Development of a Sustainability Assessment Framework for Manufacturing Industry

THESIS

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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Under the Supervision of

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2018

......dedicated
to
my family......

Birla Institute of Technology & Science, Pilani
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CERTIFICATE

This is to certify that the thesis entitled **"Development of a Sustainability Assessment Framework for Manufacturing Industry"** submitted by **Vikrant Bhakar,** ID. No. **2011PHXF0009P** for award of Ph.D. degree of the Institute embodies original work done by him under my supervision.

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ACKNOWLEDGMENT

First and foremost, I praise God, the Almighty for providing me this opportunity and granting me the capability to proceed successfully, and with his blessings, only I am able to accomplish this huge task.

I pay obeisance unto the lotus feet of **Professor Kuldip Singh Sangwan** and **Professor Abhijeet K. Digalwar** for their valuable guidance, excellent direction, everlasting encouragement and inspiration given to me without which the present work would not have been possible. It was indeed my privilege to work under the supervision of both of them. I feel indebted to them for not only teaching me each and every aspect of the art of doing research but also other important aspects of life.

I am grateful to **Prof. Souvik Bhattacharyya,** Vice-Chancellor, BITS Pilani, and **Prof. A. K. Sarkar,** Director, BITS Pilani, Pilani Campus for permitting me to pursue my research work in the field of my interest. I also express my sincere thanks to **Prof. S. K. Verma**, Dean, Academic Research Division (ARD) and **Dr. Hemant R. Jadhav**, Associate Dean, ARD for their motivation, constant support and encouragement.

I thank **Prof. P. Srinivasan**, Head of Mechanical Engineering Department for his moral support and kind assistance.

I am highly indebted to **Professor Srikanta Routroy** (Associate Dean Instruction division and DRC convener Department of Mechanical Engineering) and **Professor Rajesh Prasad Mishra** (Associate Professor, Department of Mechanical Engineering, Pilani Campus), my doctoral advisory committee (DAC) members for their valuable and fruitful discussions and suggestions, and sparing their valuable time for the evaluation of this thesis. I would also like to acknowledge whole hearted support of the faculty members of Department of Mechanical Engineering during my research work. I am in debt of Departmental Research Committee members who has provided critical insights during the departmental seminars.

I would also like to express my gratitude and thanks to **Dr. Manoj S. Soni, Dr. Girish Kant, Dr. Jitendra Rathore,** and **Dr. Sharad Shrivastava,** Department of Mechanical Engineering, for their tremendous support to carry out my research work in Indian industries.

I am also thankful to **Prof. (Dr.) Christoph Hermann,** Head of the Institute, Chair of Sustainable Manufacturing & Life Cycle Engineering, Dean of the Faculty of Mechanical Engineering, and **Dr. Gerrit Posselt**, Group Leader Die Lernfabrik, **Dr. Stefan Böhme**, Group Leader Life cycle Engineering, **Mr. Lennart Buth,** and **Mr. Alexander Leiden,** from the Institute for Machine Tool and Production Technology, Technische Universitat Bruanschweig, Germany.

I acknowledge my gratitude for **Mr. Narpat Ram Sangwa, Mr. Kailash Choudhary,** and **Ms. Nitesh Sihag** for their unstinting guidance, many valuable suggestions and kind help at various stages of the work. I cherish all the moments spent with my friends and highly talented fellow researchers, **Dr. Yogesh K Bhateshvar, Dr. V Balaji, Dr. Jitendra Kumar Gupta, Mr. Sanjeev Jakhar, Mr. Nilesh Purohit, Mr. Kapil Choudhary, Mr. Tridev Mishra, Dr. Patricia Egede, Dr. Tina Dettmer, Mr. Stefan Andrew and Mr. Pankaj Munjal.** I thank them for being there for me and making my time at BITS Pilani memorable and during my visits to Germany. I wish them a very bright future.

I would like to thank my family; my parents, **Mr. Jwala Singh Bhakar** and **Mrs. Sarawati Bhakar,** my brother, **Mr. Prashant Bhakar**, my sister in law, **Ms. Uma Sihag**, and My wife **Ms. Nitesh Sihag**. My sincere thanks to two small and loving kids of our family, **Miss Himakshi Bhakar** and **Master Parth Bhakar.** Their constant love and affection empowered me to accomplish my work. I would like to thank my parents-in-law, **Mr. Madan Lal Sihag** and **Mrs. Santosh Sihag**; brother in law **Mr. Deepender Sihag**, and sister in law **Dr. Swati Sihag**.

I also thank the non-teaching staff **Mr. Rajkumar Budania, Mr. Mailal, Mr. Dhanna Ram, Mr. K. C. Verma,** and especially **Mr. Mahender Kumar Saini** for their valuable help. My sincere thanks to all those who have directly or indirectly helped me to accomplish this task.

Vikrant Bhakar
April 2018

ABSTRACT

The growth of manufacturing is inevitable for improving the living standards of the society particularly in emerging, developing and underdeveloped countries. The industry needs to focus on making manufacturing more efficient and less polluting through lesser resources consumption and reduced emissions so that the development is viable, equitable and acceptable. In other words, manufacturing needs to be sustainable. And to make manufacturing sustainable or to improve sustainability of manufacturing, sustainability assessment is required. To improve manufacturing sustainability, it should be assessed from social, economic, and environmental perspectives in terms of resource consumption and emissions. The assessment should have appropriate indicators and appropriate reporting format so that decision makers can take the informed decisions.

The study aims at developing a manufacturing sustainability assessment framework and its elements. The objectives of the study are to develop appropriate models for the easy, effective and integrated assessment of a manufacturing organization's preparedness to adopt sustainability improvement initiatives for sustainability improvement. The study also aims at identifying appropriate indicators for assessing product sustainability, process sustainability, and sustainability policies across all resources throughout pre-manufacturing, manufacturing and post-manufacturing activities in terms of environmental, economic and social indicators. The appropriate indicators are identified from literature and tested for an Indian cement industry using an empirical study. 229 questions are identified to assess organizational preparedness for sustainability assessment and improvement.

The study contributes to the existent body of knowledge in the field of manufacturing sustainability, which is still in the nascent state of research, practice and teaching. The

proposed readiness self-assessment model is first such model for assessing preparedness of an organization. The managers can use this model with minimal efforts and without complex data acquisition to quickly find the weak areas for sustainability improvement. The developed model for sustainability assessment is expected to help practitioners in developing their organizations in a sustainable manner. It will help the top management of the manufacturing organizations in prioritizing and developing sustainable strategies for long term goals. The proposed composite sustainability assessment index can be used by the various decision makers such as government agencies, industry bodies, NGOs, banks, etc. to assess the sustainability on a dimensionless scale considering the interdependencies of various indicators. The life cycle assessment model proposed for the cement manufacturing process can be used by the various decision makers to find weak/hot spots for sustainability improvement or technology/innovation funding. The life cycle assessment results can be used to illustrate the effects of pre-manufacturing activities of a manufacturing process. The results of the case studies or empirical research in the thesis can be used to increase the awareness of sustainability and sustainable development among industry managers, government officials, NGOs, and general public to influence the public opinion and attitude toward sustainability. Most of the case studies or empirical data is taken from Indian cement industry. The developed framework can be easily extended to other industries and countries. It will be interesting to assess and compare the results by using the proposed framework in other industries and countries.

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LIST OF ABBREVIATIONS AND SYMBOLS

Symbol/Abbreviation	Description
BTU	British thermal unit
KPIs	Key performance indicators
CSFs	Critical Success Factors
HDPE	High density polyethylene
SM	Sustainable Manufacturing
SLR	Systematic literature review
MCDM	Multi criteria decision making
TQM	Total quality management
TPM	Total productive maintenance
JIT	Just-In-Time
QFD	Quality function deployment
UNCSD	United Nations Commission on Sustainable Development
IUCN	International Union for Conservation of Nature
UNDP	United Nations Development Programme
DDM	Direct digital manufacturing
DEA	Data Envelopment Analysis
AM	Additive manufacturing
AHP	Analytic hierarchy process
ANP	Analytic network process
DEMATEL	Decision Making Trial and Evaluation Laboratory
DANP	DEMATEL based on ANP
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
MCDM	Multi criteria decision making
OECD	Organization for Economic Co-operation and Development
ECM	Environmentally conscious manufacturing
ERM	Environmentally responsible manufacturing
EBM	Environmentally benign manufacturing
TPB	Theory of planned behavior
CM	Clean manufacturing
TBL	Triple bottom line
TBS	Technical building services
NGO	Non-Government Organizations

Symbol/Abbreviation	**Description**
EU	European union
P	People
Mo	Money
M	Material
E	Energy
I	Infrastructure
W	Water
A	Air
P1	Policy
P2	Product
P3	Process
SD	Sustainable Development
TPO	Total Point Obtained
Qs	Qualifying score
GQs	Gross qualifying score
Ob	Points obtained
MAXP	Maximum points
CSR	Corporate social responsibility
EFA	Exploratory factor analysis
ITC	Item-total correlation
CITC	Corrected item-to-total correlation
KMO	Kaiser-Meyer-Oklin
PCA	Principal component analysis
NO_x	Nitrous oxides
CO_2	Carbon dioxide
PVC	Polyvinyl chloride
LCE	Life cycle Engineering
LCM	Life cycle management
LCC	Life cycle costing
LCA	Life cycle analysis/assessment
EOL	End-of-life
NPD	New product development
NDM	Near dry machining
VSM	Value stream mapping
DSS	Decision support system

Symbol/Abbreviation	**Description**
DES	Discrete event simulation
PV	Photovoltaic
GWP	Global warming potential
SCM	Supply chain management
GCSM	Green supply chain management
SSCM	Sustainable supply chain management
SMM	Sustainable manufacturing mapping methodology
SMEs	Small and medium enterprises
SEM	Structural equation modeling
ISM	Interpretive structural modeling
TQM	Total quality management
R&D	Research and Development
WCSM	World-class sustainable manufacturing
UK	United Kingdom
USA	United States of America

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Manufacturing caters to not only the primary demands of society to improve living standards by providing goods but also emits a huge amount of harmful emissions. In addition, it also consumes resources like material, energy, and water. The average global consumption is expected to increase as the living standards in emerging, developing, and underdeveloped economies are expected to grow. It makes the growth of manufacturing inevitable. The industry needs to focus on making manufacturing more efficient and less polluting through lesser resources consumption and reduced emissions. There is a dire need, particularly in emerging and developing countries, to improve manufacturing performance, resulting in less pollution, less wastage, and less material and energy consumption (Sangwan and Mittal 2015). This will lead not only to environmental and social benefits but also economic benefits. This new paradigm in manufacturing, where environmental, social and economic sustainability is necessity, is known as sustainable manufacturing. The Organization for Economic Co-operation and Development (OECD) in 2011 report entitled "sustainable manufacturing initiatives" has provided the scope of sustainable manufacturing, which encompasses the evaluation of sustainable manufacturing concepts and practices, pollution control, cleaner products, and production methods, eco-efficiency, life cycle thinking, closed-loop production, and industrial ecology. Increasing cost of material and energy has helped in changing the industry perception of sustainability as a competitive tool rather than a social obligation.

Sustainability in manufacturing is mainly for the resources conservation (Tsiliyannis, 2015), eco-efficiency (Parthasarathy *et al.*, 2005), product sustainability (Mani *et al.*, 2013; Rodrigues *et al.*, 2016), process sustainability (Shin *et al.*, 2015). However, to improve sustainability of manufacturing or to make manufacturing sustainable, sustainability assessment is required. Peter Drucker, the man who invented modern business management, is credited with an important quote in business management: "if you can't measure it, you can't improve it", which is also true for manufacturing sustainability. Therefore, the first step for manufacturing sustainability improvement is its assessment from social, economic, and environmental perspectives in terms of resource consumption and emissions. Nowadays, sustainability assessment, a widely used term, covers a broad range of approaches aiming to operationalize sustainability concepts for decision-making (Dijk *et al.*, 2017). Sustainability assessment should have appropriate indicators to comprehend the sustainability of the adopted business model, to achieve the organizational sustainability objectives, and to implement the corrective measures.

1.2 RESEARCH MOTIVATION

The expected increase in world population in next 50 years and economic growth has raised serious concerns about the capacity of natural ecosystem (Herrmann *et al.*, 2014). The energy requirement by industrial sector accounts for half of the world's total energy demand (Kant and Sangwan, 2014). It is expected that by 2030 the energy requirement will increase by 40% from 175 quadrillion British thermal unit (BTU) in 2006 to 246 quadrillion BTU, out of which 85% is still generated by non-renewable energy sources like coal, petroleum, and natural gas (Fang *et al.*, 2011). The consumption of critical raw materials like steel, aluminum, copper, zinc, nickel, wood, etc. has increased manifold.

Therefore, adoption of sustainable manufacturing is required to make development viable, equitable and acceptable.

Researchers have been working on the various aspects of manufacturing sustainability during last two decades. Some standalone research has been carried out in the area of product sustainability (Brockhaus *et al.*, 2016; Lu *et al.*, 2011; Wali *et al.*, 2012), process sustainability (Wittmayer and Schäpke, 2014; Lu *et al.*, 2011; Shokrian *et al.*, 2015) and organization policies to address the sustainability (McManners, 2016; Shields *et al.*, 2002; Luo *et al.*, 2017). Similarly, standalone research is also available in the areas of people (Daily and Su, 2001; Baskaran *et al.*, 2012; Luo and Bhattacharya, 2006), money (Mittal and Sangwan, 2014; Egilmez *et al.*, 2013; Boons *et al.*, 2013), materials (Lindahl *et al.*, 2014; Meyer *et al.*, 2007; Joshi *et al.*, 2006; Dassisti *et al.*, 2012), energy (Pressley *et al.*, 2014; Hesselbach *et al.*, 2008; Li and Lin, 2016), infrastructure (Castellini *et al.*, 2012; Labuschagne *et al.*, 2005; Hesselbach *et al.*, 2008), air (Mani *et al.*, 2014; Yin *et al.*, 2014; Rachuri *et al.*, 2011), and water (Li and Chen, 2014; Ene *et al.*, 2013). Researchers have also focused on economic aspects, environmental aspects but social sustainability aspect is hardly studied (Sutherland *et al.*, 2016).

There is a need to develop integrated assessment models which encompass the product sustainability, process sustainability, sustainability policies across all resources throughout pre-manufacturing, manufacturing and post-manufacturing activities. The manufacturing sustainability should focus on environmental, economic and social aspects of sustainability.

1.3 OBJECTIVES OF THE STUDY

The objectives of the study are:

- Identification of important resources and critical factors in pre-manufacturing, manufacturing and post-manufacturing activities through a systematic literature review.
- Development of a conceptual manufacturing sustainability assessment framework by integrating product sustainability, process sustainability, sustainability policies across all resources throughout pre-manufacturing, manufacturing and post-manufacturing activities.
- Development of a sustainability readiness self-assessment model by integrating product sustainability, process sustainability, sustainability policies across all resources throughout pre-manufacturing, manufacturing and post-manufacturing activities.
- Development of a sustainability assessment model for manufacturing industry by integrating product sustainability, process sustainability, sustainability policies across all resources throughout pre-manufacturing, manufacturing and post-manufacturing activities.
- Identification of appropriate indicators for the assessment of manufacturing sustainability in terms of environmental, economic and social aspects.
- Development of a composite sustainability index for Indian cement industry.
- Assessment of a cement manufacturing process using life cycle approach.

1.4 METHODOLOGY

The following methodology has been used to achieve the objectives of the study:

- A systematic literature review (SLR) on manufacturing sustainability is performed to identify the critical sustainability factors and resources, and also to trace the growth of manufacturing sustainability in terms of the sustainability elements, sustainability levels, research methodologies, and focus areas.

- A multi-level conceptual framework is proposed for manufacturing sustainability assessment after carefully reviewing the existing models for their strengths and weaknesses. Care is taken to leverage the strengths of the existing frameworks and mitigate the weaknesses of the existing frameworks in the proposed model.
- A sustainability readiness self-assessment model is proposed for assessing the organizational preparedness for sustainability assessment and improvement using resource based theory. 229 questions are developed for the readiness self-assessment. The proposed model is tested in two organizations: an automotive manufacturing organization and a cement manufacturing organization.
- A four-level manufacturing sustainability assessment model is developed. The four levels consist of product life cycle, resources, critical factors and sustainability dimensions. The proposed model is tested for Indian cement industry using statistical analysis.
- 121 sustainability indicators have been identified, from literature, to assess the progress of an organization towards sustainability and to measure the sustainability performance of a manufacturing organization from different perspectives: critical factor perspective, resource perspective, sustainability dimension perspective, and life cycle perspective. The indicators are tested and classified for Indian cement industry using exploratory factor analysis.
- A composite sustainability index is proposed to demonstrate the usefulness of the proposed manufacturing sustainability assessment model through a case study of Indian cement industry.
- The application and importance of life cycle analysis is demonstrated through the life cycle analysis of cement manufacturing process.

