SYSTEM IN INDIAN MANUFACTURING CONTEXT

7.1 INTRODUCTION

Manufacturing has evolved through significant changes since the advent of industrial revolution. Globalization has compelled manufacturers to change their manufacturing practices. Over the time, manufacturers have adopted techniques that can focus on operational efficiency, reduce waste, generate cost efficiency in operations etc., so as to improve the productivity of organizations. In context with current global and competitive age, it is very much important for organizations to adopt manufacturing practices that are efficient, lean, eco-friendly, cost-effective, flexible and the like. World class manufacturing follows techniques and philosophies such as zero defects, just in time, make to order, streamlined flow, smaller lot sizes, total preventive maintenance (TPM), quick replacement, statistical process control, increased consistency, higher employee involvement, cross functional teams, multi-skilled employees, visual signaling etc.

There exist several old-fashioned industries that operate at low efficiency and are the primary reasons for rapid declining of natural resources. There is urgent need to implement suitable manufacturing practices for competitive business environment. Successful implementation of such systems can reduce wastage, improve machine efficiency, reduce breakdown time, improve energy and material efficiency etc., thereby optimizing production efficiency and functionality. To survive in the current competitive and global environment, it is important for the organizations to continuously look for various ways to improve the efficiency of machines, energy, materials used and thereby increasing their productivity. There is urgent need for discovering new, easy and cost-effective ways of manufacturing or providing services.

To cope with such challenges through special focus towards sustainability issues, it is time to switchover from traditional manufacturing systems (Substitution based) to advanced manufacturing systems. The main objectives addressed in this chapter are:

- To illustrate alternative manufacturing systems namely traditional manufacturing, lean manufacturing, green manufacturing and sustainable manufacturing
- To identify and discuss various attributes and sub-attributes in manufacturing systems
- To select the best manufacturing system using AHP methodology and its justification.

7.2 Brief description of alternative manufacturing systems

Experts' opinion was sought to decide on preferred alternatives towards the selection of best manufacturing system that can take care of business challenges and sustainability issues. Selected alternatives for this assessment were: Traditional manufacturing, lean manufacturing (Waste reduction-based), green manufacturing (Environmentally-benign, 3R- based) and sustainable manufacturing (6R- based). The following section gives a brief description of these alternatives.

7.2.1 Traditional manufacturing (TM): It refers to the conventional manufacturing technique that focus on producing goods based on sales forecast. It holds some reserve for unexpected demand or shortages. Traditional manufacturing has vital focus on costing and very less attention on resource conservation, control of waste, pollution and environmental degradation caused due to manufacturing activities. Salient features of TM are:

- It is substitution-based manufacturing technique
- It focusses on profit maximization and has least consideration on sustainable issues
- Production is based on sales forecast (Push type)
- Top management is the primary driver for change
- Standardized work practices lack in reality
- Problems are viewed as just that without seeing it as scope for opportunity
- Often ignores the control of waste in the process
- Work in process (WIP) is viewed as a normal part of operations although it is an unfinished work
- Puts focus on training of personnel and relies on people to not make mistakes.

It is gradually becoming difficult for traditional manufacturing systems to cope with increasing global competition, complex and changing business environment, changing customers' aspirations and so on. More advanced technologies and management philosophies will be the right approach to address these challenges.

7.2.2 Lean manufacturing (LM): It was developed by automobile giant, Toyota. It is also known as Toyota production system (TPS). Lean manufacturing uses techniques such as work cells in order to adapt changes in product design and rapidly changing production demands. Lean manufacturing through fine balancing between production flow and changing demand saves resources and cost. It also focusses on efficiency instead of reserves.

Lean manufacturing is an enterprise-wise strategy for achieving excellence by the followings:

i. Creating value from customer's perspective
ii. Creating culture of continuous performance improvement
iii. Working towards the elimination of '*all waste*' of resources and time
iv. Creating high quality, stable processes
v. Respect for all people throughout the organization.

Salient features of LM are:

- It is 'Waste reduction-based' manufacturing technique
- It is a demand-driven (based on customer demand) approach for manufacturing (Pull-type)
- It views problems as opportunities for improvement often through root cause analysis
- Work in process (WIP) reflects that the process needs to be improved. WIP is treated as a type of waste that should be reduced or eliminated
- It improves system by eliminating waste and improving current manufacturing processes
- All employees are trained in lean principles and look for ways to improve processes
- Everyone performs the same task in exactly same way until a better way is discovered
- It relies on error proofing systems so that persons do not make mistakes during operations
- It views the organization as a series of interrelated processes that can be improved.

The lean manufacturing techniques are conceptually different from traditional manufacturing processes. While traditional manufacturing is based on inventory, lean manufacturing questions the role of inventory and defines it as waste. In contrast with traditional manufacturing approach, lean manufacturing is characterized by the use of economic order quantity (EOQ), high-capacity utilization and high inventory. To transform traditional manufacturing into lean one, cultural issues as well as resistance to change takes place. Organizations having mastery in lean manufacturing have substantial cost and quality advantages over those practicing traditional mass production (Singh and Sharma, 2009; Prasad and Sharma, 2014).

7.2.3 Green manufacturing (GM): Green manufacturing tend to minimize waste and pollution through the adoption of process design and research. It supports and sustains the renewable way of generating products and/or services that do not harm the environment. Green manufacturing conserves natural resources for future generations and saves useless cost. It also promotes research and design (Prasad and Sharma, 2014).

It refers to the revitalization of production processes and the establishment of environment friendly operations in the manufacturing system. Green manufacturing has two important attributes namely green products and greening of manufacturing. Green products are less harmful to human health than traditional ones and also have less environmental impact. Greening of manufacturing refers to the use of fewer natural resources, reducing pollution and waste by minimizing resource use, recycling and reusing of materials that were otherwise considered as waste and reducing emissions. Green manufacturing has transformed industrial operations by the use of green energy, employing green processes in business operations and by developing and selling green products. The salient features of GM are:

- It is 3-R based manufacturing technique
- It can give long–term cost saving
- It helps to enhance brand image of the organization
- Better compliance to regulations is possible
- Higher interest of investors.

The 3-R's (Reduce, reuse and recycle) are the pillars for green manufacturing. It was derived in the 1990s from lean manufacturing, which is based on 1-R (Reduce) introduced in the 1980s (Jawahir and Dillon, 2007).

Green manufacturing has become an important issue in industry, driven by regulations governing manufacturing emissions, growing worldwide environmental certification requirements (ISO 14000) and an emerging consumer preference for eco-label products (Prasad and Sharma, 2014).

7.2.4 Sustainable manufacturing: It is the creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources. It also enhances employee, community and product safety. The attainment of sustainable value in manufacturing entails transformation from lean to green to sustainable manufacturing (Jawahir and Dillon, 2007).

Salient features of SM are:

- It is based on 6-R's namely reduce, reuse, recycle, redesign, recover and remanufacture
- It is innovation based closed-loop system
- Implementation of SM practices have several benefits. Some of these are:

- Increased profits
- Reduction of waste
- Safe for employees
- Safe for community
- Improved productivity
- Enhanced product quality
- Conservation of resources
- Environment friendly practices
- Improved quality of life for employees.

7.3 ANALYTIC HIERARCHY PROCESS (AHP)

Analytic hierarchy process (AHP) is a multi-criteria decision-making technique for pairwise comparison between several decision criteria using a hierarchical structure. This has been used in the present analysis to evaluate the suitability indices among alternative manufacturing systems. The excerpts of AHP methodology are explained below. Important stages towards the AHP analysis are (i) Establishment of pair-wise comparison matrix (ii) Normalization of matrix (iii) Consistency analysis. These are illustrated below.

7.3.1 Establishment of pair-wise comparison matrix

Based on Saaty's scale, numerical values 1- 9 are assigned to quantify the relative importance of attributes/sub-attributes/alternatives through pairwise comparison. A matrix [n x n] is used for this analysis. The following section explains the same:

$$\begin{bmatrix} X_{11} & X_{12} & X_{13} & & X_{1n} \\ X_{21} & X_{22} & X_{23} & & X_{2n} \\ X_{31} & X_{32} & X_{33} & & X_{3n} \\ & & & & \\ X_{n1} & X_{n2} & X_{n3} & & X_{nn} \end{bmatrix}$$

The sum of values in each column is calculated as $\sum_{i=1}^{n} X_{ij}$

7.3.2 Normalization of matrix

Normalized score has been calculated by dividing each column entry by the corresponding column sum. This can be specified as $A_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}$

The normalized pair-wise matrix can be represented by $\begin{bmatrix} A_{11} & A_{12} & A_{13} & & A_{1n} \\ A_{21} & A_{22} & A_{23} & & A_{2n} \\ A_{31} & A_{32} & A_{33} & & A_{3n} \\ & & & & \\ A_{n1} & A_{n2} & A_{n3} & & A_{nn} \end{bmatrix}$

The weighted matrix is calculated as $W_{ij} = \frac{\sum_{j=1}^{n} A_{ij}}{n}$ and can be represented as $\begin{bmatrix} W_{11} \\ W_{21} \\ W_{31} \\ \\ W_{n1} \end{bmatrix}$

7.3.3 Consistency analysis

Consistency analysis is done by multiplying the pair-wise matrix with the weight vectors and then dividing it with corresponding criteria weight. This is represented as:

$$\begin{bmatrix} C_{11} \\ C_{21} \\ C_{31} \\ \\ C_{n1} \end{bmatrix} = \begin{bmatrix} X_{11} & X_{12} & X_{13} & & X_{1n} \\ X_{21} & X_{22} & X_{23} & & X_{2n} \\ X_{31} & X_{32} & X_{33} & & X_{3n} \\ & & & & \\ X_{n1} & X_{n2} & X_{n3} & & X_{nn} \end{bmatrix} * \begin{bmatrix} W_{11} \\ W_{21} \\ W_{31} \\ \\ W_{n1} \end{bmatrix}$$

Consistency Vector is calculated as $\begin{bmatrix} C_{v\,11} \\ C_{v\,21} \\ C_{v\,31} \\ \\ C_{v\,n1} \end{bmatrix} = \begin{bmatrix} \frac{C_{11}}{W_{11}} \\ \frac{C_{21}}{W_{21}} \\ \frac{C_{31}}{W_{31}} \\ \\ \frac{C_{n1}}{W_{n1}} \end{bmatrix}$

The average value of consistency vector is denoted by λ, where $\lambda = \sum_{i=1}^{n} C_{v\,ij}$

The Consistency Index (CI) is calculated as $CI = \frac{\lambda - n}{n-1}$, n= Order of matrix

Consistency ratio CR = CI / RI, where RI (Random Inconsistency indices) is obtained from Random index table of **Saaty, 1980**.

7.4 SELECTION OF ATTRIBUTES IN MANUFACTURING SYSTEMS

The purpose of this analysis is to make a comparative evaluation of various manufacturing systems. The selected manufacturing system should be capable of addressing various challenges faced by the society as well as themselves. Based on expert opinion, four types of manufacturing systems have been carefully chosen for comparative analysis. These are: Traditional manufacturing (TM), lean manufacturing (LM), green manufacturing (GM) and sustainable manufacturing (SM). To carry out a step-by-step analysis, various attributes that contribute towards the performance of manufacturing systems have been recognized through the participation of a panel of experts. The attributes are further classified in sub-attribute level. Table 7.1 represents various attributes and sub-attributes of manufacturing systems.

Table 7.1: Various attributes and sub-attributes in manufacturing system

Sl. No.	Attributes	Sub- attributes	
1	**Flexibility**	F1	Basic flexibility
		F2	System flexibility
2	**Environmental Stewardship**	E1	Resource conservation
		E2	Waste management
		E3	Pollution prevention
		E4	Environmental management system (EMS)
3	**Economic growth**	G1	Operating cost
		G2	Return on investment (ROI)
4	**Social well-being**	S1	Health and safety of employees
		S2	Corporate social responsibility (CSR)
		S3	Socially responsible manufacturing (SRM)
5	**Productivity**	P1	Functionality
		P2	Optimization of resources
6	**Reconfigurability**	R1	System level RMS
		R2	Reconfigurable machine tools (RMT)
		R3	Reconfigurable control in open-architecture

The following section gives a brief description of these attributes and sub-attributes.

7.4.1 Flexibility

Manufacturing flexibility refers to the ability of the manufacturing systems to deal with the variation in process sequence, variation in parts manufactured, change in design or the production volume. Manufacturing flexibility can be of following types:

- **Basic flexibility**: These can be in terms of machine flexibility, material handling flexibility or operation flexibility.

  Machine flexibility refers to the ease with which a machine can carry out various operations. Material handling flexibility is the ease with which raw materials, semi-finished goods or finished goods can be transported at various places or positions safely. Operation flexibility refers to the flexibility to carry out alternate processes for manufacturing activities.

- **System flexibility**: This is related to a complete manufacturing system. It reflects the possibility of changes with regard to the whole manufacturing set-up. It can be of the following types:
  - i. Volume flexibility
  - ii. Expansion flexibility
  - iii. Routing flexibility
  - iv. Process flexibility
  - v. Product flexibility

7.4.2 Environmental stewardship

Stewardship of the environment refers to the protection of the environment through conservation, recycling, regeneration or restoration. It refers to the responsible use and conservation of various resources for the benefits of the society, future generations and all species. It is aimed towards meeting various societal needs and is accountable to the society (Worrell and Appleby, 2000). The responsibility for environmental quality should be shared by all those whose actions affect the environment. Various sub-attributes of environmental stewardship are: Resource conservation, waste management, pollution prevention, environmental management system.

- **Resource conservation:** It is concerned with the best possible use of resources (materials, energy, water). This can be achieved through conservation of water, energy and other resources and their efficient use. Judicial use of natural resources can offer maximum benefits to the present generation and can also meet the need for future generations. Conservation includes both the protection and rational use of natural resources.

- **Waste management:** Waste management or disposal of waste are the activities and actions for managing waste from its inception to the final disposal. Various stages of waste management are:

i. Collection and segregation of waste
ii. Transportation of waste
iii. Treatment and disposal of waste
iv. Monitoring of waste management process

- **Pollution prevention:** Pollution prevention is a strategy to reduce the waste generated and released into the environment. It aims at minimizing contamination of the environment by chemicals or other harmful materials. Many industries view it as a way to improve their efficiency and profitability through reduction of waste and technological advancements.
- **Environmental management system**: An environmental management system (EMS) can be developed in compliance with the ISO-14001 standard. It reflects the strategy of the organization to implement its environmental policy and addressing the governmental regulations. An EMS is a system and database that integrates various procedures and processes. It is related to the training of personnel, monitoring of environmental performance, generation of data related to environmental performance, reporting of data to internal and external stakeholders of the firm etc. ISO- 14001 is the most widely used standard for EMS.

7.4.3 Economic growth

In economics, growth is modeled as a function of physical and human capital, labor force and technology. Economic growth refers to an increase of aggregate production in an economy that leads to increased economic output. Technological advancement plays an important role towards economic growth. Economic growth is vital for better quality of life or standard of living. These can be classified as operating cost and return on investment (ROI).

- **Operating cost:** Operating costs are associated with the expenses towards maintenance and administration of business. It includes the cost of resources used, operating expenses and overhead expenses. The operating cost is deducted from revenue to arrive at operating income. This is reflected in the company's income statement.

- **Return on investment:** Return on investment (ROI) is a performance measure to evaluate the efficiency of an investment or to compare the efficiency of different investments. It is a financial ratio intended to measure the benefit obtained from an investment. ROI measures the amount of return on a particular investment, relative to the investment's cost. To calculate ROI, the benefit (or return) of an investment is divided by the cost of the investment.

$$\text{ROI} = \frac{\text{Current value of investment} - \text{Cost of investment}}{\text{Cost of investment}}$$

7.4.4 Social well-being

Social well-being refers to the relations among persons. It is reflected by the way a person behaves, interacts, communicates or socializes with other people. Social well-being helps to fulfil the basic human needs and supports their peaceful co-existence and progress. This is characterized by equal access and fulfilment of basic needs (water, food, shelter and health services) and access for elementary education.

From manufacturers point of view social well-being have sub-attributes namely health and safety of employees, corporate social responsibility (CSR) and socially responsible business (SRB).

- **Health and safety of employees**: In accordance with the Indian factories Act 1948, every establishment has to ensure the health, safety and welfare of all the workers while they are at work in the factory. Necessary provisions have to be enforced to rectify all sorts of risks during use, handling, transport, storage of goods and materials. Regular monitoring to check the cleanliness, disposal of waste and effluents, ventilation etc. are essential to maintain a hygienic work environment for the employees. Safety of the workers must be ensured through the installation and maintenance of various apparatus, tools, equipment, machines in best possible safety conditions.
- **Corporate social responsibility (CSR):** It refers to the strategies that firms employ in their corporate governance that are ethical and beneficial to the community. CSR is a firm's commitment to being socially responsible and in-line with public expectations. Various CSR initiatives taken by a firm are the followings:

i. Environmental responsibility

Environmental responsibility initiatives taken by a firm focus towards reducing pollution, greenhouse gas emissions and sustainable use of natural resources

ii. Human rights responsibility

Human rights responsibility initiatives taken by a firm can involve fair labor practices, fair trade practices and disapproving child labor

iii. Philanthropic responsibility

Philanthropic responsibility initiatives can involve funding educational programs, donating to worthy causes, supporting health initiatives, community beautification projects etc.

iv. Economic responsibility

Economic responsibility initiatives involve improving firm's business operation through the set-up of sustainable practices.

- **Socially responsible business (SRB)**: The primary goal of Socially responsible manufacturing is not just to maximize their profitability but also to bring positive changes and contribution to the ecosystem, stakeholders such as the community, customers and staff. Apart from realization of financial gains, companies obeying SRB practices voluntarily initiate well-being for the community as well as environmental aspects of the society.

7.4.5 Productivity

Productivity refers to the efficiency of production. It is expressed by the ratio of output produced to the input used in a production process, over a specific period of time. Productivity typically reflects economic growth and competitiveness of an organization. Various steps that can help to develop a more productive and successful business environment are:

i. Examination of the existing workflow
ii. Updating business processes
iii. Invest in continued employee education
iv. Procurement of smarter machining tools
v. Investment in maintenance
vi. Better organization
vii. Encourage collaboration.

Functionality and optimization of resources are important sub-attributes of productivity. These are discussed below.

- **Functionality**: Functionality is based on the state at which the product to be produced is required. Some products demand high reliability, precision, accuracy and uncompromised quality. The machines producing these products must have adequate accuracy, otherwise the products will not be able to meet their functionalities.
- **Optimization of resources:** Resource optimization is the technique to match various resources like human, machinery, finance, material, knowledge etc. with the requirements of the industries to achieve the established goals. Optimization helps to achieve desired results within a set timeframe using least possible capital or other resources. A systematic approach and long- term vision can help organizations to optimize their various resources.

7.4.6 Reconfigurability

To deal with high fluctuations in the market and demand for high variety of products, the organizations must be able to react to such changes quickly and effectively. More responsive manufacturing is the need of the hour. Reconfigurability in manufacturing allows addition, removal or reorganization of manufacturing components to cope with changes in market and demand for high product variety in a cost- effective way.

Reconfigurable manufacturing system (RMS) is designed for rapid change in structure, hardware/software components so as to quickly adjust production capacity and functionality in response to market fluctuations or regularity compliance. Sub-attributes of reconfigurable manufacturing systems are: System level RMS, reconfigurable machine tools and reconfigurable control in open architecture (Koren et al., 1999). These are discussed below.

- **System level RMS:** A system RMS configuration is a set of machines including controls and the connections among them. The adaptability feature offers short-term resetting of manufacturing systems in order to produce different variety of products. A modular system structure in RMS meets the requirements of changeability.
- **Reconfigurable machine tools (RMT):** The primary purpose of RMT machines is to cope the changes in the products or parts to be manufactured. It takes care of various changes namely workpiece size, part geometry and complexity, production volume, required process, accuracy required, material property etc.