1.5 SIGNIFICANCE OF THE STUDY

The environment sustainability has caught the attention of researchers, policy makers and common public across the world. The earth summit (1992), Kyoto protocol (1997), Doha talks (2001), Copenhagen deceleration (2009), recent Paris climate agreement, and United Nation's 17 sustainable development goals are few remarkable agreements/agendas which show the urgency and importance of the environmental and social sustainability. High resource consumption and emissions in manufacturing lead to unsustainable development. Any improvement in the manufacturing sustainability will be a significant contribution to the global sustainable development.

The systematic literature review can be used by the researchers as building block to get new research directions. The systematic literature review and all other models developed in the thesis will contribute to the existent body of knowledge which is still in the nascent state of research, practice and teaching. The proposed readiness self-assessment model is first such model for assessing preparedness of an organization. The managers can use this model with minimal efforts, without complex data acquisition, to quickly find the weak areas for sustainability improvement. The proposed manufacturing sustainability assessment model and the identified indicators can be used by the researchers in other fields to test and validate the indicators in different fields. The developed model for sustainability assessment is expected to help practitioners in developing their organizations in a sustainable manner. It will help the top management of the manufacturing organizations in prioritizing and developing sustainable strategies for long term goals. The proposed composite sustainability assessment index can be used by the various decision makers such as government agencies, industry bodies, NGOs, banks, etc. to assess the sustainability on a dimensionless scale considering the interdependencies of various indicators. The decision makers can provide different importance to different indicators or dimensions as per the need of country, region, plant, etc. The life cycle assessment model proposed for the cement manufacturing process can be used by the various decision makers to find weak/hot spots for sustainability improvement or technology/innovation funding. The life cycle assessment results can be used to illustrate the effects of pre-manufacturing activities of a manufacturing process. The results of the case studies or empirical research in the thesis can be used to increase the awareness of sustainability and sustainable development among industry managers, government officials, NGOs, and general public to influence the public opinion and attitude toward sustainability.

1.6 ORGANIZATION OF THE THESIS

Chapter 1 presents the outline of the thesis. Chapter 2 provides a systematic literature review of manufacturing sustainability. Chapter 3 develops a conceptual framework for manufacturing sustainability assessment after critically analyzing the existing frameworks from literature. Chapter 4 presents the proposed sustainability readiness self-assessment model and self-assessment questions. It also includes testing of the readiness self-assessment model using two case studies. Chapter 5 presents the proposed manufacturing sustainability assessment model. This chapter also presents a list of 121 indicators to assess the manufacturing sustainability. The identified indicators are tested using statistical analysis. Chapter 6 presents a composite sustainability index for sustainability assessment of Indian cement industry. Chapter 7 presents the application of life cycle analysis for environmental sustainability of cement manufacturing process in Indian cement industry. Chapter 8 provides the conclusions of the current research work along with limitations and future scope.

CHAPTER 2

MANUFACTURING SUSTAINABILITY: A SYSTEMATIC LITERATURE REVIEW

This chapter provides a systematic literature review on the manufacturing sustainability. The objectives of the chapter are (i) to assess the developments in manufacturing sustainability and (ii) to identify the research gap.

2.1 INTRODUCTION

The era of manufacturing started with craft production, followed by mass production, mass customization, and now direct digital manufacturing. However, besides productivity of the manufacturing processes, the outcomes of the different manufacturing paradigms also affect the society and environment (Chen *et al.*, 2015a). The increasing concern of societal and environmental impacts of manufacturing has raised the sustainability awareness among customers and stakeholders (Sangwan, 2011). This awareness can be imagined by the various policies, practices, research periodicals, standards, sustainability reports, etc. prepared by governments, research community, NGOs (Non-Government Organizations), United Nations, and industries. The industry perception of sustainability has also changed because of the increased prices of resources and energy. The industry now views sustainability as a competitive tool and not a social obligation. This has increased the research activities in this area in the last decade. Sustainability has a broad and diversified meaning. In the broader sense, it is ecological sustainability, in broad sense human sustainability and in narrow sense resource sustainability. It has environmental, political, economic, technological, and social connotations. It is being researched, from an academic perspective, by chemists, geologists, architects, civil engineers, chemical engineers, manufacturing engineers, etc. From an industry perspective, it is being practiced by product developers, process engineers, urban planners, manufacturing managers, government officials, NGOs, etc. The term sustainable manufacturing was coined in 1997 (Sangwan and Mittal, 2015). A comprehensive scope of sustainable manufacturing has been given in the report entitled "Sustainable Manufacturing Initiatives" by Organization for Economic Co-operation and Development (OECD) in 2011 which says the evolution of sustainable manufacturing concepts and practices involves pollution control, cleaner products and production methods, eco-efficiency, life cycle thinking, closed-loop production, and industrial ecology. Sustainability in manufacturing is mainly for the resources conservation (Tsiliyannis, 2015), eco-efficiency (Parthasarathy *et al.*, 2005), product sustainability (Mani *et al.*, 2013; Rodrigues *et al.*, 2016), process sustainability (Shin *et al.*, 2017), etc. Initial sustainable activities in manufacturing attempted to reduce the energy use and material consumption in production processes. Afterward, the aim of sustainability in manufacturing organizations shifted towards product sustainability (Seliger *et al.*, 2008). But, before the design of a product begins, designers should know the goals to be achieved by the product. In other words, the design team should know the organizational policies. The policies assist in the selection of appropriate indicators for the assessment of the performance. The other critical aspect of any manufacturing organization is the process used to produce the product. Therefore, the three critical factors of sustainability are sustainability policies, product sustainability, and process sustainability. Some standalone research is available in the area of product sustainability (Brockhaus *et al.*, 2016; Lu *et al.*, 2011; Wali *et al.*, 2012), process sustainability (Lu *et al.*, 2011; Shokrian *et al.*, 2015; Wittmayer and Schäpke, 2014) and organizational policies (McManners, 2016; Shields *et al.*, 2002) to address the sustainability. Most of the research is focused on the process sustainability and the product life cycle aspects have been overlooked. Manufacturing sustainability should focus on total product life cycle management (Herrmann *et al.*, 2007). Similarly, there is need to broaden the scope of manufacturing sustainability to include the whole supply chain.

This chapter aims at conducting a systematic literature review (SLR) for identifying, collecting, and analyzing the ontology of sustainable manufacturing. The focus of this chapter is limited to the sustainability in a manufacturing organization or manufacturing sustainability. This review traces the changes in manufacturing sustainability focus, type of studies, and research methodologies.

Although, there is no SLR on sustainable manufacturing or manufacturing sustainability but review papers/reports are available on: green manufacturing and similar frameworks (Sangwan and Mittal, 2015), sustainable new product development (Thome *et al.*, 2016), role of lean philosophy on sustainability (Yusup *et al.*, 2015), sustainability issues in facility location (Chen *et al.*, 2014), effect of production scheduling on sustainability (Giret *et al.*, 2015), impact of cleaner production on sustainability (Yusup *et al.*, 2014), sustainable supply chain and innovation (Rajeev *et al.*, 2017; Gao *et al.*, 2017), methodological characteristics of sustainability science (Salas-Zapata *et al.*, 2017), characterization of manufacturing processes on sustainability performance (Mani *et al.*, 2013), review of mathematical problems in sustainable manufacturing (Chan *et al.*, 2017), and review of concept of sustainable manufacturing (Moldavska and Welo, 2017).

This chapter presents a systematic literature review of sustainable manufacturing/manufacturing sustainability. 248 articles from 1998 to 2018 addressing the sustainability in manufacturing organizations are reviewed in this chapter.

2.2 RESEARCH METHODOLOGY FOR SLR

The research methodology used for the SLR is shown in Figure 2.1. A literature search was done using online databases as the use of internet and online databases is an economical and effective way for the literature search. According to Khabsa and Giles (2014), Google scholar has access to approximately 100 million scholarly documents out of 114 million accessible on the web and published in the English language. Google scholar is capable to deliver high-quality search and it has been used as a search engine for retrieving articles for the literature reviews. The two keywords used for the research are: “sustainable manufacturing (SM)” and “manufacturing sustainability” in the title of the articles. The research community has interchangeably used terms clean, green, sustainable, environmentally conscious, etc. for sustainability in manufacturing (Sangwan and Mittal, 2015). Therefore, “green manufacturing (GM)”, “clean manufacturing (CM)”, “environmentally conscious manufacturing (ECM)”, “environmentally benign manufacturing (EBM)”, and “environmentally responsible manufacturing (ERM)” are also added to the search criterion.

The peer-reviewed articles published and available online from January 1998 until February 2018 in Elsevier, Springer, Emerald, Inderscience, and Taylor and Francis databases were collected. The one article in 1997, which used the term sustainable manufacturing for the first time, is a conference article. Further, snowball (forward and backward) approach was applied to include the articles, which were missed in the above search but found to be suitable for the study. Table 2.1 explains the inclusion and exclusion criteria for the review. The literature review has been divided into three phases [phase I (PI) 1998-2004; phase II (PII) 2005-2011; and phase III (PIII) 2012-2018*] to trace the progress of the research along the timeline. This led to a large number of articles and therefore exclusion criteria based on the timeline, keywords, content analysis, etc. were used to narrow down the articles as shown in Table 2.1.

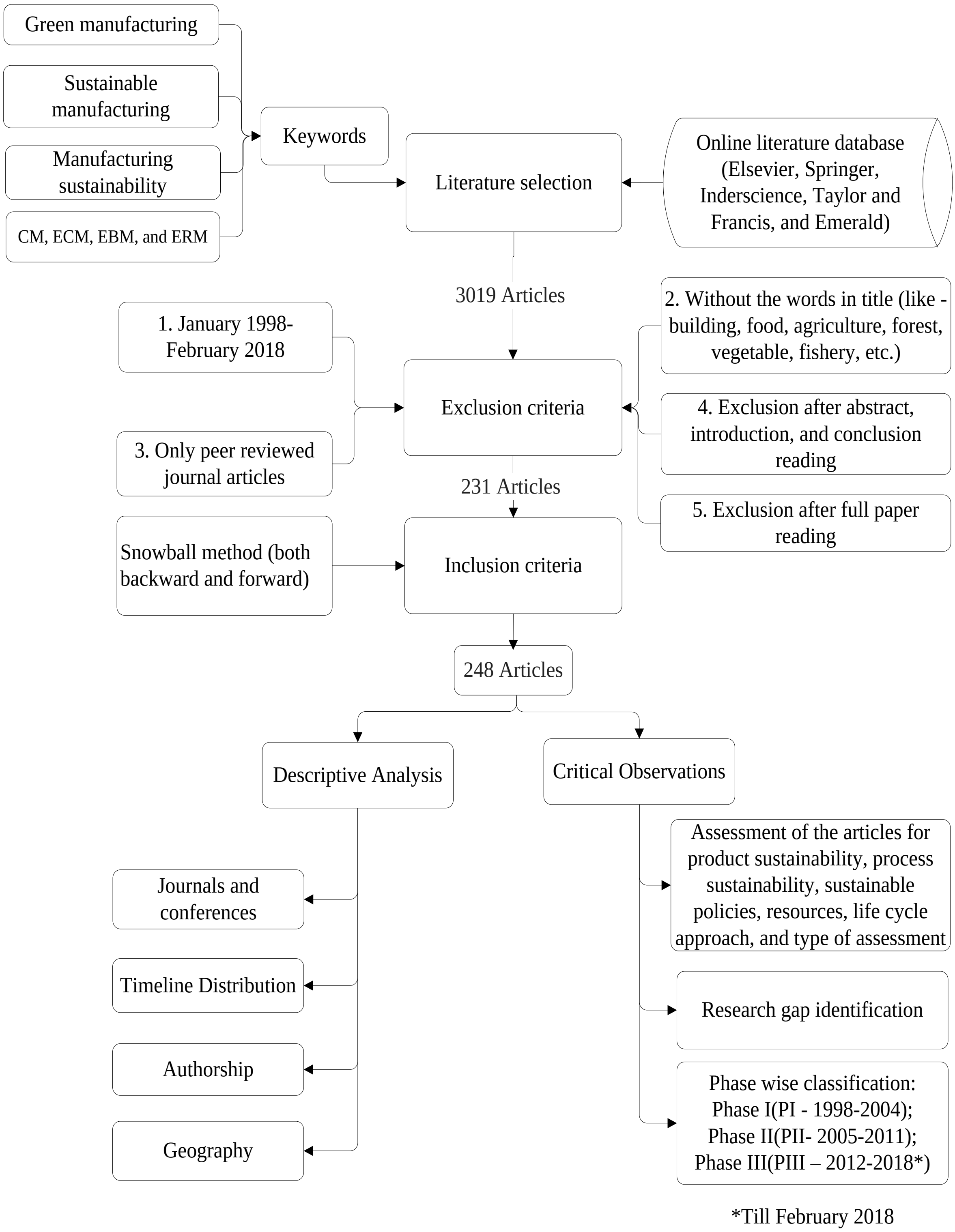


Figure 2.1 Research methodology for systematic literature review

In snowball approach, 17 papers/reports were found suitable and therefore, included for the review. The included 17 articles have high citations in the sustainability research and are from various organizations, conferences, and journals of high international repute. This provided a list of 248 articles for the review and critical observations. These 248 articles were reviewed for the aim of the study; the focus of the study; limitation of the study; consideration of policies, product, process, life cycle, and resources in the study; and level of sustainability assessment as given in Table 2.2. The descriptive analysis of these 248 articles is presented in section 2.6. The next section provides the review of articles in details in the context of their aim, approach, contribution, and limitations.