- **Reconfigurable control in open architecture:** A library of controller software components like servo control algorithms, temperature control algorithms are stored for reuse. The modules needed for the applications are configured by 'Control configurator' that integrates the controller for the selected machines and checking of real-time constraints.

Based on the above criteria, sub-criteria an analytic hierarchy structure is developed for alternative manufacturing systems. This is represented in Figure 7.1.

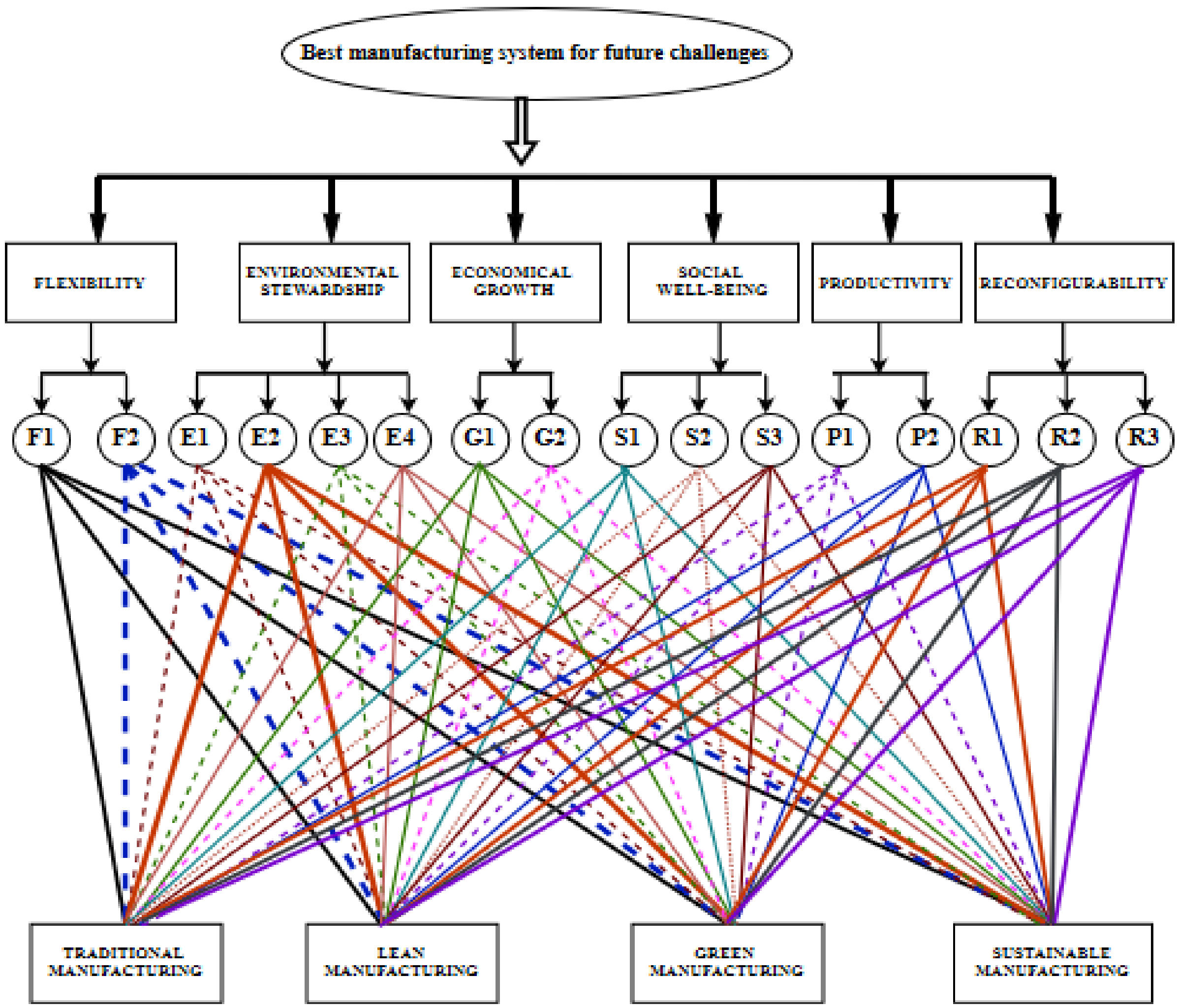

Figure 7.1: An Analytic hierarchy structure for the selection of best manufacturing system

7.5 AN AHP ANALYSIS OF TM, LM, GM AND SM SYSTEMS

AHP hierarchy (Figure 7.1) reflects selected attributes and sub-attributes for the analysis. It also represents their interactions with alternative manufacturing systems namely traditional manufacturing (TM), lean manufacturing (LM), green manufacturing (GM) and sustainable manufacturing (SM) systems. AHP methodology is used to find the priority weights of various attributes and sub-attributes. This is discussed below.

7.5.1 Priority weights for different attributes and sub-attributes

A panel consisting of three experts from Industrial background and two academicians were invited for the pair-wise comparison of the attributes mentioned earlier. For example, flexibility is assigned lower ratings (1/4, 1/3, 1/2 and 1/3 respectively) as compared to environmental stewardship, economic growth, social well-being and productivity. It however has a higher rating of 2 over reconfigurability. Based on the ratings given by experts' using Saaty's scale, the priority weights are determined. AHP follows the following steps:

i. Pairwise comparison matrix and

ii. Normalized matrix and consistency analysis.

The priority weights of different attributes are shown in Table 7.2.

Table 7.2: Analysis of different attributes

i. Pairwise comparison matrix

Attributes	F	E	G	S	P	R
F	1.000	0.250	0.333	0.500	0.333	2.000
E	4.000	1.000	2.000	4.000	2.000	6.000
G	3.000	0.500	1.000	2.000	1.000	5.000
S	0.333	0.500	3.000	1.000	2.000	3.000
P	0.500	0.333	0.333	0.500	1.000	4.000
R	0.500	0.167	0.200	0.333	0.250	1.000
Total	9.333	2.750	6.867	8.333	6.583	21.000

ii. Normalized matrix and consistency analysis

Attributes	F	E	G	S	P	R	Total	Priority weight	Consistency Measure
F	0.107	0.091	0.049	0.060	0.051	0.095	0.452	0.075	6.131
E	0.429	0.364	0.291	0.480	0.304	0.286	2.153	0.359	6.628
G	0.321	0.182	0.146	0.240	0.152	0.238	1.279	0.213	6.353
S	0.036	0.182	0.437	0.120	0.304	0.143	1.221	0.204	6.833

P	0.054	0.121	0.049	0.060	0.152	0.190	0.626	0.104	5.885
R	0.054	0.061	0.029	0.040	0.038	0.048	0.269	0.045	6.222
								CI	0.068
Max. Eigen value = 6.833								**RI**	1.240
Consistency Ratio = 0.055								**CR**	0.055

The CR value is 0.055 which is less than 0.1. This reflects judgmental consistency in the analysis. In the next step, various sub-attributes under each class (Attribute) are compared. For example, sub-attribute F1 (Basic flexibility) is compared to F2 (System flexibility). This is shown in Table 7.3.

Table 7.3: Analysis of sub-attributes for flexibility

i. Pairwise comparison matrix

Sub- attributes	**F1**	**F2**
F1	1.000	0.333
F2	3.000	1.000
Total	4.000	1.333

ii. Normalized matrix and consistency analysis

Sub- attribute	**F1**	**F2**	**Total**	**Priority weight**	**Consistency measure**
F1	0.250	0.250	0.500	0.250	2.000
F2	0.750	0.750	1.500	0.750	2.000

Max. Eigen value = 2.000

Consistency Ratio = 0.000

CR value 0.000 represents a perfect consistency.

Sub-attributes of environmental stewardship viz. E1, E2, E3 and E4 are also analyzed. This is given in Table 7.4.

Table 7.4: Analysis of sub-attributes for environmental stewardship

i. Pairwise comparison matrix

Sub- attribute	E1	E2	E3	E4
E1	1.000	3.000	4.000	0.333
E2	0.333	1.000	2.000	0.167
E3	0.250	0.500	1.000	0.200
E4	5.000	4.000	5.000	1.000
Total	6.583	8.500	12.000	1.700

ii. Normalized matrix and consistency analysis

Sub-attribute	E1	E2	E3	E4	Total	Priority weight	Consistency measure
E1	0.152	0.353	0.333	0.196	1.034	0.259	4.128
E2	0.051	0.118	0.167	0.098	0.433	0.108	4.032
E3	0.038	0.059	0.083	0.118	0.298	0.074	4.096
E4	0.759	0.471	0.417	0.588	2.235	0.559	4.755
Max. Eigen value = 4.755 Consistency ratio = 0.094						**CI**	0.084
						RI	0.900
						CR	0.094

All other sub-barriers are also similarly analyzed to find their priority weights, maximum eigen value, consistency ratio and consistency index. This is given in Table 7.5.

Table 7.5: Result of AHP analysis for the sub-attributes

Sub-attributes	Priority weights	Max. Eigen value	Consistency ratio
F1	0.250	2.000	0.000
F2	0.750		
E1	0.259	4.755	0.094
E2	0.108		
E3	0.074		
E4	0.559		

Sub-attributes	Priority weights	Max. Eigen value	Consistency ratio
G1	0.167	2.000	0.000
G2	0.833		
S1	0.241	3.030	0.016
S2	0.211		
S3	0.548		
P1	0.167	2.000	0.000
P2	0.833		
R1	0.738	3.031	0.012
R2	0.168		
R3	0.094		

Each *'alternative manufacturing system'* is now analyzed w.r.t sub-attributes. Table 7.6 analyzes the alternative manufacturing systems w.r.t basic flexibility (F1).

Table 7.6: Analysis of alternative manufacturing systems w.r.t basic flexibility (F1)

i. Pairwise comparison matrix

Alternative mfg. systems	TM	LM	GM	SM
TM	1.000	0.333	0.250	0.143
LM	3.000	1.000	1.000	0.200
GM	4.000	1.000	1.000	0.250
SM	7.000	5.000	4.000	1.000
Total	15.000	7.333	6.250	1.593

ii. Normalized matrix and consistency analysis

Alternative mfg. systems	TM	LM	GM	SM	Total	Priority weights	Consistency Measure
TM	0.067	0.045	0.040	0.090	0.242	0.060	4.029
LM	0.200	0.136	0.160	0.126	0.622	0.155	4.101
GM	0.267	0.136	0.160	0.157	0.720	0.180	4.046

SM	0.467	0.682	0.640	0.628	2.416	0.604	4.179
Max. Eigen value = 4.179 Consistency ratio = 0.033						CI	0.030
						RI	0.900
						CR	0.033

Similarly, priority weights are calculated for all alternative systems with respect to other sub-attributes. Table 7.7 signifies the same.

Table 7.7: Result of analysis for alternative manufacturing systems w.r.t sub-attributes

Sub-attributes	**Priority weights of manufacturing systems w.r.t sub-attributes**				**Max. Eigen value**	**Consistency ratio**
	TM	**LM**	**GM**	**SM**		
F1	0.060	0.155	0.180	0.604	4.179	0.033
F2	0.050	0.196	0.195	0.559	4.243	0.007
E1	0.059	0.165	0.196	0.581	4.190	0.040
E2	0.047	0.390	0.129	0.434	4.443	0.085
E3	0.054	0.138	0.231	0.577	4.291	0.056
E4	0.043	0.114	0.243	0.600	4.408	0.073
G1	0.093	0.143	0.239	0.525	4.166	0.033
G2	0.162	0.105	0.226	0.507	4.124	0.030
S1	0.066	0.117	0.321	0.496	4.410	0.077
S2	0.067	0.120	0.262	0.551	4.146	0.027
S3	0.047	0.129	0.284	0.541	4.409	0.080
P1	0.054	0.131	0.237	0.578	4.112	0.020
P2	0.064	0.268	0.167	0.502	4.160	0.037
R1	0.083	0.216	0.193	0.508	4.331	0.077
R2	0.072	0.174	0.193	0.561	4.257	0.053
R3	0.065	0.147	0.221	0.567	4.279	0.049

7.5.2 Evaluation of suitability index for different alternatives

The priority weights of sub-attributes, attributes and different alternatives are obtained from earlier analysis. These are multiplied together to evaluate the 'Suitability Index' for each alternative manufacturing system. This is represented in Table 7.8.

Table 7.8: Summary of data for the selection of best manufacturing system

S. No.	Sub-Attributes	Weights of sub-attributes	Weights of attributes	Weights of different alternatives (W_T, W_L, W_G, W_S)				Suitability index = (W_1) * (W_2) * weights of different alternatives			
		(W_1)	(W_2)	TM	LM	GM	SM	TM	LM	GM	SM
1	**F1**	0.25	0.075	0.06	0.155	0.18	0.604	0.0011	0.0029	0.0034	0.0113
2	**F2**	0.75	0.075	0.05	0.196	0.195	0.559	0.0028	0.0110	0.0110	0.0314
3	**E1**	0.259	0.359	0.059	0.165	0.196	0.581	0.0055	0.0153	0.0182	0.0540
4	**E2**	0.108	0.359	0.047	0.39	0.129	0.434	0.0018	0.0151	0.0050	0.0168
5	**E3**	0.074	0.359	0.054	0.138	0.231	0.577	0.0014	0.0037	0.0061	0.0153
6	**E4**	0.559	0.359	0.043	0.114	0.243	0.6	0.0086	0.0229	0.0488	0.1204
7	**G1**	0.167	0.213	0.093	0.143	0.239	0.525	0.0033	0.0051	0.0085	0.0187
8	**G2**	0.833	0.213	0.162	0.105	0.226	0.507	0.0287	0.0186	0.0401	0.0900
9	**S1**	0.241	0.204	0.066	0.117	0.321	0.496	0.0032	0.0058	0.0158	0.0244
10	**S2**	0.211	0.204	0.067	0.12	0.262	0.551	0.0029	0.0052	0.0113	0.0237
11	**S3**	0.548	0.204	0.047	0.129	0.284	0.541	0.0053	0.0144	0.0317	0.0605
12	**P1**	0.167	0.104	0.054	0.131	0.237	0.578	0.0009	0.0023	0.0041	0.0100
13	**P2**	0.833	0.104	0.064	0.268	0.167	0.502	0.0055	0.0232	0.0145	0.0435
14	**R1**	0.738	0.045	0.083	0.216	0.193	0.508	0.0028	0.0072	0.0064	0.0169
15	**R2**	0.168	0.045	0.072	0.174	0.193	0.561	0.0005	0.0013	0.0015	0.0042
16	**R3**	0.094	0.045	0.065	0.147	0.221	0.567	0.0003	0.0006	0.0009	0.0024
Overall suitability indices for different alternatives								**0.0748**	**0.1546**	**0.2273**	**0.5436**

Figure 7.2 displays a Pareto chart which is based on suitability index and is obtained from Table 7.8. It characterizes the suitability index for alternative manufacturing systems. The chart clearly highlights that SM is the best manufacturing option among the chosen alternatives. The chart reflects that SM has much higher suitability index value (0.5436) as compared to values of 0.2273 (GM), 0.1546 (LM) and 0.0748 (TM).

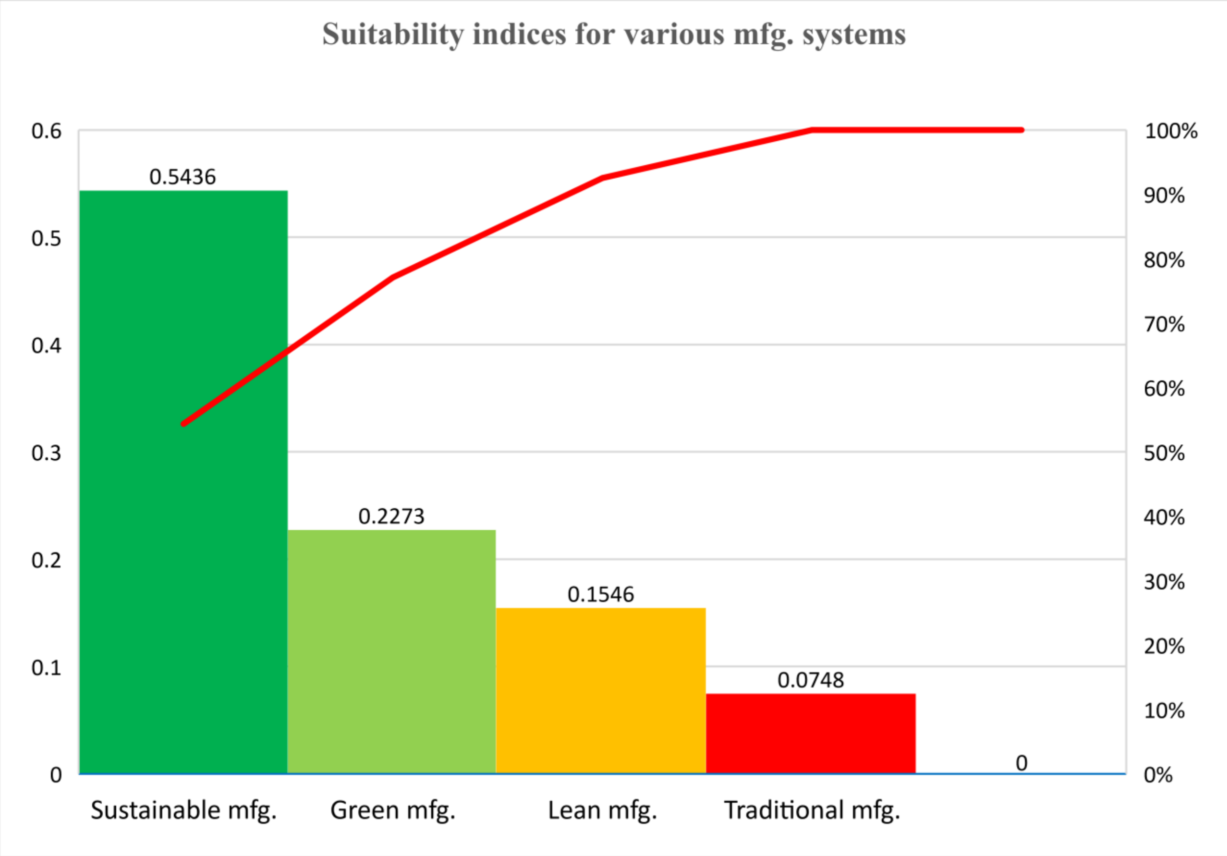

Figure 7.2: Pareto chart showing suitability indices for different manufacturing system

7.6 DISCUSSION

Table 7.8 represents a detailed analysis for the evaluation of suitability index for alternative manufacturing systems. Figure 7.2 displays their suitability indices as shown in a Pareto chart. Based on the analysis it is evident that SM (Sustainable manufacturing) is the best and preferred manufacturing choice among alternatives. This is by virtue of its much higher suitability index of 0.5436 as compared to others (0.2273, 0.1546 and 0.0748).

From the above analysis it can be said that developing countries like India must adopt SM practices in their business operations. Implementation of SM practices will help organizations to reorient their manufacturing setups, process optimization, adoption of eco-friendly practices and such other activities, thus enabling them to succeed in challenging business environment, complying with government regulations and towards long-term sustainable goals.

Manufacturers need to appreciate and comprehend that sustainable investment for the implementation of SMS is the need of the competitive business environment in modern era and it has huge return potential. The possible impetus for this can be reduction of waste, reduced use of resources, manufacturing high-quality value-added products, gain in productivity, greater employee participation, employee's satisfaction, social well-being, meeting long-term sustainability goals etc.

Various sub-attributes of sustainable manufacturing are depicted in Figure 7.3.