Table 2.1 Summary of articles for systematic literature review

Keyword in the title of the article → **Exclusion and inclusion criteria ↓**	**Sustainable manufacturing**	**Manufacturing sustainability**	**Green manufacturing**	**ECM, ERM, EBM, and CM**
(i) Articles found during 1998 – 2018*; a) without the words: "-development -six -fat -supply -education -building -food -agriculture -forest -bio -water -rice -heat -crop -urban -vegetable -agricultural -tourism -transport -milk -fishery –mixture" b) Excluding patents and citations	1270	573	985	191
(ii) Articles after exclusion criterion: a) Articles from English Language only b) Accessibility and availability on the web c) The only peer-reviewed articles from Taylor and Francis, Elsevier, Inderscience, Springer, and Emerald	132	96	96	28
(iii) Articles after the second round of exclusion (abstract, introduction, and conclusion reading)	93	88	71	26
(iv) Articles after last exclusion criterion (full paper reading)	76	74	57	24
(v) Articles added by forward and backward snowball approach	**17**			
Total articles for SLR	**248**			

*Till February; ECM – Environmentally conscious manufacturing, ERM – Environmentally responsible manufacturing, EBM – Environmentally benign manufacturing, CM - Clean manufacturing;

The name of the journals with abbreviations from which 248 articles have been taken

Journal of cleaner production – JCP; International Journal of Production Research – IJPR; International Journal of Production Economics – IJPE; Journal of Manufacturing Technology Management – JMTM; Journal of Manufacturing Technology Management – CIRP ANN-MANUF TECHN; International Journal of Sustainable Engineering – IJSE; The International Journal of Advanced Manufacturing Technology – INT J ADV MANUF TECH; Production planning and control – PPC; Journal of Intelligent Manufacturing – J Intell Manuf; Clean Technology Environment Policy – CLEP; International Journal of Precision Engineering and Manufacturing – IJPEM; Computers & Industrial Engineering – CIE; Ecological Indicators – Ecol. Indic.; Journal of Environmental Management – JEM; CIRP Journal of Manufacturing Science and Technology – CIRP-JMST; International Journal of Operations & Production Management – IJOPM; Journal of Manufacturing Systems – JMS; Benchmarking: An International Journal – BIJ; International journal of green economics – Int J GM; International Journal of Sustainable Manufacturing – IJSM; Social Responsibility Journal – SRJ; Industrial Lubrication and Tribology – ILT; Robotics and Computer-Integrated Manufacturing – Robot Comput Integr Manuf; Measuring Business Excellence – MBE; The International Journal of Life Cycle Assessment – IJLCA; Annual Reviews in Control – Annu Rev Control; Applied Ergonomics – Appl Ergon; Chemical Engineering Science – Chem. Eng. Sci.; Cogent Business & Management – Cogent Business & Mgt; Education for Chemical Engineers –Education for Chemical EC; Energy; Environmental Innovation and Societal Transitions – EIST; Ergonomics – Ergono.; Foresight; Global Journal of Flexible Systems Management – GJFSM; International Journal of Agile Systems and Management – IJASM; International Journal of Business Performance Management – IJBPM; International Journal of Environment and Sustainable Development –IJESD; International Journal of Computer Integrated Manufacturing – IJCIM; International Journal of Process Management and Benchmarking – IJPMB; International Journal of Project Management – INT J PROJ MANAGE; International Journal of Strategic Engineering Asset Management – Int J Strat Eng Asset Manag; Journal of Industrial and Production Engineering – JIPE; Kybernetes; Knowledge Management Research & Practice – KMRP; Manufacturing Letters – MFG LET; Production Engineering – PROD Engg; Resources, Conservation and Recycling – RESOUR CONSERV RECY; Sustainable Production and Consumption – SPC; Textiles and Clothing Sustainability – TCS; Applied Energy – AE; Engineering Applications of Artificial Intelligence – EAAI; Environmental Development – ED; European Journal of Innovation Management – EJIM; European Journal of Operational Research – EJOR; Frontiers of Mechanical

Engineering – FME; Industrial Management & Data Systems – IMDS; International Journal of Business and Globalization – IJBG; International Journal of Environment and Waste Management – IJEWM; International Journal of Environmental Technology and Management – IJETM; International Journal of Knowledge-Based Development – IJKBD; International Journal of Manufacturing Technology and Management – IJMTM; International Journal of Process Management and Benchmarking – IJPBM; International Journal of Procurement Management – IJPM; International Journal of Productivity and Quality Management – IJPQM; International Journal of Services and Operations Management – IJSOM; International Journal of Society Systems Science – IJSSS; International Journal of Project Management – Int JPM; International Journal of Strategic Engineering Asset Management – IJSEAM; International Journal of Surface Mining, Reclamation and Environment – Int. J. Surf. Mining, Reclam. Environ; International Journal of Sustainable Development & World Ecology – Int. J. Sustain. Dev. World Ecol.; Journal of Central South University – JCSU; JOM Journal of the Minerals, Metals and Materials Society – JOMMMS; Journal of Modelling in Management – J Mod. Mgt; Journal of Operations Management – J Operation Mgt; Management Decision – MD; Journal of Science and Technology Policy in China – JSTPC; Management of Environmental Quality: An International Journal – MEQJ; Research Policy – RP; The Engineering Economist – TEE; Tsinghua Science and Technology – TST; World Review of Science, Technology and Sust. Development – WRSTSD; World Journal of Science, Technology, and Sustainable Development – WJSTSD; International Journal of Development Issues – IJDI; Journal of environmental economics and policy – JEEP; Journal of High Technology Management Research – JHTMR; Renewable and Sustainable Energy Reviews – RSER; Sustainable Energy Technologies and Assessments – SETS; Technological Forecasting & Social Change – TFSC; International Journal of Management Science and Engineering Management – IJMSEM, Environmental Science and Pollution Research – ESPR; and Self Reports.

2.3 MANUFACTURING SUSTAINABILITY

2.3.1 Product Sustainability

Westkämper (2000) focused to evaluate the role of product life cycle management in the manufacturing sector. The study provides recommendations in terms of the global requirements of manufacturing and discusses the same in the context of IMS (intelligent manufacturing systems) research program of EU. The study limits the discussion to the product life cycle management ignoring the social aspects of sustainability.

Zhu and Deshmukh (2003) analyzed the LCE performance of the design decisions and environmental impact of a product. The study finds that the inclusion of the life cycle engineering in product design can reduce the cost and environmental impacts of the whole life cycle. The authors analyzed the product life cycle and design using Bayesian decision theory.

Labuschagne and Brent (2005) developed a conceptual framework with the triple bottom line including product, project, and asset life cycle. The study assesses the current state of product life cycle management and product life cycle definitions in the real-time projects to propose the conceptual framework for sustainability.

Barreto et al. (2010) investigated the role of product life cycle management in green manufacturing practices. The study favors a close relationship between green manufacturing processes and product life cycle management support to the paradigm of green manufacturing. The study is limited to discussion of factors like recycling, energy consumption, water and air management, green performance, etc. along with regulation and policies.

Lu et al. (2011) presented a framework for the product and process metrics for sustainable manufacturing. The study considers the life cycle engineering approach for the product and process analysis with 6R as a prerequisite. It also defines the different metrics for a product in terms of triple bottom line.

Bilge et al. (2016) presented a manufacturing architecture for sustainable value creation and its application for products, processes, and services. The proposed framework includes four stages: elements of 6R, project management stage, equipment life cycle stage, and product life cycle stage.

Jasinski et al. (2016) presented a framework for the sustainability assessment of automotive manufacturing. The study establishes a new definition of midpoint and endpoint impacts of product life cycle including manufacturing activities for the social and economic dimensions of sustainability.

Veleva and Ellenbecker (2001), developed a framework which provides flexibility to industry to develop their own indicators and also encourages participation of both workers and managers in developing the sustainability indicators. It highlighted six aspects of sustainable production – natural environment, material and energy use, economic performance, workers, social justice and community development, and products.

Azapagic (2004) developed indicators for industrial minerals, metallic, and construction industry. It discusses the stakeholders and issues relevant to the product in different industries for the development of the indicators.

Jovane et al. (2008) presented a reference model for proactive actions to achieve competitive sustainable manufacturing. This model consists of environmental, economic, societal, and technological issues for the product, process, and innovation to improve sustainability.

Ellram et al. (2008) presented an integration of three-dimensional concurrent engineering (3DCE) with new product development (NPD) and environmentally responsible manufacturing (ERM). The 3DCE represents the simultaneous design of the product, process, and supply chain to improve the conventional outcomes of new product development such as time to market, costs, and customer acceptance.

Alblas et al. (2014) explored the sustainability perspective in new product development (NPD) process. In this study the controlling organ is NPD management and the target system is NPD process. The study found that NPD process needs a proactive approach to sustainability instead of a reactive approach.

Product design significantly influences the cost of disassembly; component inspection; and repair, remanufacturing and recycling (Chung and Wee 2008). Chung and Wee (2008) assessed the impact of the green product design, the new technology evolution and remanufacturing on the production inventory policy. An integrated deteriorating inventory model with green-component life cycle value design and remanufacturing. The study using time-weighted inventory approach found that new technological evolution, product take-back ratio, and holding cost are the crucial factors for green supply chain inventory control.

Hong *et al.* (2009) presented a research model defining interrelationship between strategic green orientation, product development, supply chain coordination, and green business performance. The model suggests the relationship of product development practices and supply chain coordination on strategic green orientation. It finds that multiple research methods can provide better insights into the complex dynamics of product life cycle.

Vinodh and Rathod (2010) used Quality Function Deployment (QFD) to integrate environmental elements in the product design. The paper applied quality function deployment for environmental design and product development of rotary switches. Yang *et al.* (2012) developed a strategic model using quality function deployment. The study aims to describe how green manufacturing systems can be improved in the context of product design and also to persuade the consumer about the quality of environment-friendly products.

Garbie (2013) presented a new approach of ‘design for sustainable manufacturing enterprise (DFSME)’. The important factors/aspects considered for analyzing sustainability are international issues; contemporary issues; innovative products; reconfigurable manufacturing system; manufacturing strategies; business model; flexible organizational management; and performance measurements.

Giovannini *et al.* (2012) developed a software-based solution for sustainability in manufacturing. The study considers a knowledge base system for resources, products, and processes to address the objective. It also checks the interelationship among product parts, resources, manufacturing process.

Tsai *et al.* (2013) proposed a model to address the profitability analysis of product mix based on ABC (activity-based costing) and TOC (theory of constraints). The paper proposes a mixed-integer programming model for analysing of profitability of a product mix.

Garetti and Taisch (2012) provided a vision towards sustainability in the manufacturing sector. It says sustainable manufacturing, products and services; energy-efficiencient manufacturing; key technologies; standards; and education are the key areas for future manufacturing research. Business models and processes, product life cycle management, resource, energy management, and enabling technologies for sustainable manufacturing, products and services; energy efficient manufacturing; and key technologies are elaborated.

Lee *et al.* (2012) developed a framework for simulation-based energy sustainability analysis. The framework has four levels: the first defines the product manufacturing system, second defines the simulation model with all the necessary elements, the third is about simulation engine, and the last is for sustainability calculation on the basis of sustainability simulation. The developed framework is more focused on the product life impacts on the environment and represents a weak sustainability.

Short *et al.* (2012) estimated the status of eco-sustainable product design or design for sustainability in UK and Sweden. The study mainly focuses to address the issue of product design and sustainability. However, sustainability is not completely addressed in the defined method and the study does not address any dimension of sustainability.

Liu and Huang (2013) developed a methodology using interval parameter programming (IPP) for biodiesel manufacturing sustainability assessment. The study gives a new idea of the optimized route for product distribution problem and reducing transportation effects.

Nagalingam *et al.* (2013) discussed the performance measures for product recovery in environmental and economic context. The study utilizes literature and mathematical modeling to assess the economic and environmental benefits of product returns and recovery. The paper mainly focuses on 3R approaches.

Rashid *et al.* (2013) found that the products designed for open loop product system are unable to cope up with the dynamics of uncertainties inherently present in the closed loop systems result in lower quality and lesser demand.

Moreira *et al.* (2015) proposed an integrative framework for product design for green aircraft completion industry. Various product design approaches and eco-design methods for the development of ecological textiles for aircraft completion industry are studied and a new textile product is developed. The study is limited to the aircraft completion (textile) industry (product development).

Garbie (2014) focused on micro-level sustainability with an aim to address sustainability in manufacturing enterprises. The three pillars of sustainability are modeled, estimated and incorporated into a general sustainable develoment index. The sustainability is represented through performance metrics, indicators, and pillars.

Eastwood and Haapala (2015) developed a sustainability assessment methodology to understand the various economic, environmental, and social impacts of a product. It is also observed that this methodology supports sustainability oriented design process for a product.

Ilgin *et al.* (2015) presented a literature review on multi-criteria decision models in environmentally conscious manufacturing and product recovery. It is found that most commonly used environmental criteria for environmentally conscious manufacturing and product recovery are – green product design, reduction of material and energy use, use of environmentally better technology, emissions control, green purchasing, green packaging, etc. The study is limited to the review of multi-criteria decision models for environmentally conscious manufacturing and product recovery.

Hallstedt *et al.* (2015) developed a new method named sustainability assessment and value evaluation (SAVE) for an aerospace organization to assess and evaluate the sustainability of product design and manufacturing. The SAVE method allows the sustainability assessment in a structured way and it introduces the sustainability in the early product design phase.

Khan and Islam (2015) focused on the sustainability of material and product in the apparel manufacturing sector. The scope covers the general textile products and material.

Tsiliyannis (2015) focused on the possibilities of sustainability improvement of manufacturing firms through resource preservation via cyclic manufacturing. The author examined the key indicators to assess resource preservation such as recycling and reuse rate, the average life of a product, number of reuse cycles, etc.

Orji and Wei (2016) developed a methodology for cost calculation in industrial dynamics. It is observed that the total life-cycle cost of a product in case of green manufacturing will be lower than conventional manufacturing.

Ford and Despeisse (2016) investigated the pros and cons of additive manufacturing (AM) and its impact on the sustainability of manufacturing industries. The study reports that advanced manufacturing process is facilitating sustainability in four categories: material input processing; redesigning the product and process; product customization; and cyclic manufacturing. Important advantages and challenges of AM related to sustainability are also discussed.

Govindan *et al.* (2016b) studied the importance of product recovery process for a manufacturing firm to achieve economic, environmental and social sustainability. A generic mathematical model is proposed to assess the improvement in manufacturing sustainability due to product recovery, for a closed loop supply chain network consisting a hybrid manufacturing unit, product warehouse, distribution and collection centers, and a hybrid product recovery facility.

Peruzzini and Pellicciari (2017) presented a research focused on human factors in manufacturing. The study incorporates user experiences from old and new designs, in a case study. The study proposes an analytical approach to support sustainable manufacturing by analyzing the user experience of manufacturing and assembly processes starting from the early design stages. The proposed approach is used to redesign a machine to improve its economic, environmental and human-related impacts.

Hong *et al.* (2012) addressed the issue of benchmarking sustainability practices for a business organization. The study incorporates four elements for defining the benchmarking process: strategic drivers (responsive product strategy), internal response practices, external network configurations, and sustainability outcomes.

Abdul-Rashid *et al.* (2017) presented an empirical research for assessing the role of sustainable manufacturing practices in Malaysian companies. The main sustainable manufacturing practices considered in the study are: sustainable product design and development, sustainable manufacturing process, sustainable supply chain management, and sustainable end-of-life management.

Holmström *et al.* (2018) proposed a new design theory for the introduction of direct digital manufacturing (DDM) into manufacturing firms for improving sustainability capabilities. The study evaluates the current practices of prototyping, tooling, on-demand part manufacturing, and customized parts manufacturing; and future practices of DDM based incremental product improvement and dynamic supply chain reconfiguration to improve products and processes.

Mani *et al.* (2018) presented the supply chain social practices used by the Portuguese firms to deal with the issue of social sustainability. The identified supply chain social sustainability practices are: child and forced labour, diversity, discrimination, health and safety, unethical practices, philanthropy, labor practices, human rights, wages, education, sustainable sourcing, local sourcing, product responsibility, employee welfare, employment creation, poverty alleviation, local economic development, and stakeholders engagement.

2.3.2 Process Sustainability

IChemE (2002), Institution of Chemical Engineers, suggested a framework for the measurement of sustainability in the process industry. This framework provides measurable indicators to enable the organizations to assess and set targets for sustainability improvement.

Labuschagne and Brent (2005) developed a framework for product life cycle sustainability assessment and its interaction with manufacturing processes in the process industry.

Fei *et al.* (2005) assessed a machining system in terms of minimization of resource consumption, minimization of environmental discharge, and synthesized minimization of both. The effect of green manufacturing practices such as the optimizing system for raw material cutting, the matching system for energy saving in machining, the design of highly efficient dry hobbing machine tools, the decision making support system in machining processes, etc. are studied.

Parthasarathy *et al.* (2005) assessed the eco-efficiency in manufacturing processes in chemical industry by using quantitative analysis of energy and raw material consumption. This study focuses on environmental sustainability. The focus on economic and social aspects is low.

Marksberry (2007) analyzed the manufacturing process of dry machining, near dry machining (NDM), and micro flood (MF) technology; and observed that the tool life varies with metalworking fluids (MWFs) and flow rate. It is also observed that micro flood (MF) technology performs better than other two machining processes. Marksberry and Jawahir (2008) developed a prediction model to estimate the tool wear and tool-life performance of the NDM process. It is found that tool-wear improves four times in NDM as compared to dry machining process.

Seliger *et al.* (2008) identified approaches for sustainable manufacturing and their applications to improve processes. The study gives an overview of existing approaches and tools for adopting sustainable manufacturing.

Hicks and Matthews (2010) focused on the topic of manufacturing system improvement, especially process sustainability. The study discusses process improvement, maintenance, quality, tool design and changeover, equipment redesign, modification and changeover, product modification, new product introduction, and other manufacturing philosophies for the improvement of manufacturing systems.

Genaidy *et al.* (2010) discussed the effect of worker expertise on the sustainability of manufacturing processes. The study uses a working compatibility methodology to assess the perspective of workers (both qualified and expert) on the quality of employee-work environment interfaces in a small manufacturing enterprise.

Jayal *et al.* (2010) addressed sustainability in the manufacturing industry, including supply chain and product life cycle. The study provides a model, metrics, and optimization techniques at the product, process, and system levels. The main focus of the model is a manufacturing process. It provides product evaluation during life cycle phases for dry, near dry, and cryogenic machining.