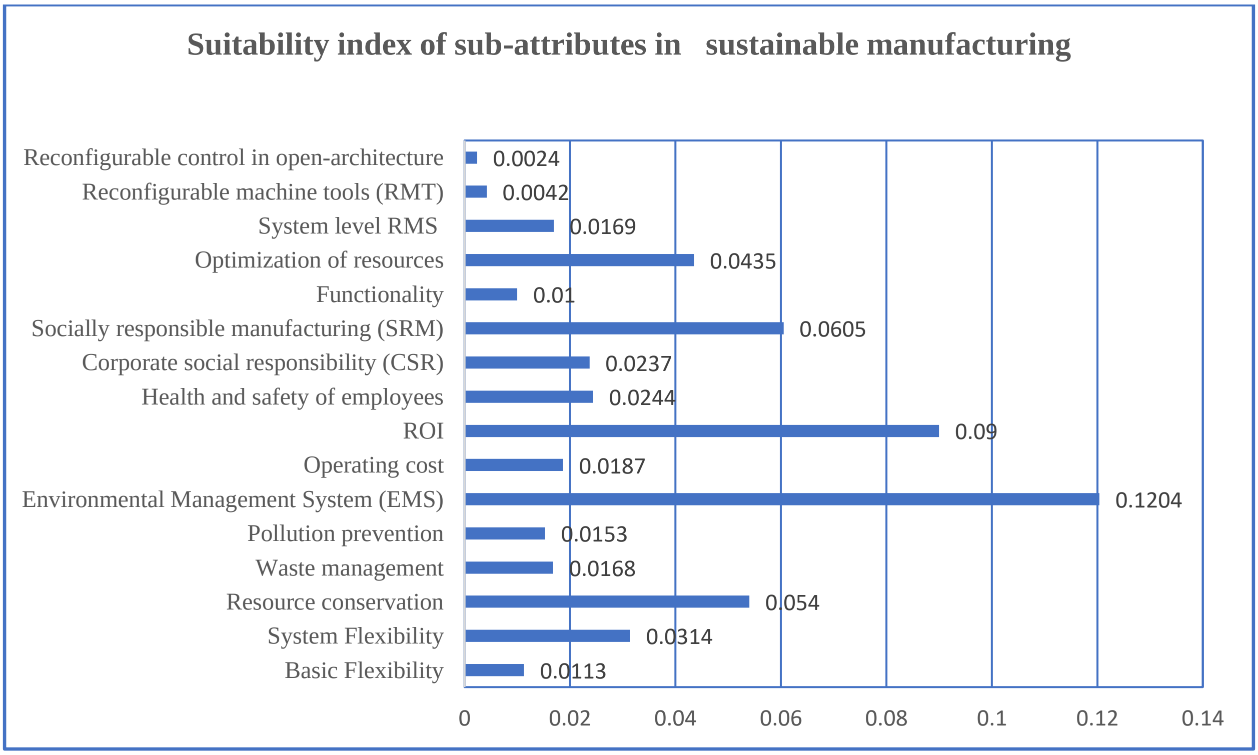

Figure 7.3: Chart depicting various sub-attributes of sustainable manufacturing

The analysis highlights that setting-up and adherence to environmental management system (EMS) having a suitability index of 0.1204, has the highest influence towards the development of SMS. This is followed by ROI having suitability index of 0.09 and socially responsible manufacturing (SRM) with suitability index of 0.0605.

7.7 CONCLUSION

Sustainable business creates business excellence through economic gains, healthy work environment, conservation of natural resources, development of a strong community and the like. More and more companies have started to invest for environmental and socially conscious business practices as they perceive that SM practices have huge potential to make a difference and to earn more profits.

This chapter was aimed at finding the best manufacturing system that can suitably address business challenges under global environment. A comparative evaluation of various manufacturing practices was carried out by using AHP methodology. The study selected four alternative systems namely TM, LM, GM and SM for the analysis. The analysis evaluated suitability indices for the alternatives. SM is found to be the best alternative having highest suitability index of 0.5436. Survey of related literatures also highlights the key role of SM practices towards sustainability challenges under global competitive environment. The next alternatives (based on relative importance) are found as GM. LM and lastly the TM. The study has vital significance as this analysis has been validated through AHP methodology.

Based on the above analysis, it is expected that manufacturers can opt SM practices among other alternatives in order to reap overall paybacks. Recent global trend also compliments the same. The AHP analysis highlights that environmental management system (EMS), return on investment (ROI) and socially responsible manufacturing (SRM) are the top three contributing attributes in SM systems and should therefore be dealt with due care.

CHAPTER VIII

SYNTHESIS OF THE RESEARCH WORK

8.1 INTRODUCTION

Manufacturing has gone through rapid changes especially in last century to keep pace with the rising need of the populace. The demand of society is changing rapidly. Consumers now aspire for eco-friendly and green products with better quality, improved design, adaptable features, aesthetics and that too at the lowest possible price. These can only be met through the advancement of technology and improved manufacturing systems. The manufacturing system must have high degree of flexibility and reconfigurability in both hardware and software systems to satisfy rapid changing demand. In view of the above and to remain competitive in the market, sustainable manufacturing practices are the preferred choice among the manufacturers. The selection of best manufacturing system illustrated in chapter 7 also compliment the same. Implementation of sustainable manufacturing system over the already existing system is a challenging task and poses high risk, if tried without adequate and prior assessment. A careful study of sustainable manufacturing practices was done from literature review and case studies from reputable web sites. This helped to acquaint and analyze this relatively new field, its various dimensions and elements that affect SMS. Particular attention was paid to the barriers of sustainable manufacturing. This chapter presents the synthesis of research work presented in previous chapters. The main objectives of this chapter are:

- To present a comprehensive picture in the present work
- To summarize different studies carried out in previous chapters
- To establish linkages among various analysis carried out in this work

8.2 SYNTHESIS OF THE RESEARCH WORK

Synthesis of research integrates existing knowledge and research findings related to an issue. The synthesis is aimed at the generalization and applicability of the findings in order to develop new knowledge through the process of integration (Wyborn et al., 2018).

The present work is devoted towards the analysis of various barriers and enablers for the implementation of SMS particularly in context of Indian industries. The research carried out is in line with the objectives specified in chapter 1. The achieved objectives are listed below:

- Literature related to SMS have been studied and key issues have been discussed

- The gaps in existing literatures have been identified
- Various elements, issues and barriers that affect the SMS have been identified through literature review and brainstorming by experts
- An ISM based hierarchy model has been developed to establish the inter-relationships among the selected barriers
- The driving and dependence power of barriers have been calculated by MICMAC analysis
- Quantitative analysis of barriers using GTA. They are ranked based on their intensity
- AHP methodology has been used for the selection of best manufacturing system among alternatives. It has been established that SM is the best choice based on suitability index. It should therefore be the preferred choice among Indian manufacturers.
- Various enablers have been analyzed for the success of SMS using AHP and R^3I technique

The methodologies adopted in the present work has been presented in Table 8.1 and is further represented in Figure 8.1.

Table 8.1: Methodologies used in this research

S. No.	Objectives	Methodology used	Study No.
1	To identify various enablers and barriers of sustainable manufacturing	Literature survey, expert opinion (involving industry experts and academia)	I
2	To recognize current trends and perceptions of Indian industries towards the acceptance and implementation of SMS and validate it	Questionnaire based survey, ANOVA analysis	II
3	To develop an ISM model to analyze the selected barriers of SMS	Interpretive structural modelling	III
4	Quantitative evaluation of barriers	Graph theoretic approach	IV
5	To analyze identified enablers for the success of SMS	AHP and R^3I combined methodology	V
6	To find the best manufacturing system in Indian manufacturing context	Analytic hierarchy Process	VI

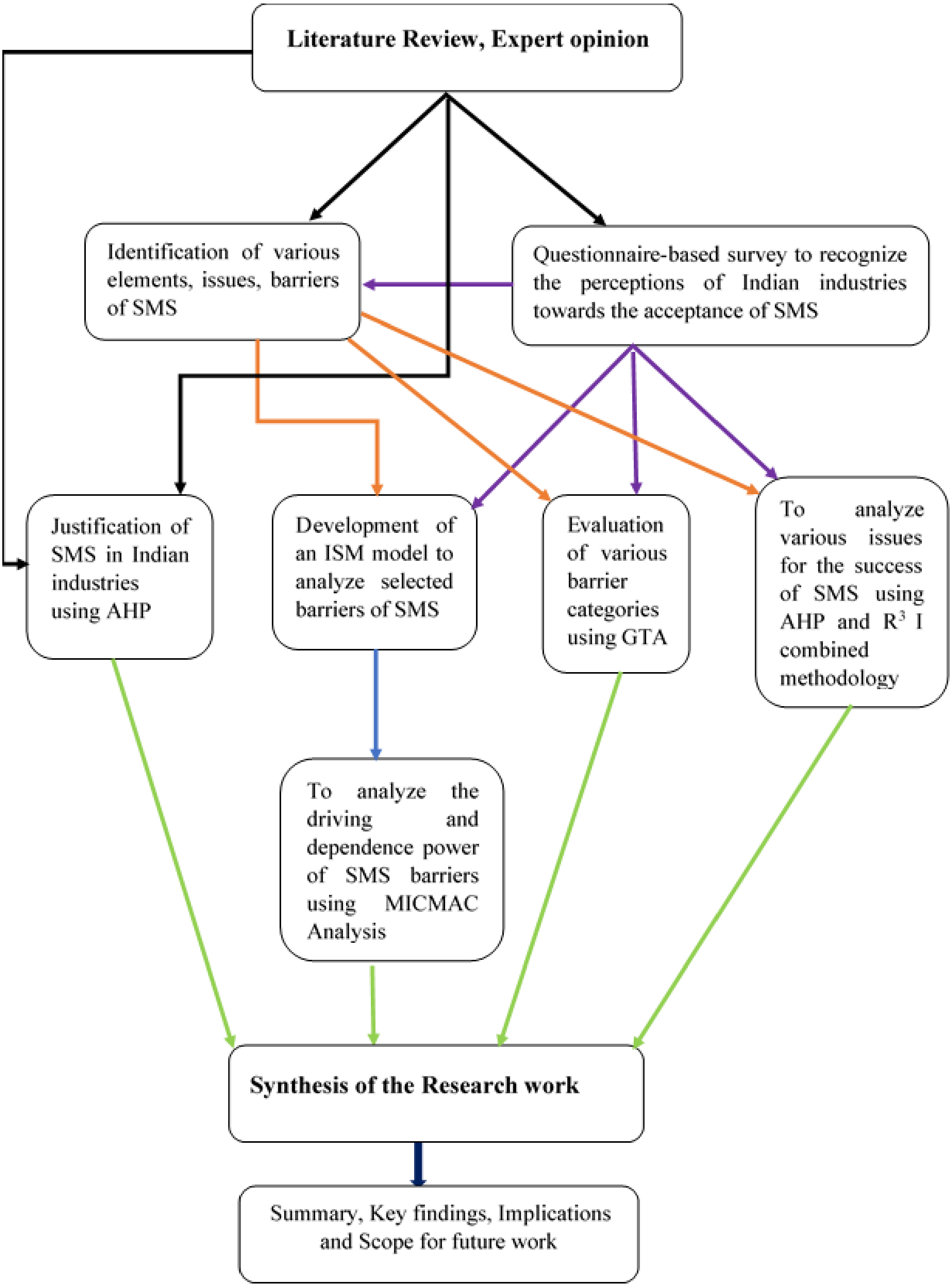

Figure 8.1: Integration of methodologies used in the research

The followings may be considered as significant out of the present research.

8.2.1 Literature review

A comprehensive literature review was carried out on various issues related to sustainable manufacturing and sustainability challenges. The study included various issues of sustainable manufacturing, gaps in literatures, various methodologies such as ISM, AHP, GTA, R^3I, ANOVA reported in this work. Literature review helped to frame the questionnaire for the survey. It has been perceived that industries must continuously upgrade their manufacturing systems and adopt best manufacturing practices for their success in business.

8.2.2 Questionnaire development and validation

Literature review helped in framing the questionnaire for the survey. The questionnaires were sent to various industries to seek their opinion. Responses obtained from survey were compiled to get the statistical data for analysis. Data obtained from the survey has been validated by ANOVA method.

8.2.3 Modelling the barriers by ISM Approach

Chapter 4 describes ISM analysis for selected barriers towards the development of SMS. An ISM model has been established that signifies the hierarchy of barriers and their mutual relationships. MICMAC analysis helped to categorize the barriers based on their driving and dependence power. The ISM model depicts that the barrier namely 'Lack of government support towards developing new technologies' has highest drive power and is vital towards the induction of SMS. Other important barriers with high driving powers are 'Improper business ethics/ company policy', 'Lack of top management support' etc. Lack of sensitivity by top management can blur the organization's vision towards long term sustainable development. The developed model and analysis are valuable for the managers to understand the influence of these barriers and their mutual interactions for the smooth transition towards SMS.

8.2.4 Quantitative analysis of various barriers using GTA approach

Chapter 5 describes the GTA analysis for various categories of barriers. A mathematical analysis has been done for various barriers and sub-barriers. Barriers were grouped into five categories based on their relevance. The intensity was evaluated for each category of barrier as well as for the whole system. The analysis reflects that technological barrier followed by financial barrier are two most important barriers. The managers will be able to draw vital inferences from this analysis that will help in the execution of SMS.

8.2.5 Analysis of various enablers using AHP and R^3I combined methodology

Chapter 6 has been dedicated towards the analysis of various enablers and their sub-elements using AHP and R^3I combined methodology. AHP methodology evaluates the priority weights of selected enablers. The ranking of various enablers as obtained from the analysis in order of preference are: (i) Environment related issues (ii) Economic related issues (iii) Technology and allied issues (iv) Social and behavioral issues. The result obtained from AHP analysis has been checked for its authenticity using entropy approach (R^3I technique). The R^3I analysis validates the result obtained from AHP analysis. The study establishes the ranking of various issues and their sub- elements towards adopting SMS. The study is significant for the managers willing to adopt sustainable manufacturing system in their organization.

8.2.6 Justification for the adoption of SMS

Chapter 7 is dedicated to designate the best manufacturing system out of selected alternatives in Indian manufacturing context. Analytic hierarchy process has been used to rate various attributes and sub- attributes by pairwise comparison. Global weight has been calculated to weigh their suitability index. Based on their suitability index, it has been established that SMS is the preferred choice among Indian manufacturers.

8.3 CONCLUSION

This chapter presents the synthesis of research work. The linkages between various approaches used in this work has been discussed. Figure 8.1 represents a flow diagram towards the integration of all methodologies used in this work. A comprehensive literature review was carried out to identify various enablers and barriers of SMS. Interpretive structural modeling (ISM), analytic hierarchy process (AHP) and graph theoretic approach (GTA) are used for the modeling and analysis of SMS. The relationships among selected barriers have been established using ISM methodology. Mathematical analysis of various barriers has been carried out using GTA technique. AHP and R^3I analysis has been used for the analysis of critical success factors towards the progress of SMS. Analytic hierarchy process has been used for the selection of best manufacturing system in Indian manufacturing context. The salient features in this study are:

i. Various barriers and critical success factors towards the development of SMS has been analyzed using various MCDM techniques

ii. GTA analysis highlights that technological barrier is the predominant barrier for the adoption of sustainable manufacturing system. Important sub-barriers in this category are: Lack of support towards eco- innovation-oriented research, poor focus on energy efficiency and energy efficient process, lack of research and development initiatives, lack of standardized metrics or performance benchmarks, poor focus on employees' training on sustainable technologies and practices. Other important barriers to follow are financial barriers and environmental barriers.

iii. ISM analysis compliments that lack of government support towards developing new technologies is the barrier with very high driving power. Other significant barriers with high driving power are: Improper business ethics/ company policy, lack of top management support, lack of vision for long term sustainable development etc.

iv. AHP and R^3I analysis highlights that concern for mitigating environment related issues act as strong catalyst for adopting SMS. A transition towards sustainable manufacturing requires efforts to minimize the negative environmental impact. Appropriate waste management and emission control will act as strong enablers in this direction.

CHAPTER IX

SUMMARY, KEY FINDINGS, IMPLICATIONS AND SCOPE FOR FUTURE RESEARCH

9.1 INTRODUCTION

Rising global competition, changing customer demands, dynamic market, sustainability issues, changing regulations are forcing manufacturers across the globe to adopt sustainable manufacturing practices. Sustainable manufacturing is therefore the favored area of research in the field of manufacturing. However, various issues of SMS have not yet been extensively explored. Existing literatures on the associated enablers and barriers are not adequately helping the organizations to promote sustainable manufacturing systems. Adoption of SMS in developing countries like India is abysmally low. This has motivated the researchers to pursue research in exploring and analyzing various SMS issues, enablers and barriers. This chapter presents the summary of the research, major contribution, key findings of the research, major implications, limitations, future scope of research and lastly conclusion of the research work.

9.2 SUMMARY OF THE RESEARCH WORK

AHP analysis has justified SMS as the preferred choice for Indian manufacturing environment. This section gives a concise review of the research work undertaken in this study. The work undertaken in this research includes the followings:

- A holistic literature survey to identify important issues, enablers and barriers in the field of SMS
- Development of questionnaire based on literature review and questionnaire survey to obtain responses from industries. The survey response helped to comprehend the inclination of Indian manufacturers towards the adoption of sustainable manufacturing system
- Data obtained from questionnaire survey has been validated using ANOVA analysis
- Various issues in the questionnaire includes environmental, economic, social, technological, implementational issues

- An ISM based hierarchy model has been developed to understand the mutual relationships among selected barriers. MICMAC analysis helped to find out the driving and dependence power of these barriers
- GTA based analysis has been used to quantify and assess the role of barriers in SMS
- AHP technique has been used to select best manufacturing system out of selected alternatives in Indian context. SMS is found to be the best manufacturing system by virtue of highest suitability index
- A combined AHP and R^3I methodology has been used to analyze various enablers for the success of SMS.

9.3 MAJOR CONTRIBUTION OF THE RESEARCH

Among others, economic motivation for reducing cost may be considered as one of the major impetus to carry-out this research. Environmental and societal factors like government incentives, customer pressure, environmental legislation, new standards etc. are triggering manufacturers to integrate sustainability in their corporate strategy and business ethics. Literature survey reveal that manufacturers are able to achieve sustainability and sustainable practices through the consideration of three dimensions of sustainability (people, planet, profit).

The followings are major contributions achieved through this research:

- The present research provides an exhaustive review of literatures on sustainable practices, sustainable issues and implementation of SMS
- Various enablers and barriers which can affect the implementation of SMS were identified
- A total of 31enablers were identified for the success towards SMS. These were analyzed by using AHP and R^3I methodology
- An ISM model is developed by incorporating 17 barriers towards the mitigation of SMS
- A GTA methodology is used to analyze 5 categories of barriers. Their intensity is assessed in numerical scale and ranking has been done
- Sustainable manufacturing has been perceived as the best manufacturing system in Indian manufacturing context based on suitability index. AHP methodology has been used for this purpose.

9.4 KEY FINDINGS OF THE RESEARCH

The key findings which emerged from this research are as follows:

- Sustainable manufacturing has been perceived as the preferred choice among majority of manufacturers
- The ISM model and MICMAC analysis has incorporated 17 barriers that affect SMS. The analysis reflects that 08 barriers namely 'lack of government support towards developing new technologies', 'improper business ethics/ company policy', 'lack of top management support', 'poor motivation and teamwork of the employees', 'lack of vision for long-term sustainable development', 'lack of standardized metrics or performance benchmarks', 'poor education and environmental awareness of workmen' and 'lack of capital to set up green projects' are in independent barrier category. By virtue of high driving power these barriers can greatly influence all other barriers. Management should implement pro-active interventions in alleviating these *key barriers*.