Paju *et al.* (2010) developed sustainable manufacturing mapping methodology (SMM) to illustrate the application of VSM (value stream mapping). The proposed method uses the principles from the existing methods of VSM, DES, and LCA. SMM can use publicly available life cycle impact data as input. It measures the process variability and interdependencies. Faulkner and Badurdeen (2014) addressed the issue of sustainability using sustainable value stream map (Sus-VSM). The study found that Sus-VSM can be used for identifying the different wastes generated in a manufacturing process.

Vieira *et al.* (2010) used LCA methodology to assess the environmental impact of the cylinder made from recyclable materials which is not only more ergonomic and elegant but also much cleaner and safer.

Shao *et al.* (2011) found the optimal cutting condition for minimum emissions in a machining process. The model provides a recommendation on optimizing parameters which can be used for the selection and procurement of equipment to minimize the CO_2 emissions.

Lu *et al.* (2011) presented a framework for developing comprehensive product and process metrics for sustainable manufacturing. The framework addresses all three aspects of the triple bottom line – environmental, economic, and social.

Araujo and Oliveira (2012) identified the performance measures and indicators for manufacturing process sustainability. The study suggests energy, materials, water, emissions, effluents, and waste as the core aspects of sustainability in manufacturing. Mani *et al.* (2014) proposed energy, energy efficiency, embedded energy, CO_2, waste, water, emission, etc. as the key sustainability performance indicators for manufacturing process sustainability.

Giovannini *et al.* (2012) developed a software-based solution for sustainability in manufacturing processes. A product-centric ontology is proposed in which concepts of products, processes, and resources are associated with functions and sustainable manufacturing knowledge. The knowledge-based system is able to automatically identify change opportunities and proposed alternatives on the basis of the existing production scenario.

Smith and Ball (2012) presented guidelines for material, energy, and waste (MEW) minimization. Developed guidelines were applied in a UK manufacturing company, which deals with machining and assembly process for industrial equipment. It finds that the availability of data for MEW is very important for qualitative mapping of processes.

Yuan *et al.* (2012) developed a decision support framework for improving the sustainability of an ALD (atomic layer deposition modeling) manufacturing process for pollution prevention and environmental sustainability. The authors indicate that the energy consumption in manufacturing processes is an important reason for environmental emissions. The scope of the study covers the nano-scale manufacturing process but the framework is also applicable to general manufacturing.

Vimal and Vinodh (2013) assessed the sustainability of manufacturing processes. Five case studies are used to assess the characteristics of process sustainability among automotive and electronics industries.

Chuang and Yang (2014) presented a three layered model for the evaluation of the green performance and identified the critical success factors. The study focuses on green design, green manufacturing processes, and green packaging.

Dornfeld (2014) assessed various options of green technology. The study incorporates manufacturing impact and control measures, process improvements, system improvements, and manufacturing versus use phase impact.

Lee *et al.* (2014) presented a conceptual and simulation-based model to evaluate the sustainability of manufacturing organizations. The study validated the model in an automotive stamping process.

Kumaraguru *et al.* (2014) evaluated manufacturing process sustainability on the basis of a faceted classification. Various identified classifiers are energy type, mechanism, material state change, material type, initial material state, and precedence. Facet classification method can also be used to develop life cycle inventory dataset for manufacturing processes.

Shao *et al.* (2017) presented a method named sustainable process analytics formalism (SPAF). The typical parts of SPAF consist of generic analytics language, sustainability metrics and process description, and reduction procedure. The methodology provides step by step guidance for users to perform sustainability analysis. Data from production, energy management, and life cycle assessment is used for modeling and analysis. The use of methodology has been demonstrated through a case study of investment planning for energy management.

Chen *et al.* (2015) analyzed the digital manufacturing process from the sustainability perspective. The study utilizes a literature-based methodology to understand the impact of direct digital manufacturing (DDM) over the traditional manufacturing systems.

Eastwood and Haapala (2015) developed a sustainability assessment methodology for manufacturing processes. The proposed methodology has six-step goal and scope definition, metrics selection, process definition, mathematical model construction, model application, and result and analysis.

Kim *et al.* (2015) developed a decision-guidance framework to improve sustainability in manufacturing processes while addressing the deficiencies in the existing LCA frameworks. The proposed framework consists of six phases: goal and scope definition, data collection, model generation, sustainability performance analysis, interpretation, and decision support and guidance.

Raileanu *et al.* (2015) proposed an agent-based approach for measuring real-time energy consumption in job-shop manufacturing processes. The study focuses on optimization of energy consumption in manufacturing processes through operation scheduling.

Shin *et al.* (2017) developed a decision support system (DSS) that enables manufacturers to formulate optimization problems at multiple manufacturing levels, to represent various manufacturing data, to create compatible and reusable models, and to drive easily optimal solutions for improving sustainability performance. The DSS considers multiple objectives of the manufacturing process to understand the various aspects of sustainability. The developed tool is also used to visualize the energy and material flow in the manufacturing processes.

Shojaeipour (2015) developed an automated evaluation tool, based on environmental standards, to identify and quantify the environmental impacts of a set of feasible manufacturing process plans and to select a near-optimal solution for the desired process plan. The selection methodology is based on the analytic hierarchy process (AHP) considering emissions, waste productions, and hazardous materials.

Singh *et al.* (2016) proposed a sustainability evaluation method for SMEs by using fuzzy AHP and FIS (fuzzy interference system) approach. Fuzzy AHP is applied to determine the relative weights of measures and indicators and the hierarchal FIS is applied to drive the overall sustainability performance. The indicators are divided into four performance measures - finance, customer, internal process, and learning and growth – as per balanced scorecard framework.

Bilge *et al.* (2016) presented a novel manufacturing architecture for sustainable value creation and its application for products, processes, and services. The method combines analyses and syntheses by applying the principles of sustainability to increase awareness about the challenges of implementing sustainable manufacturing principles. The proposed model includes four stages: elements of 6R, project management stage, equipment life cycle stage, and product life cycle stage.

Dassisti *et al.* (2016) proposed an approach consisting of supplying in-process information concerning energy consumption and other process state conditions through thermography.

It is observed, through a case study, that the approach resulted into a better assessment of sustainability profile of the whole production process in terms of energy consumption and environmental impacts by capturing the critical and dynamic changes in the process.

Jasinski *et al.* (2016) proposed an automotive sustainability assessment framework based on 26 midpoint and 9 endpoint environmental, resource, social, and economic impact categories. The proposed framework can be used as a decision-supporting tool at the early stages of the vehicle development process.

Ford and Despeisse (2016) summarised the advantages and challenges and discussed the implications of additive manufacturing on the sustainability in terms of the sources of innovation, business models, and the configuration of value chains. It is found that additive manufacturing provides benefit across the product and material life cycle but there are substantial challenges to these benefits being realized at each stage of the life cycle.

Abdul-Rashid *et al.* (2017) presented an empirical research for assessing the role of sustainable manufacturing practices in Malaysian companies using structural equation modeling. The results show that competitiveness, company culture, and public awareness have a positive impact on sustainable manufacturing practices. Further, the supply chain management is identified as the most important practice for implementation of sustainable manufacturing.

Habidin *et al.* (2017) examined the critical success factors of sustainable manufacturing practices in Malaysian automotive industry. The results show that social responsibility is a critical factor influencing the success of sustainable manufacturing practices. The study identified critical success factors for sustainable manufacturing practices.

Castellanos *et al.* (2018) presented a techno-economic integrated tool for tariff and transportation that enables the study of different strategies (technological innovation minimization of capital expenditures and optimization of supply chain flows) by coupling techno-economic model with a tariff and transportation algorithm to optimize supply chain layouts for the solar photovoltaic (PV) module manufacturing. The study recommends process optimization and provides techno-economic drivers for improving the sustainability.

Dunuwila *et al.* (2018b) and Dunuwila *et al.* (2018a) assessed the adoption of sustainable manufacturing practices in crepe rubber production in Sri Lanka. The study incorporates three methodologies: material flow accounting (MFA), material flow cost accounting (MFCA), and life cycle assessment (LCA) to analyze the material loss, economic loss and global warming potential (GWP) for the rubber processing.

Golini and Gualandris (2018) empirically investigated the relationship among globalization, integration, and sustainable innovation in the manufacturing networks. The research finds that the adoption of sustainable production practices at the plant level is significantly and positively associated with globalization and integration of the firm-wide manufacturing network. However, the adoption of sustainable sourcing practices is more strongly affected by integration in the external supply chain.

2.3.3 Sustainability Policies

Spangenberg and Bonniot (1998) presented a draft system of interlinkage indicators at the macro level which permits to connect key driving forces in the fields of environmental, economic, and social affairs for sustainability policy development. The performance indicators are linked to quantifiable policy targets.

Azzone and Noci (1998) identified performance measurement systems of green manufacturing strategies on the basis of environmental and economic indicators. The improvement of a company’s environmental performance requires a change in product planning and procurement policies. The introduction of environmental management practices has significantly affected operational policies.

Shields *et al.* (2002) articulated that the overlaps among policy, science, and publics' values and objectives can't be ignored. Policy, and particularly sustainability policy, is value driven. The paper argues that for the contextual application of these values to be realistic, society must understand the status and functioning of social, economic, and environmental systems and be aware of the consequences of their choices. Policy makers will be more likely to create attainable policy goals if they understand the importance of interaction between the environment and society and the implications of choosing one objective over another. Indicators that have been derived from participatory processes, indicators that are chosen because they are meaningful to the public and reflect an understanding of their values and objectives facilitate achievement of public's objectives as embodied in policies.

Curkovic (2003) presented performance measures for environmentally responsive manufacturing (ERM) using empirical research. The performance measures are identified from total quality management perspective. It is observed that an explicit model is needed to establish the relationship among strategic/policy systems, operational systems, information systems, and results, which can support the ERM implementation.

Zhu and Sarkis (2004) assessed the relationship between green supply chain management (GCSM) practices in the context of environmental and economic performance for Chinese enterprises. The study has also investigated the quality management policies or JIT manufacturing principles influence on the relationship between the GCSM practices and sustainability performance.

Gaughran *et al.* (2007) discussed sustainability challenges of the industrial world, the sustainable management issues, and the strategies that help in maintaining corporate responsibility and gaining competitive advantages. The paper argues that manufacturers should devise and implement new strategies for energy management and distribution logistics. It is also observed that the indicators of energy demand and supply should be incorporated in the supply chain planning and processing strategies. The study has shwon benefits from various alternative policies.

Rashid *et al.* (2008) reviewed the sustainable manufacturing policies for improved material performance. The study found four primary sustainable manufacturing policies – waste minimization, material efficiency, resource efficiency, and eco-efficiency. The study further identifies the key characteristics of these policies (definition, scope, practicality, and compatibility) and compares these policies.

Seliger *et al.* (2008) identified a research and development plan for sustainable manufacturing focusing on use-productivity. The study suggested that sustainable manufacturing in its next generation should focus on use-productivity. The paper provided three key strategies for use-productivity – implementation of innovative technology, improvement of the use intensity, and extension of the product life cycle.

Chung and Wee (2008) investigated the impacts of green product design, the new technology evolution, and the re-manufacturing on the production inventory policy. The study has provided an integrated deteriorating inventory model with green product (component) life cycle value design and re-manufacturing. It finds that the technological evolution, take-back ratio and the system holding costs are key factors affecting the decision making in a green supply chain inventory control.

Hong *et al.* (2009) presented a research model defining interrelationship among strategic green orientation, product development, supply chain coordination, green performance outcomes, and business unit performance. The firm's strategic green orientation involves past green practices, implementation of innovative environment improvement program and future commitment for environmental practices. This strategic green orientation is supported by inter-organization innovation practices of integrated product development practices, effective coordination of supply chain network, and relevant and measurable performance outcomes.

Lee (2009) focused on the process of green management adoption in SMEs. The study used an empirical analysis technique and finds out that the organizational structure, innovation capability, human resources, cost savings, and competitive advantages influence organizational change towards green practices.

Delai and Takahashi (2011) developed a reference model for measuring corporate sustainability. The model can be used by the organizations to integrate sustainability measures into the current performance measurement system, to embed sustainability into daily activities and to forge a sustainability culture.

Deif (2011) presented a system model for green manufacturing paradigm by capturing the various planning activities to move towards greener and eco-efficient manufacturing. The proposed model is a comprehensive qualitative answer to the question of how to design and/or improve green manufacturing systems as well as a roadmap for future quantitative research for better evaluation green manufacturing. The discussed green manufacturing strategies are cost, quality, flexibility, and time.

Yang *et al.* (2012) developed a strategic model for green manufacturing systems using quality function deployment. The study mainly focuses on environmental sustainability with an emphasis on suppliers and customers. The results show that strengthening the quality assurance and procurement capability are the most important missions for building green manufacturing systems.

Böhringer *et al.* (2012) assessed the effect of environmental and energy expenditure on German manufacturing organizations. The econometric analysis identifies a positive impact of environmental investment on production growth. However, the results don't support the hypothesis that the positive production impact is induced by environmental or energy expenditures.

Gunasekaran and Spalanzani (2012) addressed the important issue of sustainable business development in both service and manufacturing sectors by proposing a framework with seven elements. The study found that both internal (strategic objective, top management vision, employee safety and well-being, cost savings, productivity, and quality) and external (government regulations, profit, and non-profit organizations) pressures promote sustainability.

Hong *et al.* (2012) addressed the issue of benchmarking sustainability practices for a business organization. The study incorporates four elements for defining the benchmarking process: strategic driver (responsive product strategy), internal response practices (lean practices), external network configurations (supply chain restructuring), and sustainability outcomes (environmental performance and firm performance). The study opines that organizations should incorporate the sustainability practices at both strategic and employee levels.

Law and Gunasekaran (2012) identified three main factors motivating the adoption and implementation of sustainable development strategies in the high tech manufacturing sector of Hong-Kong. The relationship between motivating factors (management, internal, and external) and company's willingness and readiness (supportive measures) to adopt sustainable development strategies is provided. The study finds that the manufacturing organizations are highly motivated but the support from management in the form of policies is not very strong to adopt sustainability in business.

Roxas and Chadee (2012) highlighted the issue of ESO (environmental sustainability orientation) in the small and medium enterprises (SMEs). The ESO refers to the proactive strategies and policies to address the natural environment in the business processes. The study finds that if SMEs aim for proactive ESO, then financial resources do not affect significantly environmental sustainability.

Jayaraman *et al.* (2012) assessed the effect of sustainable manufacturing practices on the consumer perspective and revenue generation of a paint manufacturing company in India. A strong correlation between environmental concerns of the customers and the perceived proactive environmental strategies is observed from the empirical study. It is observed that proactive environmental practices protect the environment and increase competitiveness.

Garbie (2013) presented a new approach 'design for sustainable manufacturing enterprise'. The important factors considered in the new approach are international issues; contemporary issues; innovative products; reconfigurable manufacturing system; strategies for manufacturing; business models; flexible organizational management; and performance measurement.

Digalwar *et al.* (2013a) investigated the performance measures of green manufacturing in the Indian scenario. The study used an empirical investigation of 12 performance measures related to organizational policies, employees, environment, customers, products, and processes.

Mittal and Sangwan (2013a) presented an interrelationship and hierarchical structural model for barriers to environmentally conscious manufacturing (ECM). The selected barriers are related to policies, management commitment, resources, consumers, benefits, etc. Mittal and Sangwan (2014c) presented a ranking of ECM barriers using a multi-criteria decision-making technique. The selected 12 barriers are divided into economic, internal, policy, and societal barriers.

Singh *et al.* (2013) identified environmentally conscious manufacturing performance measures for the manufacturing industry in India. The study mainly considered the performance measures related to management, employees, products and processes, logistics, costs, and benefits.

Liu and Huang (2013) introduced an interval parameter programming (IPP) based strategic planning methodology for assessing the sustainability performance of biodiesel manufacturing technologies and processes under uncertainties. The study focuses on the strategic planning problem of distribution and transportation.

Chen *et al.* (2014a) addressed the issue of sustainability aspects of decision making in production facility location and the role of location in evaluating manufacturing sustainability. The study proposes a framework for facility location using the triple bottom line, manufacturing strategy, and performance perspectives.

Gabaldón-estevan *et al.* (2014) assessed the influence of European environmental regulations on the European ceramic tile manufacturing organizations, especially Spanish ceramic tile manufacturing organizations. The study mainly focuses on environmental issues in the tile manufacturing along with legislation, legitimation, and market. It is found that the new European regulations combined with complex international economic scenario is jeopardizing the European tile manufacturing industry.