  There is no autonomous barrier in the driving-dependence diagram implying that all the identified barriers are of paramount importance from sustainability viewpoint.
- A detail analysis of various barriers has been done using GTA technique. Barriers have been classified in five categories namely environmental barriers, social and behavioral barriers, financial barriers, technological barriers, implementation and operational barriers. The intensity of barriers is evaluated by calculating the value of permanent matrix. The analysis reveals that technological barriers (B_4) is the predominant barrier towards the progress of sustainability. This can be justified by the fact that the efficiency of manufacturing greatly depends on available technology. Financial barriers (B_3) is the second major barrier. Financial barrier is important for any investment decisions concerning new technology, new process or any decision involving capital requirement towards sustainability. Other barriers also hinder the development towards SMS based on their relative intensity values. The results so obtained, provide meaningful inputs to the managers in order to formulate appropriate strategies for smooth transition towards SMS.
- AHP and R^3I methodology has been used to analyze various enablers for the success towards SMS. Enablers are classified in four groups namely environment related issues (E_1), economic related issues (E_2), social and behavioral issues (E_3) and technology and allied issues (E_4). Based on AHP analysis, these are ranked based on

their priority weights. Environment related issues (E_1) have highest priority weight of 0.42 and is ranked 1. Priority weight of all 31 sub-enablers have also been evaluated. R^3I methodology has been used to validate the result obtained from AHP analysis.

- AHP has been used to analyze best manufacturing system out of selected alternatives in Indian context. Based on the suitability index, SMS has been recognized as preferred choice among Indian manufacturers.

9.5 IMPLICATIONS OF THE RESEARCH

The present work has significant contribution to the literature of 'Sustainable manufacturing system'. The research explored the gaps in current literature in the area of SMS. The findings reveal important directions for the adoption of SMS in Indian manufacturing environment. The research is valuable for manufacturing industries, academicians, managers and the top management. Various MCDM techniques used in this analysis are ISM, GTA, AHP, R^3I, ANOVA. The questionnaire-based survey presented in this research can be explored for further research on environmental, economic, social, technological and other issues of SMS.

9.5.1 Implication for the industries

The research deals with important barriers, enablers related to sustainable manufacturing. The outcome of the present research is beneficial for manufacturing industries particularly in India. The analysis of various issues in the present research will motivate the firms to adopt SMS. The developed models using ISM, GTA, AHP and inferences drawn thereof, can be beneficial to improve their overall performance and progress towards SMS.

9.5.2 Implication for the academicians

The current research has provided some important suggestions for academicians. Some of these are highlighted below:

- The study will be helpful for researchers in the field of 'sustainable manufacturing'
- The analyses on various issues related to sustainable manufacturing provide insights for further research in this field
- The techniques used, developed models and inferences using ISM, GTA, AHP, R^3I techniques may support the academicians to carry out similar or further research
- ANOVA analysis has been used for the validation of survey data. This can be used by academicians in their research

- ISM methodology has executed order and direction on the complexity of relationship among various barriers of SMS. Researchers can use ISM for establishing relationships and to rank identified elements in their study area
- AHP and entropy methods have been used in this research to evaluate criteria weights of various attributes towards SMS and to rank them. Such type of analysis is very important for the academicians to determine priority weights of various elements in similar kind of studies.

9.5.3 Implication for the managers

The present research has developed ISM models incorporating important barriers. It can provide meaningful insights for the managers who are decision makers in their manufacturing units. Managers may focus on alleviating barriers based on their driving power, dependence power and relative standings. Intensity of barriers obtained through GTA analysis may guide towards the development of SMS. The analysis of critical success factors (enablers) by using AHP can further enable the success towards SMS. Developed models will enable managers to visualize the complex relationships among the barriers. Based on this, the managers can make strategic decisions that can help in smooth transition towards SMS.

9.6 LIMITATIONS AND SCOPE FOR FUTURE WORK

This section provides the limitations in this research. It also recommends some important suggestions for future research in the area of SMS. These are as follows:

- ISM model has been developed by incorporating barriers. Expert opinion was sought for preparing the SSIM matrix. This might have introduced some amount of bias due to individuals' perception and knowledge. Similar sort of biasness might have aroused during GTA and AHP analysis
- The research can be further explored by incorporating more barriers and enablers for the progress towards SMS
- The ISM model has not been statistically validated. Structural equation modelling or any other technique may be used for the validation
- The impact of identified enablers and barriers in different practical situation has not been carried out in present research
- The study is based on literature review and experts' opinion. It was quite difficult to get the responses from industry professionals due to their busy schedule

- The study has given a direction towards the likelihood of SMS implementation but might not be an exact and precise solution.

The present research can be extended further in the following directions:

- Some other MCDM techniques like DEMATEL, TOPSIS etc. can be used for further analysis
- ISM modeling incorporating enablers might be developed in future research
- Theoretical implications of the study can be of far-reaching consequence as the current research work can be extended to include other industries. Further research can be carried out by identifying company specific barriers which are aligned with their specific orientations
- Case studies can be carried out to examine the impact of various barriers and enablers in different practical situations
- A higher order research consisting of 'm' no. of barriers and 'n' no of expert panels may be formulated for future research.

9.7 CONCLUSION

Sustainable manufacturing practices have become the preferred choice among the industries. This study is an attempt to help manufacturers to implement SMS in their organizations. Literature review highlights that available literatures are lacking in reliable guidelines for the successful implementation of SMS. In view of this gap, the current study takes the opportunity to analyze various barriers and enablers towards the effective implementation of SMS. The implementation of SMS in industries is a challenging task as there exists several issues that affect the execution of SMS. Various barriers and enablers towards SMS are identified by review of literatures. Their ratings are obtained from survey responses. Relationship among various barriers have been established by ISM hierarchical model. MICMAC analysis helped to analyze their driving and dependence power. Key barriers identified from ISM analysis are: Lack of government support towards developing new technologies (15), improper business ethics/ company policy (6), lack of top management support (3), poor motivation and teamwork of the employees (4), lack of vision for long term sustainable development (8), lack of standardized metrics or performance benchmarks (11), poor education and environmental awareness of workmen (1) and lack of capital to set up green projects (5). These barriers can greatly influence all other barriers. It is crucial for top management to formulate suitable strategies with active support from the government and all stakeholders for the smooth transition towards SMS. GTA analysis signifies that technological barrier followed by financial barrier are the two significant barriers towards the attainment of sustainability goals. Capital investment towards new technologies is therefore essential for the successful implementation of SMS in the organizations. Suitability index value for alternate manufacturing systems have been evaluated in Indian manufacturing context using AHP technique. Sustainable manufacturing has been perceived as the preferred choice among Indian manufacturers. AHP and R^3I based combined methodology analyzes critical success factors (enablers) for SMS. It highlights the key role of environment related issues (E_1) having highest intensity value of 0.28006 for the success of SMS. This is followed by other issues namely economic related issues (E_2), technology and allied issues (E_4) and lastly the social and behavioral issues (E_3).

In view of the existence of several associated multifaceted elements and sub-elements in manufacturing systems, their fruitful analysis for the transitioning towards SMS is a real challenge. There is no reliable procedure or guidelines that can guarantee the successful implementation of SMS in all industries- the existing literatures can't adequately support the organizations in this direction. The present analysis is therefore aimed towards a systematic analysis and meaningful insights to the managers willing to select best manufacturing practices and to implement sustainable practices in their manufacturing set-up. An attempt was made to pinpoint significant barriers as well as critical success factors towards the implementation of SMS. The study will endeavor to strengthen the existing literatures on sustainable practices. Academicians and future researchers can carry out further research by reviewing the current research. To conclude with, industries must assume accountability, follow ethical norms, standardized work practices, comply with guidelines set by regulatory authorities and all such practices that can help them to promote sustainable practices in their manufacturing systems.

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APPENDIX- I

QUESTIONNAIRE

YMCA UNIVERSITY OF SCIENCE AND TECHNOLOGY
FARIDABAD (HARYANA)- 121006

Research Supervisors:

(i) Prof. Tilak Raj, YMCA University of Science and Technology, Faridabad, Haryana- 121006

(ii) Prof. B. B. Arora, Delhi Technological University, Rohini, Delhi.

Subject: A research project on various issues towards the adoption and implementation of Sustainable manufacturing systems

Dear Sir / Madam,

In view of global competitions and challenges across manufacturing sectors, adoption of new and latest technologies and eco-friendly practices are highly solicited. Sustainable manufacturing practices can provide opportunities towards producing customized products, financial growth, environment-friendly products and practices, societal growth and the like.

As part of PhD research on 'Analysis of energy efficient sustainable manufacturing systems', a survey of Indian industries has been taken up on various issues towards the adoption of sustainable manufacturing system. To make it possible, the industry and academia are requested to share their views through this questionnaire. Your valuable feedback in this regard will be highly appreciated. It is requested to kindly spare your valuable time in filling the enclosed questionnaire as observed in your organization. The purpose of the survey is purely academic and all responses will be kept strictly confidential.

It will be highly appreciated if you can send the filled-in questionnaire within 15 days.

With warm regards,

Yours' Sincerely,

(Subrata Kumar Patra)

Research Scholar

Encl: 1. Questionnaire

2. Self-addressed envelope

SURVEY QUESTIONNAIRE

SECTION 1: ORGANIZATION PROFILE

(a) Name of the organization…………………………………………………

(b) Plant location and address ………………………………........................

……………………………………………………………………..………

(c) Nature of operation like manufacturing/ service/ maintenance etc. (Please specify)

....

(d) Name the products manufactured in your organization:

………………………………………………………………………………….

(e) Does your company have ISO 9000 certification? Yes / No ………….

(f) Does your company have ISO 14000 certification? Yes / No ……….....

(g) Does your company have clearly defined Company Policy? Yes / No ……….....

If answer to question (g) is Yes please mention the Company Policy (If you please)

……………………………………………………………………………………

Please proceed to answer the followings if you are associated with a Manufacturing organization.

Please put tick [✓] or type [T] in the appropriate box.