Zhai *et al.* (2014) presented cost-benefits and CO_2 reduction potential in General Motors manufacturing through use of renewable energy systems. The study assesses different scenarios for renewable energy systems to reduce CO_2 and improve cost benefits. The study supports decision makers to formulate the necessary guidelines for optimal selection and deployment of clean energy systems.

Mittal and Sangwan (2014a) identified policy, internal, and economic drivers and presented a structural model of drivers. The study used exploratory factor analysis, confirmatory factor analysis, and SEM to develop the model. Mittal and Sangwan (2014b) also presented an ISM based model to assess the hierarchy and interrelationship among policy, internal, and economic drivers of ECM.

Dubey and Ali (2015) explored the antecedents of green manufacturing practices in Indian manufacturing. It is observed that total quality management (TQM), R&D and technology, supplier relationship management, and lean manufacturing are important practices for green manufacturing and to improve supply chain performance.

Govindan *et al.* (2015) identified green manufacturing practices using a hybrid MCDM model combining DANP with PROMETHEE. The study provides five dimensions (environmental, potential, regulatory, internal, and external) and their criteria for the selection of best green manufacturing practices using the hybrid MCDM model.

Spiegel *et al.* (2015) assessed the current situation of sustainability in manufacturing by investigating the sustainability strategies and their communication. The study uses a five-step methodology: analyze the corporate sustainability strategies, analyze the operational sustainability strategies, associate with sustainability dimension and themes, develop a matrix of interdependencies, and critical evaluation and concluding remarks. Study of web-based information of 100 companies reveals that energy waste and diversity are the most named sustainability goals. Support of charity program, smarter programming, reuse of waste heat, efficient lighting systems, and child care/work time models are the most cited sustainability strategies.

Siemieniuch *et al.* (2015) presented an overview of the sustainability drivers for sustainable development in terms of human and ergonomic factors. The analysis involves a discussion of global sustainability drivers and the challenges for the manufacturing organizations in the coming future.

Mani *et al.* (2016) focused on the incorporation of practices to improve social sustainability in the Indian manufacturing industries. The lack of pressure from the employee unions is the root barrier to the adoption of social sustainability in India followed by the lack of pressure by stakeholders. Lack of customer requirement, lack of pressure from social organizations, lack of zeal on the part of skillful policy entrepreneurs are next influential barriers. Lack of regulatory compliance and lack of awareness are the least influential barriers of social sustainability.

Mannan *et al.* (2016) studied Indian small and medium enterprises (SMEs) for the possibilities of incorporation of innovation and sustainability in their manufacturing practices using an interpretive structural model. It is found that "Governance" has the highest driving power, whereas, "Employee Nature" and "Working culture" have the lowest driving power.

Rajala *et al.* (2016) addressed the issue of environmental sustainability in a US-based carpet manufacturing organization. The study examines the links among the managerial agency, organizational identity, and business eco-systems for business model greening. The findings of the study suggest managerial role in organizational structure for making an ecosystem-oriented decision.

Sutherland *et al.* (2016) highlighted the effect of manufacturing activities on the social aspect of sustainability. It explores social impacts identified by national level social indicators, frameworks, and principles. The efforts to integrate social and another dimensions of sustainability are considered, with attention to globalization challenges including off-shoring and re-shoring. This study works as an eye opener from a social sustainability perspective and can be used for developing sustainability assessment method.

Bhanot *et al.* (2016) presented an integrated approach for sustainable manufacturing drivers and barriers using decision making trial and evaluation laboratory. The study further utilized maximum mean de-entropy algorithm integrated with ISM to model the hierarchical structure of identified drivers/enablers and barriers. The study mainly assessed the drivers and barriers related to organizational policies and manufacturing processes for sustainability.

Dubey *et al.* (2016) assessed the role of big data analytics to achieve world-class sustainable manufacturing (WCSM). Leadership, regulatory pressures, supplier relationship management, employee involvement, customer relationship management, total quality management, total productive maintenance, lean manufacturing, environmental performance, social performance, and economic performance are assessed for their influence on WCSM. It is concluded that big data analytics can serve as a driver for WCSM practices in developing countries like India.

Singh *et al.* (2016) proposed a hierarchical method combined with AHP and VIseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) for ranking of sustainable manufacturing strategies in manufacturing organizations. The study uses a literature-based methodology combined with IVF-AHP and VIKOR MCDM techniques.

Thirupathi and Vinodh (2016) presented an analysis of sustainable manufacturing factors using ISM and SEM modeling. Economic factors (profits, investment, and resources), environmental factors (emissions, waste, logistics, etc.), social factors, (safety, health, noise, etc.), business strategies, and R&D activities are modeled to study the interrelationship among sustainability enablers namely economic prosperity, environmental well-being, social well-being, performance management, and research and development.

Jasinski *et al.* (2016) presented a framework for sustainability assessment of automotive manufacturing. The study aims to develop policies for the product-development with emphasis on environmental sustainability.

Li *et al.* (2016) proposed efficient heuristics to find a schedule that minimizes the makespan subject to the constraints that the total cost (energy cost and environment clean-up cost) is not more than a given threshold value. The study mainly assessed the machine tool manufacturing industry with an emphasis on energy and pollution.

Kong *et al.* (2016) investigated the factors effecting the manufacturing organizations for implementation of governmental green policies in China. The work assesses the key factors of manufacturers' awareness, the understanding of energy efficient technology, and the long-term macroeconomic benefits related to policy diffusion in Chinese manufacturing firms.

Gilli *et al.* (2017) evaluated the drivers and decoupling trends of environmental pressures arising (directly or indirectly) from manufacturing production and consumption. The study shows the changes in Kg CO_2 performance of the different countries around the world and effect of different drivers on the environmental performance (in terms of Kg CO2). It is observed that implementation of sustainable policies can drive the emission reduction from manufacturing activities.

Ocampo (2017) explored the probabilistic fuzzy analytical network process approach in identifying the content of manufacturing strategy, infrstructural decisions that attempt to integrate sustainability and classical manufacturing strategy framework in the presence of organization size as a relevant component in decision making.

Singla *et al.* (2018a) assessed various technological pull and push strategies to achieve sustainable development of the manufacturing organizations in India. The selected demand pull strategies (stringent implementation of government regulations, transforming capabilities, unionized labor, and customer attributes) and technology push strategies (innovative capability, research and development, corporate strategy, and export orientation) are modeled according to their subfactors/indicators.

Aboelmaged (2018) examined the impacts of technological, organizational, and environmental drivers on SM practices, and the impact of these practices on competitive capabilities (quality, cost, delivery, and flexibility). The study provides implications for policymakers and practitioners to boost the sustainable manufacturing practices.

The review of 248 articles is presented in Table 2.2. The review highligts the aim, focus and limitations of the article. The review also point out the sustainability elements (product sustainability, process sustainability, sustainability policies, life cycle approach, resources, and level of assessment) used in the article.

Table 2.2 Manufacturing sustainability literature review

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
1.	Spangenberg and Bonniot (1998)	Germany	To present sustainability indicators at macro and micro levels and their linkages through meso-level elements.	Sustainability policies and sustainability indicators	Indicators do not reflect micro or industry/business level assessment.			×		×	N
2.	Westkämper (2000)	Germany	To evaluate the role of life cycle management in the manufacturing sector	LCM	The social aspect of sustainability ignored	×			×		N
3.	UNCSD (2001)	USA	To provide the guidelines and methodology for the development of sustainable development indicators	Sustainable development	Macro-level focus. Some of the indicators cannot be used for manufacturing sustainability.					×	N
4.	Veleva and Ellenbecker (2001)	USA	To present a framework for sustainable production and its indicators	Sustainable production	Top level indicators are difficult to measure/use. No guidelines for the selection of indicators.	×				×	N
5.	Shields *et al.* (2002)	UK	To provide justification of sustainability indicators effectiveness for social learning using a hierarchical model	Sustainability indicators	Generalized discussion on sustainability indicators. Sustainability indicators not provided.		×	×			N
6.	IChemE (2002)	UK	To address the sustainability of process industry	Environmental sustainability	Social and economic aspects of sustainability ignored.					×	N
7.	Basu and Kumar (2004)	UK	To develop a sustainability performance measurement framework for mining and mineral industry	Innovation and technology	Lacks life cycle approach.		×			×	N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
8.	Azapagic (2004)	UK	To develop the indicators for industrial minerals, metallic, and construction industry	Large-scale organizations	Limited to large organizations	×				×	N
9.	Arivalagan and Sudhakar (2005)	India	To assess the relationship between environmental sustainability and value addition for paper and pulp manufacturing	Environmental and economic aspect	The social aspect of sustainability is ignored.	×					P
10.	Parthasarathy *et al.* (2005)	USA	To provide a general sustainability implementation discussion in the chemical industry.	Environmental sustainability	Social aspects ignored	×	×				P
11.	Labuschagne and Brent (2005)	South Africa	To demonstrate the application of life cycle engineering in project management	Process industry	Limited to the process industry. Focus on project management	×	×		×		N
12.	Gaughran *et al.* (2007)	Ireland	To discuss the importance of sustainability in the industrial sector	Environmental sustainability	Social and economic aspects of sustainability are ignored.			×		×	N
13.	Liyanage (2007)	Norway	To highlight the issue of operation and maintenance sustainability in manufacturing organizations	Triple bottom line	The study addresses only operation and maintenance aspects.	×	×				N
14.	Marksberry (2007)	USA	To reduce the consumption of metalworking fluids	Machining	Limited to metalworking fluids in a machining operation.		×				P
15.	Adams and Ghaly (2006)	Canada	To present a framework for sustainability assessment of agriculture industry.	Triple bottom line	Focus on the agricultural industry. Region-specific.		×			×	P
16.	Jovane *et al.* (2008)	Italy	To discuss the sustainability and sustainability in manufacturing	Sustainability	Only a critical discussion on sustainability	×	×		×		N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
17.	Marksberry and Jawahir (2008)	USA	To develop a predictive model for estimating the tool wear and tool-life performance during near dry machining	Machining	Limited to environmental and energy aspects of a machining operation		×				P
18.	Rashid *et al.* (2008)	UK	To review the sustainable manufacturing strategies for material performance	Material performance	Limited to sustainable strategies and material performance			×			N
19.	Seliger *et al.* (2008)	Germany	To review sustainability approaches	Manufacturing	Implications not discussed	×	×	×			N
20.	Liow (2009)	Australia	To develop energy efficient micromachining facility	Micro-machining	Limited to the machining process		×				P
21.	Genaidy *et al.* (2010)	USA	To describe the contribution of humans to business sustainability	Social sustainability	Limited to people and other elements ignored		×				P
22.	Hall and Howe (2010)	UK	To discuss the chemical industry sustainability in Europe	Environmental sustainability	A narrow overview of sustainability in the chemical industry.			×			N
23.	Vieira *et al.* (2010)	Portugal	To demonstrate the application of composite materials (less polluting) in cylinder manufacturing	Environmental sustainability	Limited to environment sustainability	×	×				P
24.	Hicks and Matthews (2010)	UK	To address process sustainability in a manufacturing system improvement	Process sustainability	Limited to process sustainability improvement	×	×	×			N
25.	Jayal *et al.* (2010)	USA	To presents an overview of trends in the development of sustainable products, processes, and systems	Manufacturing	Limited to the sustainability in machining	×	×				N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
26.	Paju *et al.* (2010)	Finland	To introduce sustainable manufacturing mapping methodology (SMM)	SMM	Social and economic sustainability ignored		×		×	×	N
27.	Jain and Kibira (2010)	USA	To present a multiresolution modeling of sustainable manufacturing	Simulation and modeling	Limited to the modeling of social and environmental dimensions		×				N
28.	Pham and Thomas (2012)	UK	To deliver a sustainability solution for industry using “fit manufacturing” framework	Economic sustainability	Limited to economic sustainability			×			P
29.	Shao *et al.* (2011)	USA	To develop a decision support system for sustainable manufacturing	Machining	Limited to environmental sustainability in machining		×				P
30.	GRI Guidelines (2011)	Netherla-nds	To provide sustainability reporting guidelines and framework for the manufacturing industry	Sustainability reporting	Some indicators are difficult to evaluate. Lack of guidance for choosing the indicators.	×	×	×		×	N
31.	Lu *et al.* (2011)	USA	To present a framework for the development of product and process metrics for SM	Sustainability metrics	Product and process indicators are not enough to cover the whole manufacturing value chain	×	×		×		N
32.	Searcy (2011)	Canada	To present corporate sustainability performance measurement system	Assessment process	Limited to corporate sustainability assessment process	×	×		×		N
33.	DJSI (2011)	Switzerl-and	To track the corporate sustainability performance of the organizations	Sustainability index	Limited to stock performance assessment	×					N
34.	Araujo and Oliveira (2012)	Brazil	To develop sustainability indicators and themes for the manufacturing industry	Triple bottom line	No explicit list of indicators to assess sustainability	×	×		×	×	N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
35.	Delai and Takahashi (2011)	Brazil	To develop a reference model for measuring corporate sustainability	Corporate Sustainability	Guidance to select sustainability issues not provided	×		×		×	N
36.	Davies (2012)	UK	To provide a conceptual framework to incorporate sustainability in a manufacturing environment.	Environmental sustainability	Limited to environment sustainability			×			N
37.	Giovannini *et al.* (2012)	France	To visualize the energy and materials flow using a software tool	Environmental sustainability	Lacks social and economic aspects of sustainability	×	×				P
38.	Gunasekaran and Spalanzani (2012)	USA	To address sustainable business development in services and manufacturing	Triple bottom line	Limited to a vision for sustainability		×	×			N
39.	Hong *et al.* (2012)	USA	To address the issue of benchmarking sustainability practices in manufacturing	Environmental sustainability	Limited to environmental sustainability	×		×			N
40.	Law and Gunasekaran (2012)	China	To identify key factors influencing the execution and adoption of sustainability in Hong Kong manufacturing sector	Motivation for sustainability	Limited to the organizational motivation for adopting sustainability			×			N
41.	Lee *et al.* (2012)	South Korea	To develop a framework for simulation-based energy sustainability analysis	Environmental and economic aspects	Limited to environmental sustainability	×	×		×	×	P
42.	Roxas and Chadee (2012)	Australia	To highlight the issue of environmental sustainability orientation in the small and medium enterprise (SMEs)	Environmental sustainability	Limited to the environmental sustainability of SMEs			×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
43.	Short *et al.* (2012)	UK	To estimate the status of eco-sustainable product design or design for sustainability in UK and Sweden	Product design	Limited to product design and related sustainability	×					P
44.	Jayaraman *et al.* (2012)	India	To assess the consumer perspective and increase in revenue due to sustainable manufacturing	Economic sustainability	Limited to consumer perception of sustainable practices	×		×			P
45.	Despeisse *et al.* (2012)	UK	To review the literature on the best practices for sustainable manufacturing	Sustainability best practices	More emphasis to environmental sustainability factors			×			N
46.	Garbie (2013)	Oman	To address the needs of sustainable manufacturing enterprises	Sustainability Index	Limited to few aspects and their role in sustainability	×	×	×		×	N
47.	Smith and Ball (2012)	UK	To develop guidelines for material, energy, and waste (MEW) minimization	Operational data	Limited to MEW flow at the operational level	×					P
48.	Vinodh and Joy (2012)	India	To assess sustainable manufacturing practices among Indian SMEs	Best practices	Limited to SMEs			×		×	N
49.	Yuan *et al.* (2012)	USA	To develop a decision support framework for sustainability improvement using atomic layer deposition method	Environmental sustainability	Limited to environmental sustainability performance, especially CO_2 reduction		×				P
50.	Garetti and Taisch (2012)	Italy	To provide a vision towards sustainability in the manufacturing sector	Key areas of sustainable manufacturing	Limited to the discussion. No method and tools provided	×	×		×		N
51.	Egilmez *et al.* (2013)	USA	To address the eco-efficiency in US manufacturing organizations	Economic Input-output – LCA	Limited to number of environmental indicators				×		N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
52.	Strezov *et al.* (2013)	USA	To address sustainability of steel and iron companies along with steel and iron making technologies	Environmental and process sustainability	Limited application due to process specific indicators	×				×	P
53.	Vimal and Vinodh (2013)	India	To assess the process orientation of manufacturing organizations for sustainability	Process sustainability	Limited to process sustainability indicators	×	×	×			F
54.	Ziout *et al.* (2013)	Jordan	To develop a multi-criteria decision support system for manufacturing system reuse	Reuse	Limited to manufacturing system reuse	×	×			×	F
55.	Joung *et al.* (2013)	USA	To develop a set of sustainable manufacturing indicators	Sustainability indicators	Limited to the categorization of sustainability indicators	×	×	×		×	N
56.	Liu and Huang (2013)	USA	To assess the sustainability of biodiesel manufacturing technology using interval parameter programming	Biodiesel manufacturing	Limited to indicators of social and economic sustainability		×	×			P
57.	Nagalingam *et al.* (2013)	Australia	To assess the economic and environmental benefits of product returns and recovery	3R	Limited to few factors and end of life stage	×			×		N
58.	Rashid *et al.* (2013)	Sweden	To develop a conceptual framework for resource conservation in manufacturing	Resource conservation	Limited to environmental sustainability	×			×		N
59.	Alblas *et al.* (2014)	Netherl-ands	To explore the sustainability perspective in new product development	System theory of control	Manufacturing aspect of sustainability not addressed	×		×			P

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
60.	Amirmostofian *et al.* (2014)	Finland	To address the issue of sustainability risk management in European manufacturing sector	Sustainability reporting	Limited to report based assessment of risks			×			P
61.	Chen *et al.* (2014a)	Sweden	To propose a rapid sustainability assessment tool for SMEs	Sustainability assessment	Limited to sustainability assessment of SMEs	×				×	F
62.	Chen *et al.* (2014b)	Sweden	To address the issue of sustainability aspects of decision making in production facility location	Facility location	Limited to factors affecting facility location	×		×			N
63.	Faulkner and Badurdeen (2014)	USA	To address the issue of sustainability using value stream mapping (Su-VSM)	VSM	Limited to assessment of economic and social sustainability					×	P
64.	Golini *et al.* (2014)	Italy	To assess the role of the site for sustainable performance	Site selection	Limited to site assessment for sustainability		×				N
65.	Herrmann *et al.* (2014b)	Germany	To address the issue of sustainability and its implication for the future factories	Future factories	Limited to conceptual approach for future factories		×				N
66.	Kumaraguru *et al.* (2014)	USA	To evaluate manufacturing process sustainability on the basis of faceted classification	Faceted classification method	Limited to manufacturing process classification				×		N
67.	Lee and Lee (2014)	USA	To develop a sustainability research inventory	Sustainability research articles	Limited to literature collection	×	×				N
68.	Mani *et al.* (2014)	USA	To address the issue of sustainability measurement of manufacturing processes	Environmental sustainability	Insufficient indicators	×	×		×		P

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
69.	Moosavirad *et al.* (2014)	Australia	To address the issue of sustainability in outsourcing	Environment sustainability	Limited to environmental sustainability and outsourcing		×				P
70.	Valkokari *et al.* (2014)	Finland	To create a manufacturing sustainability roadmap	Sustainability	Limited to governance based conceptual model		×				N
71.	Dornfeld (2014)	USA	To assess various options for green technology	Green technology	Limited to environmental sustainability		×		×		N
72.	Jin and Noh (2014)	South Korea	To present a stochastic model for identification of green manufacturing benefits	Green benefits	Limited to the technology adoption decision	×	×				P
73.	Lee *et al.* (2014)	South Korea	To present a conceptual approach to evaluate the sustainability of manufacturing organizations	Sustainability index	Complex and limited applicability	×	×		×		P
74.	Shao *et al.* (2017)	USA	To present a decision guidance methodology to support manufacturing systems	Decision support system	Limited to environmental sustainability assessment		×				P
75.	Singh *et al.* (2014)	Malaysia	Fuzzy based sustainability assessment of SMEs	Sustainability of SMEs	Limited metrics for assessment	×					P
76.	Baumann and Genoulaz (2014)	France	To develop a framework for sustainable performance characterization and assessment of SCM practices	Supply chain	Lacks appropriate metrics of SCM sustainability assessment			×			N
77.	Alves and Alves (2015)	Brazil	To develop a model for production management and cultural change in a manufacturing organization	Sustainability Culture	Limited to four indicators of sustainability, lean and cultural shift						P

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
78.	Chen *et al.* (2015)	Sweden	To present a comprehensive analysis of the digital manufacturing process and traditional manufacturing	Digital manufacturing	Limited discussion on direct digital manufacturing	×					P
79.	Eastwood and Haapala (2015)	USA	To develop a sustainability assessment methodology for manufacturing	Life cycle inventory	Limited to product design and material selection	×			×		P
80.	Garbie (2014)	Oman	To assess the sustainability of manufacturing organizations using a sustainability index	Sustainability index	Life cycle aspect of sustainability not addressed	×	×		×		N
81.	Giret *et al.* (2015)	Spain	To address the issue of production scheduling in relation to the sustainability of manufacturing organizations	Production scheduling	Limited to production scheduling	×					N
82.	Hallstedt *et al.* (2015)	Sweden	To assess sustainable product design and manufacturing for an aerospace industry	Environmental Sustainability	Limited focus on energy consumption and design criteria. Limited to environmental sustainability.	×		×			P
83.	Harik *et al.* (2015)	North Africa	To assess the current situation of an organization through aggregation of the triple bottom line (TBL) and manufacturing aspects	Sustainability index	A very narrow focus of manufacturing	×	×			×	F
84.	Khan and Islam (2015)	Banglad-esh	To assess the sustainability of material and product for apparel manufacturing	Environmental sustainability	Limited to partial environmental sustainability	×					P

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
85.	Kim *et al.* (2015)	USA	To develop a sustainability assessment framework for manufacturing	Environmental sustainability	Limited to partial environmental sustainability		×				P
86.	Koho *et al.* (2015)	Finland	To address the sustainability challenges of manufacturing organizations	Sustainability	Limited to outcome discussion of two projects	×	×				N
87.	Longoni and Cagliano (2015)	Spain	To assess the alignment of lean manufacturing with environmental and social sustainability	Lean and environmental sustainability	Limited to lean tool and techniques based social and environmental sustainability	×					N
88.	Rajak and Vinodh (2015)	India	To assess the social sustainability of manufacturing organizations	Social sustainability	Limited to social sustainability using few performance measures		×				P
89.	Shin *et al.* (2017)	USA	To develop a decision support system using sustainability performance optimization tool	Decision support system	Complex methodology to incorporate sustainability		×				P
90.	Singh *et al.* (2016)	Malaysia	To evaluate the sustainability of SMEs by using fuzzy AHP and fuzzy inference system approach	Sustainability evaluation	Limited indicators for assessment	×					P
91.	Spiegel *et al.* (2015)	USA	To assess the sustainability in manufacturing by investigating the strategies	Manufacturing strategies	Insufficient indicators			×			N
92.	Sureeyatanapas *et al.* (2015)	Thailand	To develop an empirical framework for the assessment of corporate sustainability for Thai sugar manufacturing industry	Sustainability index	Limited to sugar manufacturing	×	×				F
93.	Trentesaux and Giret (2015)	France	To present an autonomous self-reliant holonic system for sustainable manufacturing	Operations control	Limited to a narrow area (controls) of manufacturing			×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
94.	Tsiliyannis (2015)	Greece	To propose a resource preservation cycle rate to assess closed loop supply chain	Closed-loop production	Complex mathematical approach. Limited applicability for sustainability assessment			×	×		N
95.	Yusup *et al.* (2015)	Malaysia	To check the role of lean philosophies in sustainability	Environmental and economic aspects	Limited to lean production based sustainability	×	×				N
96.	Dubey *et al.* (2015)	India	To develop a world-class sustainable manufacturing framework	World class sustainable manufacturing	Limited to the relationship building of sustainable manufacturing with other manufacturing philosophies		×	×			N
97.	Matsuda and Kimura (2015)	Japan	To present digital factory approach for the adoption of sustainable manufacturing	Digital eco-factory	Limited to virtual solutions	×	×				N
98.	Raileanu *et al.* (2015)	Romania	To develop an approach for energy measurement in operation scheduling	Operation Scheduling	Limited to environmental sustainability (especially energy)		×				P
99.	Shojaeipour (2015)	USA	To develop an environmental sustainability assessment tool for the manufacturing sector	Process planning	Limited to environmental sustainability	×	×				P
100.	Siemieniuch *et al.* (2015)	UK	To present drivers for sustainable development in terms of human and ergonomic factors	Ergonomics	Limited to ergonomic perspective			×			N
101.	Thomas *et al.* (2015)	UK	To develop an operational model for competitiveness and resilience in manufacturing	Operational sustainability	Limited to productivity enhancement techniques	×	×	×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
102.	Wang *et al.* (2015)	China	To develop a conceptual framework to test sustainability performance in terms of triple bottom line	Lean and green aspects	Limited to lean and green initiatives	×	×	×			N
103.	Dassisti *et al.* (2016)	Italy	To address the shortcomings of LCA to improve sustainability assessment	LCA and thermography	Limited to environmental assessment		×				P
104.	Egilmez *et al.* (2016)	USA	To assess the ecological sustainability of the manufacturing industries across USA	Eco-LCA	Limited cradle to gate LCA for environmental sustainability		×				P
105.	Ford and Despeisse (2016)	UK	To study the impact of additive manufacturing on sustainability	Additive manufacturing	Limited to additive manufacturing sustainability	×	×		×		P
106.	Govindan *et al.* (2016a)	India	To develop a facility location framework for sustainable supply chains	Facility location	Uncertainty in data, interdependence, government regulations, local politics, etc. neglected	×			×		P
107.	Govindan *et al.* (2016b)	India	To study the importance of product recovery process for a manufacturing organization	Product recovery	Limited discussion on procurement and distribution processes	×			×		P
108.	Jayakrishna *et al.* (2016)	India	To define measures to quantify the sustainability of a manufacturing organization	Sustainability	Limited to abstract level sustainability attributes	×			×	×	F
109.	Linke (2016)	USA	To review the production of tools with different bonds and their constituents.	Grinding wheel	Limited to bonding material sustainability		×				N
110.	Mani *et al.* (2016)	India	To improve social sustainability in the Indian manufacturing industries	Social sustainability	Lack of statistical validation		×	×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
111.	Mannan *et al.* (2016)	India	To figure out the possibilities of incorporation of innovation and sustainability in SMEs	Sustainability	Lack of statistical validation			×			N
112.	Rajala *et al.* (2016)	Finland	To address the issue of sustainability, especially environmental sustainability	Environmental sustainability	Limited to environmental sustainability			×			P
113.	Roxas and Chadee (2016)	Philippi-nes	To improve environmental sustainability in the context of knowledge management	Knowledge management	Limited discussion on the relational capital analysis and knowledge management for sustainability improvement			×			N
114.	Sutherland *et al.* (2016)	USA	To highlight the effect of manufacturing activities on the social sustainability	Social sustainability	Limited to social sustainability			×	×		N
115.	Thomas *et al.* (2016)	UK	To analyze the effect of sustainable practices on the financial profile	Economic sustainability	Social and environmental aspects of sustainability ignored	×	×	×			N
116.	Bhanot *et al.* (2016)	India	A framework of sustainable manufacturing drivers and barriers	Drivers and barriers	Lacks core sustainability perspective		×	×			N
117.	Bilge *et al.* (2016)	Germany	To develop a conceptual model for sustainability implementation in manufacturing	Environmental sustainability	Limited to environmental sustainability	×	×		×	×	P
118.	Brodsky *et al.* (2016)	USA	To develop a decision support system for manufacturing systems	Environmental sustainability	Complex methodology. Limited to environmental sustainability		×				P
119.	Dubey *et al.* (2016)	India	To address the effect of big data analytics on world-class sustainable manufacturing (WCSM)	WCSM	Limited applicability to sustainability improvement		×	×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
120.	Luqmani *et al.* (2016)	UK	To develop sustainable business innovation factors in the manufacturing sector	Sustainable Innovation	Data limited to carpet manufacturing		×		×		P
121.	Ocampo *et al.* (2016)	Philippi-nes	To assess the sustainability of manufacturing organizations using sustainability index	Sustainability assessment	Limited number of sustainability indicators	×	×			×	F
122.	Singh *et al.* (2016)	Malaysia	To select sustainable strategies for manufacturing organizations	Strategy selection	Limited to the ranking of sustainable manufacturing strategies	×		×			P
123.	Thirupathi and Vinodh (2016)	India	To model sustainable manufacturing enablers for Indian automotive companies.	Sustainable manufacturing enablers	Limited to sustainable manufacturing enablers			×			P
124.	Winroth *et al.* (2016)	Sweden	To develop sustainability assessment indicators for production in an SME	Sustainability indicators	Limited to production process sustainability	×	×				N
125.	Jasinski *et al.* (2016)	UK	To develop a framework for sustainability assessment of a car from the early design stage	LCA	Representation of the social and economic midpoint and endpoint categories is not clear	×	×	×			N
126.	Journeault (2016)	Canada	To address the issue of corporate sustainability by integrated balance scorecard	Balance scorecard	No indicators or methodology for sustainability assessment	×			×		N
127.	Azzone and Noci (1998)	Italy	To identify performance measurement systems for green manufacturing strategies	Environmental and economic indicators	Social aspects not addressed	×		×		×	N
128.	Zhang (1999)	USA	To introduce green quality function deployment	QFD, LCE, LCC	Social aspects not addressed	×			×		N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
129.	Gungor and Gupta (1999)	USA	To provide an overview of ECM and product recovery options using a literature review	ECM & Product recovery	Limited to the literature review on the factors affecting product recovery and ECM	×	×		×		N
130.	Nagel and Meyer (1999)	Germany	To present results of applied research activities on end-of-life options at Fraunhofer Institute in Germany	End-of-life options	Limited to results of electronics recycling possibilities	×					N
131.	Sarkis (1999)	USA	To present a combined approach of ANP and DEA for ECM program selection	ANP and DEA	Limited to methods for ECM program selection			×			N
132.	Thurston (1999)	USA	To address several aspects of environmentally conscious design and manufacturing	Decision-making approach ECM	Limited to discussion of various approaches to reach ECM goal	×					N
133.	Madu *et al.* (2002)	USA	To develop a hierarchic framework for the environmentally conscious design	Product design and AHP	Limited to green product design	×			×		P
134.	Durham (2002)	USA	To provide an overview of environmentally benign manufacturing	Net shape manufacturing	Limited to net shape cast component. Environmental assessment only	×			×	×	P
135.	Zhu and Deshmukh (2003)	USA	To analyze the LCE performance of the design decisions and environmental impact for a product	Bayesian decision theory and LCA	Limited to the application of Bayesian decision theory for product life cycle and design	×			×		**N**
136.	Curkovic (2003)	USA	To identify and assess performance measures of ERM using empirical research	Performance measures of ERM	Limited to the comparative selection of performance measures of ERM			×			N
137.	Pineda-henson and Culaba (2004)	Philippi-nes	To assess the green performance of a manufacturing process using AHP	LCA and AHP	Limited to gate to gate analysis of semiconductor assembly system	×	×		×	×	P