1. Total employees in your organization:
   (A) Less than 100 [ ] (B) 101 to 500 [ ] (C) 501 to 1000 [ ]
   (D) More than 1000 [ ]
2. Annual turnover of the organization (Rs. in Crore)……………………
   (A) Less than 10 [ ] (B) 10 to 50 [ ] (C) 50 to 100 [ ]
   (D) 100 to 500 [ ] (E) More than 500 [ ]
3. Number of different Production shops in your organization
   (A) Single [ ] (B) 2- 4 [ ] (C) 5-8 [ ] (D) More than 8 [ ]
4. Varieties of components manufactured in your organization
   (A) 1-5 [ ] (B) 6- 10 [ ] (C) 11- 20 [ ]
   (D) More than 20 [ ]
5. Percentage of components being manufactured inside your organization
   (A) Less than 25% [ ] (B) 25-50% [ ] (C) 50-75% [ ] (D) 75-100% [ ]

SECTION 2: RESPONSE RELATED TO MANUFACTURING

1. Please rate the following critical success factors towards the adoption of SMS in your organization:

Sl. No.	Critical success factors for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
1	Availability of Capital and organizational resources					
2	Business ethics/ Company policy					
3	Commercial advantages					
4	Corporate Social Responsibility					
5	Cost control					
6	Ease of soft loans and credit facilities by financial institutions					
7	Eco-innovation-oriented research					
8	Emission control					
9	Employee health, safety and welfare					
10	Energy efficiency					
11	Environment management systems					
12	Focus on 3 R’s Principles					
13	Government support and environmental legislation					
14	Implementation and operational issues					
15	Incentives and subsidies funded by government to promote sustainable technologies					
16	Investment towards technology and innovation					
17	Market demand for Green products					
18	Motivation and teamwork of the employees					
19	Population explosion					
20	Process control					
21	Public awareness on environmental issues					
22	Pursuit towards clean and renewable energy					
23	Quality control					
24	Resource conservation					

Sl. No.	Critical success factors for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
25	ROR (Rate of return) on investment towards sustainable technologies					
26	Standardized metrics or performance benchmarks					
27	Support for developing new Technologies (Research and development)					
28	Top Management support and commitment					
29	Vision for long term sustainable development					
30	Waste management					
31	Workers' training and education on sustainable technologies and practices					

2. Please rank the impact of following barriers towards the adoption of SMS in your organization

Sl. No.	Barriers for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
1	Improper business ethics/ Company policy					
2	Improper Pollution and waste management practices					
3	Inadequate focus on 4 R's Principles					
4	Inappropriate Environment management systems					
5	Lack of appropriate Technologies					
6	Lack of capital to set up green Projects					
7	Lack of eco- innovation-oriented research					
8	Lack of Government support towards developing new Technologies					
9	Lack of standardized metrics or performance benchmarks					
10	Lack of Top Management support					
11	Lack of vision for long term sustainable development					

12	Poor compliance to environmental legislations					
13	Poor education and environmental awareness of workmen					
14	Poor focus on conservation of Natural resources					
15	Poor focus on energy efficiency and energy efficient process					
16	Poor Monitoring and Control					
17	Poor motivation and teamwork of the employees					

3. **Please rate the impact of following barriers in various category towards the adoption of SMS in your organization:**

(a) Environmental barriers towards the adoption of SMS

Sl. No.	Environmental barriers related to SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
1	Lack of societies consciousness on environmental issues and sustainable development					
2	Lack of initiatives towards resource conservation by stakeholders					
3	Lack of sensitivity of policy designers towards eco-friendly products and practices					
4	Poor monitoring and control of EMS (Environment management system) by the concerned regulatory agencies					
5	Inefficient pollution control systems and waste management practices					

(b) Social and Behavioral barriers towards the adoption of SMS

Sl. No.	Social and Behavioral barriers for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
1	Employee resistance to organizational change					

Sl. No.	Social and Behavioral barriers for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
2	Lack of public awareness and societal pressure on sustainability related issues					
3	Lack of Internal Motivation influenced by values, attitude and emotions					
4	Demographic barriers including income, education level, culture, location of home					
5	Poor Corporate social responsibility culture					

(c) Financial barriers towards the adoption of SMS

Sl. No.	Financial barriers for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
1	Lack of Financial resources					
2	Deficit towards high investment cost towards implementing SMS					
3	Inadequate government support in the form of incentives and subsidies towards promoting sustainable manufacturing practices					
4	Hurdles for releasing soft loans and credit facilities by financial institutions					
5	Protection and safeguarding manufacturers or service providers against possible financial losses					

(d) Technological barriers towards the adoption of SMS

Sl. No.	Technological barriers for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
1	Lack of standardized metrics or performance benchmarks					

Sl. No.	Technological barriers for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
2	Poor focus on energy efficiency and energy efficient process					
3	Poor focus on employees' training on sustainable technologies and practices					
4	Lack of support towards eco- innovation-oriented research					
5	Lack of research and development initiatives					

(e) Implementation and Operational barriers towards the adoption of SMS

Sl. No.	Implementation and Operational barriers for SMS	Very Low	Low	Moderate	High	Very High
		1	2	3	4	5
1	Lack of Top Management support and commitment					
2	Ignorance towards sustainability concepts					
3	Absence of appropriate Skills and relevant competencies					
4	Logistical Barriers					
5	Lack of clear vision regarding ROI and Payback					

4. RESPONDENT PROFILE

1. Name of respondent (If you please) ……………………………………………………….

2. Designation……………………………………………………………………………

3. Your association (in years) with this current organization:
(a) Less than 5 [ ] (b) 5-10 [ ] (c) 10-15 [ ] (d) More than 20 [ ]

4. Your functional area: (a) Production [ ] (b) Maintenance [ ] (c) Design [ ]
(d) Quality [ ] (e) Any other (please specify) …………………

5. Would you like to share the findings of the survey? (a) Yes [ ] (b) No [ ]

Please mention steps (If you please) that you think may lead to an energy efficient sustainable manufacturing in your organization:

Thank you very much for your valuable feedback. Kindly send it back to following address:

Subrata Kumar Patra (Research Scholar)
Department of Production Engineering
G.B. Pant Institute of Technology
Okhla, New Delhi- 110020
Mob. No. 9654354394
E-mail: patrask2005@yahoo.co.in

APPENDIX- II

BRIEF PROFILE OF THE RESEARCH SCHOLAR

Mr. Subrata Kumar Patra is presently working as Senior Lecturer in the Department of Production Engineering, G. B. Pant Institute of Technology, Okhla, New Delhi, India. He had completed B.E. in Production Engineering and Management from Regional institute of Technology, Jamshedpur in 1994. He had worked with Usha Alloys and Steel Division, Jamshedpur and thereafter with Hindalco Aluminum division, Renukoot, UP in various capacities. He did his Masters' degree from Panjab University in 2011 and presently pursuing PhD from J. C. Bose University of Science and Technology, YMCA, Faridabad. He has more than 19 years of teaching and 06 years of Industrial experience in the field of Manufacturing, Sustainable manufacturing, Industrial Engineering, Mechanical maintenance etc.

He has published over 10 research papers in various national and international journals of repute and conferences. Some of these journals are: International Journal of Operational Research, Industrial Engineering Journal, International Journal of Engineering and Manufacturing Science, International Journal of Advanced Production and Industrial Engineering, Trends and Advances in Mechanical Engineering, International Conference on Advanced Production and Industrial Engineering, International Journal of Engineering Sciences Paradigms and Researches etc.

APPENDIX- III

LIST OF PUBLICATIONS OUT OF THESIS

LIST OF PUBLISHED PAPERS

Sl. No.	Title of Paper	Name of Journal where published	No.	Volume and Issue	Year	Page
1	Development – constructive or destructive	International Journal of Engineering Sciences (IJMRS)		ISSN (Online): 2277-9698	2012	165-169
2	Consumption and Manufacturing for the future challenges – the Sustainable way	Proceedings of the National Conference on Trends and Advances in Mechanical Engineering, YMCA, Faridabad, Haryana	ISBN 978-93-5087-574-2	---	2012	627-632
3	Sustainability Issues in Energy Efficient Manufacturing Systems- A Review	International Journal of Engineering and Manufacturing Science	ISSN: 2249-3115	Vol. 5, Number 1	2015	1-8
4	Enhancement in Sustainability in a Manufacturing System	International Journal of Advanced Production and Industrial Engineering, IJAPIE-2016-01-104	ISSN: 2455-8419	Vol. 1(1)	2016	14-16
5	Sustainable Industrial Manufacturing	Proceedings of National Conference - Trends and Advances in Mechanical Engineering	ISBN: 978-93-5268-269-0		2017	339-343
6	Issues in Sustainable manufacturing and	International Conference on	ISBN		2016	

Sl. No.	Title of Paper	Name of Journal where published	No.	Volume and Issue	Year	Page
	analysis of selected barriers using AHP	Advanced Production and Industrial Engineering; I.K. International publishing House Pvt. Ltd.	978938-5909511			
7	An analysis of selected parameters in an energy efficient Sustainable manufacturing system using AHP	International Journal of Advanced Production and Industrial Engineering, IJAPIE-2017-02-211	ISSN: 2455-8419	Vol. 2(2)	2017	01-04
8	Identification of Elements towards establishing Sustainable manufacturing system: an analysis using AHP and R3I combined methodology	Industrial Engineering Journal	ISSN: 2581-4915	Vol. 12, Issue 5	2019	1-17
9	Modeling towards the augmentation of manufacturing efficiency – an ISM Approach	International Journal of Engineering Sciences Paradigms and Researches	ISSN (Online): 2319-6564	Vol. 48, Special Issue	2019	334-341

LIST OF ACCEPTED PAPERS

Sl. No.	Title of Paper	Name of Journal where published	No.	Volume and Issue	Year	Page
1	An analysis and Modeling of selected barriers in Sustainable	International Journal of Operational Research	DOI: 10.1504/ IJOR.2021. 10019638	Under Publication schedule	---	1-26

Sl. No.	Title of Paper	Name of Journal where published	No.	Volume and Issue	Year	Page
	manufacturing system using ISM technique	(IJOR), Inderscience				
2	An analysis of selected barriers towards the implementation of an energy efficient sustainable manufacturing system: A Graph Theoretic approach	International Journal of Operational Research (IJOR), Article ID: IJOR 19742	Proof approved; under Publication	Under Publication	---	1-22