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
138.	Zhu and Sarkis (2004)	China	To assess the relationship between green supply chain management (GCSM) practices with environmental and economic performance	GCSM	Limited to quality management and JIT assessment			×			N
139.	Fei *et al.* (2005)	China	To assess green manufacturing in machining	Machining	Limited to resource consumption and environmental discharge minimization		×			×	N
140.	Hua *et al.* (2005)	China	To assess the aggregate risk in green manufacturing projects	Aggregate risk	Limited focus on aggregate risk green manufacturing projects			×			N
141.	Gutowski *et al.* (2005)	USA	To assess EBM practice in manufacturing firms	EBM practices	Limited to observations from Japan, Europe, and USA				×	×	N
142.	Bras *et al.* (2006)	USA	To present results of a workshop on EBM	EBM practices	Limited to results of EBM workshop conducted in Alabama, USA	×	×		×		N
143.	Subaı *et al.* (2006)	France	To assess the possibility of including ERM in scheduling problem using mathematical models	Scheduling	Limited to scheduling	×	×			×	N
144.	Yan *et al.* (2007)	China	To provide a green manufacturing process planning support system for optimizing environment based planning	Process planning support system	Only a few environmental aspects of the manufacturing process are addressed		×			×	N
145.	Manley *et al.* (2008)	USA	To demonstrate the importance of green chemistry via 12 principles & indicators.	Environmental sustainability	Only focuses on the importance of green chemistry and it limits itself to environmental part of organizational sustainability	×	×				N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
146.	Chung and Wee (2008)	Taiwan	To assess the impact of green product design, new technologies, and re-manufacturing in context of inventory policy	Deteriorating Inventory model	Focus only on an inventory model	×		×	×		N
147.	Ellram *et al.* (2008)	USA	To presents an integration of three-dimensional concurrent engineering (3DCE) with new product development (NPD) and ERM	NPD and 3DCE	Limited to integration of NPD, ERM, and 3DCE	×	×				N
148.	Hong *et al.* (2009)	USA	To present research model defining interrelationship among strategic green orientation, product development, supply chain coordination, green and business performance.	Product development and supply chain	Limited to environmental sustainability and product development	×	×	×			N
149.	Lee (2009)	Germany	To assess green management adoption in SMEs	Green management adoption	Limited to SMEs			×	×		N
150.	Siniawski and Bowman (2009)	USA	To present a review of cutting fluids in machining	Metalworking fluids	Limited to the discussion on metalworking fluids in machining	×	×				N
151.	Rao (2009)	India	To present an MCDM model for selection of ECM program	MCDM	Limited to provide a ranking methodology for ECM programs	×	×		×		N
152.	Barreto *et al.* (2010)	USA	To investigate the role of product life cycle management in green manufacturing practices	Product life cycle management	Limited to discussion on factors like Recycle, Energy consumption, water and air management, and green performance along with regulation and policies	×	×		×		**N**

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
153.	Eltayeb and Zsailani (2010)	Malaysia	To assess the effect of green purchasing drivers in Malaysian manufacturing sector	Green Purchasing	Limited to drivers of green purchasing						N
154.	Li *et al.* (2016)	China	To propose a model for planning and implementation of green manufacturing in Chinese manufacturing	Energy and Pollution	Limited to energy and pollution in machine tool manufacture industry	×		×	×		N
155.	Shang *et al.* (2010)	Taiwan	To investigate green supply chain management capability and performance of Taiwanese manufacturing firms.	Green supply chain management	Limited to six aspects of Taiwanese electronics manufacturing organizations	×	×		×		N
156.	Ilgin and Gupta (2010)	Turkey	To present an overview of ECM and product recovery options using literature	ECM and Product recovery	Limited to a review of the literature on ECM and product recovery option	×	×		×		N
157.	Vinodh and Rathod (2010)	India	To present QFD based approach for environmentally conscious design	QFD and ECM	Limited to a product design and its environmental aspects	×					N
158.	Baresel-bofinger *et al.* (2011)	Greece	To assess the effect of green knowledge management and use of environmental intellectual capital in the implementation of GSCM	GCSM	Limited to the environmental and economic aspects of GSCM	×	×		×		N
159.	Deif (2011)	Egypt	To plan and develop green manufacturing systems	Planning green manufacturing	Limited to environmental aspects		×	×	×	×	P

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
160.	Sangwan (2011)	India	To assess justification of green manufacturing systems using various criteria	Assessment and ranking	Limited to multi-criteria decision model for various criteria and sub-criteria of GMS	×	×			×	N
161.	Tsai *et al.* (2011)	Taiwan	To assess activity based system for capital investment in green manufacturing systems	Green initiative cost	Limited to assess cost-related benefits and few environmental aspects					×	N
162.	Koh *et al.* (2012)	India	To assess adoption of green supply chain management and low carbon practices in Indian industry	Low carbon green supply chain	Limited to empirical research on drivers and barriers to low carbon green supply chain management						N
163.	Kung *et al.* (2012)	Taiwan	To assess interrelationship between green management and environmental performance	Green value chain	Limited to relationship assessment between the green value chain and environmental performance	×	×		×		N
164.	Pirraglia and Saloni (2012)	USA	To develop an environmental improvement index for manufacturing using a proposed model	Environmental index	Limited to environmental index on the basis of four factors only					×	P
165.	Wong *et al.* (2012)	Hong Kong	To assess the role of green operations and environmental management on performance and pollution reduction	Green operations	Limited to empirical assessment of electronics manufacturers green operations	×	×				N
166.	Yang *et al.* (2012)	Taiwan	To develop a strategic model using quality function deployment	QFD	Limits the work towards environmental sustainability (supplier and customers)	×	×	×			**N**
167.	Böhringer *et al.* (2012)	Germany	To assess the effect of environmental and energy expenditure.	Environmental expenditure	Limited to empirical assessment of environmental and energy expenditure			×			

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
168.	Dey and Cheffi (2013)	UK	To develop a green supply chain performance framework	GCSM	Limited to environmental aspects of supply chain performance		×	×		×	P
169.	Digalwar *et al.* (2013a)	India	To investigate the performance measures of green manufacturing performance in India	Green manufacturing performance measures	Limited to environmental criteria	×	×	×			N
170.	Ahemad *et al.* (2013)	India	To assess green manufacturing practices	Green performance practices	Limited to empirical research in a specific region	×	×		×		N
171.	Ahemad *et al.* (2013)	India	To present a systematic review of green manufacturing articles	Literature review	Limited to literature review of green manufacturing practices and measures	×	×			×	×
172.	Sultan (2013)	Mauritius	To present an overview of green initiatives in the textile industry of Mauritius	Green initiative and barriers	Limited to green initiatives and barriers in textile manufacturing	×	×	×			P
173.	Tsai *et al.* (2013)	Taiwan	To propose a model for profitability analysis of product mix based on ABC and TOC	Environmental aspect	Limited to optimize green paint coat for metal parts as a single objective	×	×				P
174.	Mittal and Sangwan (2013a)	India	To present a hierarchical and interrelationship structural model of ECM barriers	Barriers to ECM	Limited to hierarchical model of barriers for ECM			×			N
175.	Singh *et al.* (2013)	India	To identify 11 ECM performance measures	Performance measures	Limited to performance measure identification using empirical research	×	×	×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
176.	Chuang and Yang (2014)	Taiwan	To present a model for green manufacturing performance evaluation and identification of key success factors	Green assessment	Limited to environmental assessment	×	×				P
177.	Gabaldón-estevan *et al.* (2014)	Spain	To assess the effect of environmental issues on European manufacturing especially Spanish ceramic tile manufacturing	Ceramic tile manufacturing	Limited to environmental issues of tile manufacturing	×		×		×	N
178.	Govindan *et al.* (2015)	India	To identify the drivers of green manufacturing in south Indian firms	AHP and green manufacturing drivers	Limited to empirical assessment of in the Indian context			×			N
179.	Hu *et al.* (2014)	USA	To propose an oligopoly game theory based model to analyze the effect of green and ordinary manufacturing	Mathematical model	Limited to comparative of two or more products	×		×			N
180.	Mitra and Datta (2014)	India	To assess green supply chain practices in Indian manufacturing	GCSM	Limited to very few environmental and economic aspects of supply chain	×					N
181.	Moreira *et al.* (2015)	UK	To propose an integrative framework for product design in green aircraft completion industry	Sustainable product development	Limited to aircraft completion (textile) industry	×	×		×		N
182.	Rehman *et al.* (2014)	India	To investigate the relationship between drivers of green manufacturing	Green drivers, ISM	Limited to interrelationship of drivers			×			N
183.	Zhai *et al.* (2014)	USA	To present a cost-benefit and CO_2 reduction potential through renewable energy systems at General motors	Cost-benefit and CO_2 mitigation	Limited to the effect of CO_2 reduction using renewable energy			×			P

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
184.	Mittal and Sangwan (2014a)	India	To identify ECM drivers and present a structural model of drivers	ECM Drivers	Limited to identify and provide a structural model of ECM drivers			×		×	N
185.	Mittal and Sangwan (2014b)	India	To present an ISM model of ECM drivers	ECM Drivers	Limited to ISM model of ECM drivers			×			N
186.	Mittal and Sangwan (2014c)	India	To rank the barriers of ECM using fuzzy TOPSIS using MCDM	ECM Barriers	Limited to rank the barriers to ECM using MCDM methods			×			N
187.	Dubey and Ali (2015)	India	To explore the antecedents of green manufacturing practices in Indian manufacturing	GCSM	Limited to performance measures and their effect on green supply chain		×	×			N
188.	Govindan *et al.* (2015)	India	To identify best green manufacturing practices using MCDM techniques	Green manufacturing practices	Limited to identify best practice and no practical application is considered	×		×		×	P
189.	Guo *et al.* (2015)	Taiwan	To evaluate the corporate social responsibility indicators for green production	Environmental Indicators	Limited to environmental indicators and few social indicators		×			×	N
190.	Huang *et al.* (2015)	China	To investigate the pressures and drivers for Chinese SMEs for green supply chain management	GCSM	Limited to drivers and pressures for Chinese SMEs			×			N
191.	Orji and Wei (2015a)	China	To assess supplier behavior using fuzzy system dynamics	Supplier selection	Limited to supplier selection using system dynamics modeling			×			N
192.	Rehman *et al.* (2015)	India	To develop an instrument to investigate the awareness and implementation of green manufacturing	Green manufacturing practices	Limited to environmental and productivity improvement aspects		×				N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
193.	Sangwan and Mittal (2015)	India	To review green manufacturing and similar framework	Review	Limited to a review of articles for green manufacturing and similar framework				×	×	N
194.	Ilgin *et al.* (2015)	Turkey	To present a literature review on MCDM in ECM and product recovery	Review of MCDM techniques	Limited to review of MCDM techniques for ECM	×	×		×		N
195.	Al-ayouty *et al.* (2016)	Egypt	To assess the growth of clean manufacturing industry in Egypt	Environmental sustainability	Limited to assess the growth and increased concern of environmental protection in the industrial sector		×	×			P
196.	Gandhi *et al.* (2016)	India	To assess success factors for green supply chain management	GCSM	Limited to 24 success factors evaluation using AHP and DEMATEL	×		×			N
197.	Li *et al.* (2016)	China	To develop a mathematical model for optimized scheduling in manufacturing	Scheduling	Limited to scheduling						P
198.	Kong *et al.* (2016)	China	To understand the factors effecting the manufacturing organizations for implementation of governmental green policies in China	Green manufacturing policies	Limited to factors affecting policy diffusion in Chinese manufacturers		×	×			N
199.	Li and Lin (2016)	China	To develop a Malmquist Luenberger productivity index for green	Green productivity Index	Limited to few aspects of the manufacturing sector		×				P
200.	Makhesana and Patel (2016)	India	To investigate the use of solid lubricants in machining processes	Machining	Limited to check the possibility of solid lubricants usefulness		×				N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
201.	Meng *et al.* (2016)	China	To develop a mathematical simulation model for optimum EOL solutions	EOL	Limited to EOL options	×					N
202.	Orji and Wei (2016)	China	To develop a methodology for cost calculation in industrial dynamics	Life cycle costing	Limited to cost analysis throughout product life cycle	×			×		N
203.	Rehman *et al.* (2016)	India	To present an empirical assessment of green manufacturing practices	Green manufacturing practices	Limited to identification of success factors and performance measures	×	×	×			N
204.	Routroy and Kumar (2016)	India	To identify significant areas in green supply chain management using FAHP	GCSM	Limited to green capability in supply chain		×				N
205.	Seth *et al.* (2016)	India	To identify green manufacturing performance measures and critical success factors for Indian cement industry	Green manufacturing performance measures	Limited to empirical evidence in cement industry and performance measures		×	×			N
206.	Yu and Hou (2016)	China	To propose an MCDM based green supplier selection model	Supplier selection	Limited to green supplier selection						N
207.	Hrovatin *et al.* (2016)	Slovenia	To assess factors effecting Slovenian manufacturing sector for energy efficiency and clean technology investment decision	Energy efficiency and clean technology	Limited to assess factors of energy efficient investment	×	×	×			N
208.	Abdullah *et al.* (2017)	Malaysia	To assess the implementation of sustainable manufacturing (SM) practices in Malaysian palm oil mills	SM practices	Limited to assessment of SM practices in a specific industry	×	×	×	×		N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
209.	Aboelmaged (2018)	UAE	To assess the impacts of drivers on SM practices and second the impact of these practices on competitive capabilities.	SM drivers & practices	Limited to small sample size of data		×	×		×	N
210.	Chavarría-Barrientos *et al.* (2017)	USA	To demonstrate a methodology to design a sensible, smart, and sustainable manufacturing organizations	Smart manufacturing	Limited to complex approach for design and development		×	×			N
211.	Caldera *et al.* (2018)	Australia	To identify the key characteristics of sustainable business practices for Australian SMEs	Natural resource-based view	The sample investigated is small and empirical evidence are required		×	×	×	×	N
212.	Castellanos *et al.* (2018)	USA	To present techno-economic integrated tool for tariff and transportation to support the solar photovoltaic (PV) module manufacturing	Solar photovoltaics	Limited to economic aspects of solar PV production		×	×			P
213.	Chan *et al.* (2017)	UK	To classify the mathematical problems dealing with the management of sustainable manufacturing systems	Mathematical problem	Limited to a review of planning and execution problems in manufacturing		×	×	×		N
214.	Dissanayake *et al.* (2017)	Sri Lanka	To present an approach to fair trade in the textile industry of Sri-lanka	Fair Trade	Limited to a case study of handloom industry in Sri Lanka		×	×			N
215 - 216	Dunuwila *et al.* (2018b) & Dunuwila *et al.* (2018a)	Sri Lanka	To assess and improve the sustainability performance of natural rubber processing	Rubber manufacturing	Limited to material flow analysis and global warming potential assessment		×		×		P

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
217.	Esfahbodi *et al.* (2017)	UK	To assess the role of governance in the adoption of sustainable supply chain management (SSCM) practices and their influence on environmental and financial aspects	Supply chain pressures	Limited to SSCM practices and their influence in UK's manufacturing sector	×	×	×			N
218.	Fox and Alptekin (2018)	Turkey	To investigate different manufacturing distribution taxonomies	Manufacturing distribution taxonomies	Limited to advantages and disadvantages of manufacturing distribution system			×			N
219.	Garbie (2017)	Egypt	To identify the challenges faced by emerging economies to implement sustainability	Sustainability implementation challenges	Limited to performance measures and challenges	×	×	×			N
220.	Gilli *et al.* (2017)	Italy	To present the relationship between environmental performance and related drivers at the global level	Environmental performance	Limited to environmental factors			×			N
221.	Golini and Gualandris (2018)	Italy	To investigate the relationship among globalization, integration, and sustainable innovation in manufacturing networks	Sustainable production and sourcing	Not applicable to plant level and organizational level assessment			×			N
222.	Habidin *et al.* (2017)	Malaysia	To identify the critical success factors (CSF) of SM practices	SM practices	Limited to four SM practices – manufacturing process, SCM, social responsibility, and environmental management		×	×			N
223.	Holmström *et al.* (2018)	Finland	To propose a theory for direct digital manufacturing (DDM) technology and DDM based operational practices	DDM	Limited to DDM practices			×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
224.	Ighravwe and Ayoola Oke (2017)	Nigeria	To provide a viewpoint of sustainability maintenance and ranking of maintenance strategies	Sustainable maintenance	Limited to select maintenance strategies			×			N
225.	Jabbour *et al.* (2018)	France	To identify the CSFs for the synergy between industry 4.0 and environmentally sustainable manufacturing	Industry 4.0 & environmental SM	Limits to develop a theoretical framework			×			N
226.	Katiyar *et al.* (2017)	India	To provide a comprehensive framework for measuring the performance of a supply chain	Supply chain performance	Limited to empirical-based data collection and weights of factors	×	×			×	P
227.	Latif *et al.* (2017)	USA	To present a sustainability index for manufacturing organizations	Manufacturing sustainability index	Limited to three aspects of sustainability (energy efficiency, waste management, and workers' health and safety)		×			×	P
228.	Li and Mathiyazhagan (2018)	India	To identify sustainability assessment indicators for the automotive manufacturing industry	Sustainability indicators	Limit to identification of sustainability indicators		×		×	×	N
229.	Luo *et al.* (2017)	India	To develop a sustainable production framework on the basis of the theory of planned behavior	Behavioral aspect of sustainability	Limited to behavioral aspects of social sustainability			×			N
230.	Mani *et al.* (2018)	Portugal	To present the supply chain social practices in the Portuguese firms	Social sustainability practices	Limited to social sustainability practices			×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
231.	Moktadir *et al.* (2018)	Banglad-esh	To identify, assess, prioritize, and rank drivers of SM practices in the leather industry of Bangladesh	SM practices	Limited to few drivers of sustainability in leather industry			×			N
232.	Moldavska and Welo (2017)	Norway	To present a review of literature on sustainable manufacturing and its definitions	SM definitions	Limited to a SM definitions	×	×		×	×	N
233 - 234	Nujoom *et al.* (2017) and Nujoom *et al.* (2018)	UK	To develop multi-objective optimization mathematical model for the ecological and economic parameters	Mathematical modeling	Limited to energy, cost, and CO_2					×	P
235.	Ocampo (2017)	Philippi-nes	To provide an approach to capture uncertainty in group decision making using a multi-criteria decision-making model	MCDM technique	Limited to removing uncertainties in decision making			×			N
236.	Vimal *et al.* (2017)	India	To assess the sustainable manufacturing performance using a graph theory approach	Sustainability assessment	Limited to qualitative measures			×			N
237.	Skellern *et al.* (2017)	Australia	To provide a conceptual model of attributes of sustainable transitions	Sustainable transitions	Limited to few aspects of sustainable transitions			×			N
238 - 241	Singla *et al.* (2017a, 2017b, 2018a, 2018b)	India	To assessed various technological pull and push strategies to achieve sustainable development in the manufacturing organizations	Pull and push strategies	Limited to push and pull strategies			×			N

Table 2.2 Manufacturing sustainability literature review (Contd.)

S. No.	Author	Country	Aim	Focus	Limitation	Product	Process	Policy	Life cycle	Resources	Level of assessment
242.	Shubham *et al.* (2018)	India	To investigate the Indian manufacturing plant for the role of institutional isomorphism mechanisms	Isomorphism	Limited to organizational pressures			×			N
243.	Shibin *et al.* (2017)	India	To provide a decision support system to redesign a car assembly line using a simulation-based optimization approach	Decision support system	Limited to car assembly line in a welding shop		×	×			N
244.	Shankar *et al.* (2017)	India	To identify the SM practices for Indian manufacturing organizations	SM practices	Limited to interrelationship among SM practices			×		×	N
245.	Park and Kremer (2017)	USA	To provide an approach to categorize the available SM indicators	Text mining SM indicators	Only categorization of indicators in five categories.	×	×	×		×	N
246.	Peruzzini and Pellicciari (2017)	Italy	To investigate the user experience factors for SM	Human factors	Limited to compare old and new design factors		×				P
247.	Abdul-Rashid *et al.* (2017)	Malaysia	To assess the role of sustainable manufacturing practices in Malaysian companies	SM practices	Limited to few SM practices			×			N
248.	Abdul-Rashid *et al.* (2017a)	Malaysia	To investigate the important drivers effecting the sustainability performance of Malaysian manufacturing industry	SM drivers	Limited to qualitative assessment of important drivers	×	×	×	×		N

N – No assessment; P – Partial assessment, F – Full assessment

2.4 DESCRIPTIVE ANALYSIS

Descriptive analysis provides the basic features of the collected data. The descriptive analysis is done to summarize the data (articles) in term of journals and conferences contributing towards the collected literature, timeline distribution, authorship, and geography. This will help the future researchers in the area to look forward to these journals for literature and publication. Timeline analysis of the data is expected to trace the chronological pattern of the growth of the research till date. Authorship data provides information whether the research in this area is pursued by individuals or through collaborative work with others. The geographical analysis will provide statistics of the areas (nations) which have contributed to the selected literature and the nations which have provided empirical studies.

2.4.1 Journals and Conferences

The analysis indicates that the 248 articles are from 91 peer-reviewed journals, 3 conference proceedings, and 4 organizational reports. The 17 journals have more than 3 articles as shown in Figure 2.2. The top four journals contributing to the literature are: ‘Journal of Cleaner Production (JCP)’, ‘International Journal of Production Research (IJPR), ‘International Journal of Production Economics (IJPE)’, and ‘Journal of Manufacturing Technology Management’. Figure 2.3 shows that the maximum number of articles are published in Elsevier, followed by Taylor & Francis, Emerald, and Springer.

2.4.2 Timeline Distribution

The timeline distribution of the articles considered in the SLR is shown in Figure 2.4. High growth of articles in 2010 and afterward is observed. This may be because Copenhagen declaration in 2009 acted as a stimulant for the researchers in this area.

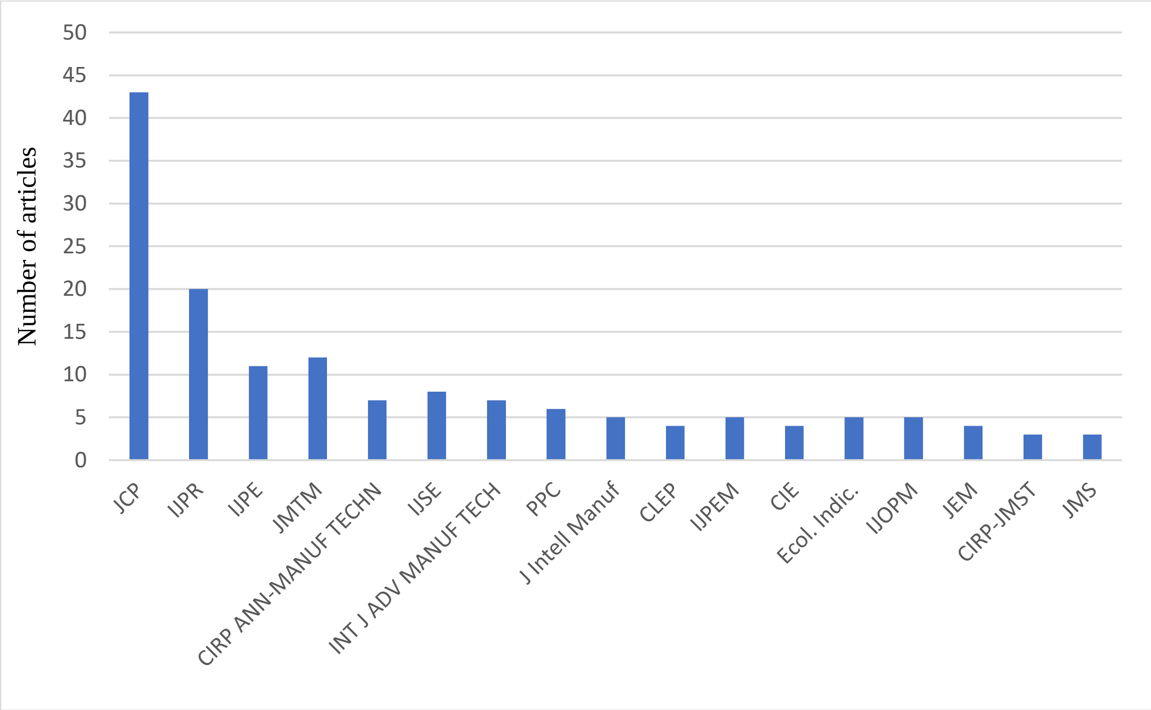


Figure 2.2 List of journals with three or more than three SLR articles

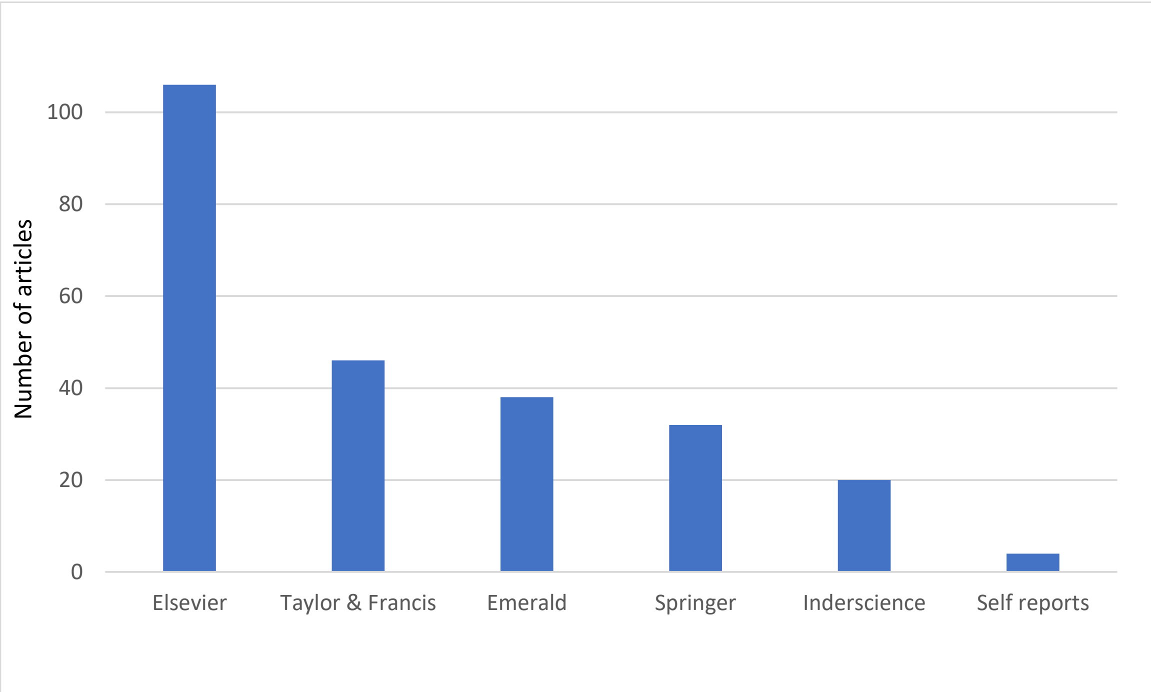


Figure 2.3 SLR articles by various databases

The number of articles is increasing year on year except for the year 2013 and 2017. The articles in 2018 are only upto February 2018.The decrease in number of articles in 2013 may be due to the Industry 4.0. This may be due to the initiation of Industry 4.0 concept in manufacturing after 2012. The focus of researcher may have shifter to integrate sustainability with industry 4.0 (Dubey *et al.*, 2016; Matsuda and Kimura, 2015).

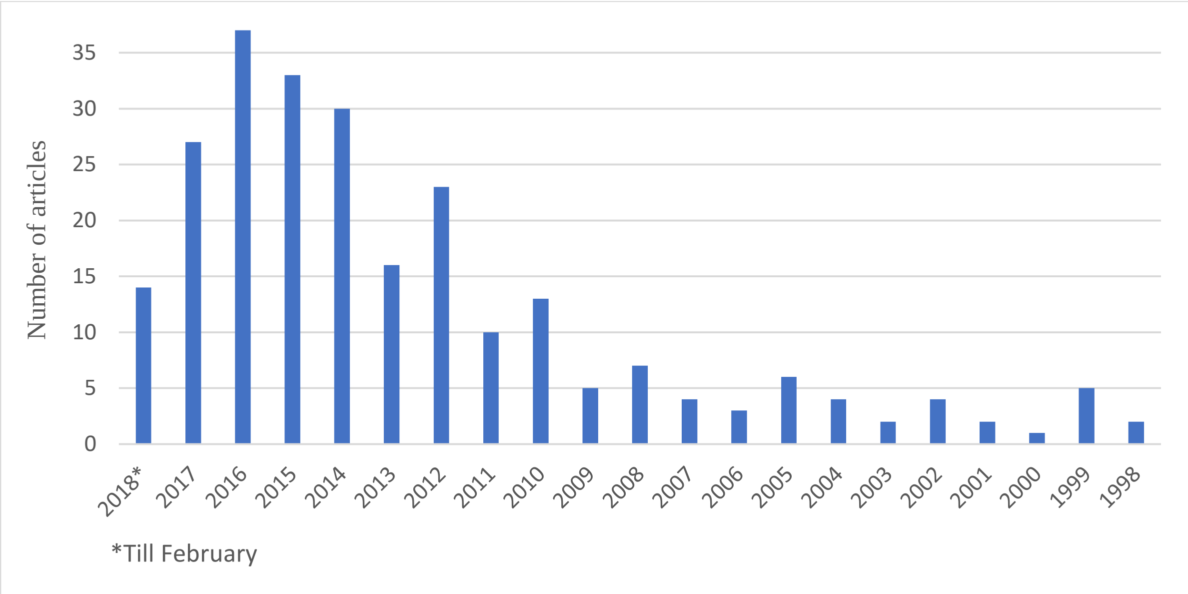


Figure 2.4 Timeline distribution of the SLR articles

2.4.3 Authorship

The authorship analysis gives an idea whether the research is done individually or in collaboration with others. 30 articles were authored by individuals, 73 by two researchers, 73 articles by three authors, 45 by four authors, and the remaining 27 articles have more than four authors. It is also observed that more than 87% of the articles have more than one authors and the collaboration is not only among academicians of the same institute/university but also among more than two institute/universities and nations. Approximately 27% of the articles have international collaborations. Jovane *et al.* (2008) have eight authors from seven countries, Valkokari *et al.* (2014) have eight authors from four countries, Chen *et al.* (2015) have six authors from four countries, and Dubey *et al.* (2016) have five authors from four countries. Sutherland *et al.* (2016) with 11 authors from three different countries and six different institute/universities have the highest number of authors. Out of 67 articles from international collaborations; 54 articles were published between 2012 and 2018. The analysis also reveals that the topic of manufacturing sustainability is pursued by academicians as well as practitioners. The average number of authors per article are three.

2.4.4 Geography

The geographical distribution of the reviewed literature is shown in Figures 2.5 & 2.6. The methodology used for this geographical distribution is – geographical location of the case organization else the country of the first author. This review covers articles from 33 different countries. It reveals that USA has contributed highest number of articles (54 articles) followed by India (49 articles), UK (24 articles), and China (15 articles). This representation along with the ranking of countries on the basis of a number of articles is shown on a global map (Figure 2.6) to show the penetration of the research on manufacturing sustainability. The Figure 2.6 is developed using (developed by using map customizer, 2016). The next section highlights the content analysis of the reviewed articles.

2.5 CONTENT ANALYSIS

This section presents the content evaluation of the reviewed literature in terms of levels of assessment, elements of assessment and types of research methodologies used in the research.

2.5.1 Levels of Assessment

The reviewed articles are divided into three phases as discussed earlier and shown in Figure 2.7. All articles are divided into three types depending upon the number of sustainability dimensions considered in the article:

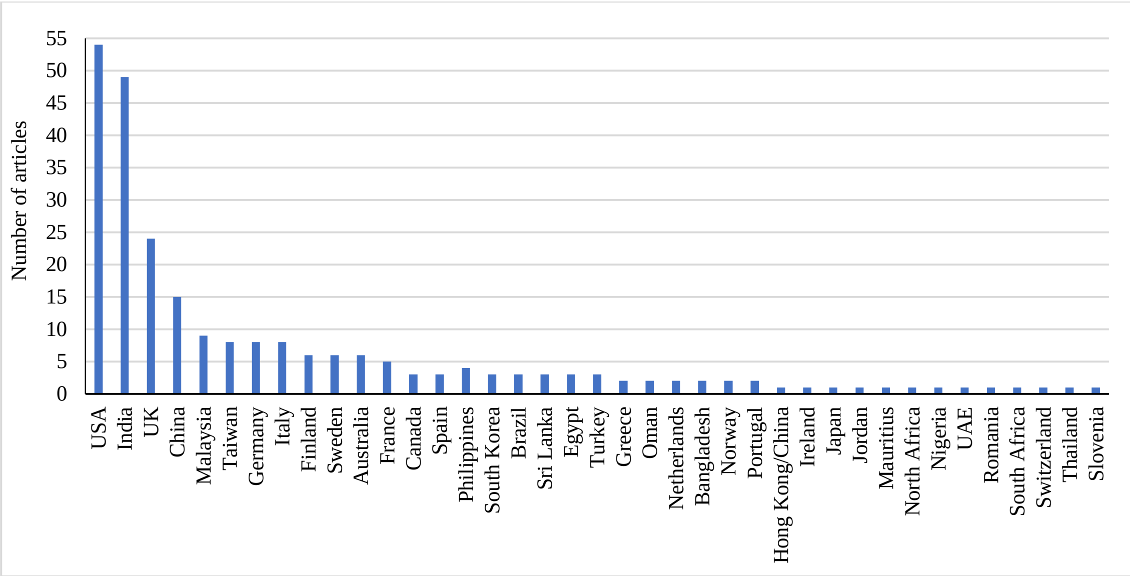


Figure 2.5 Geographical distribution of the SLR articles

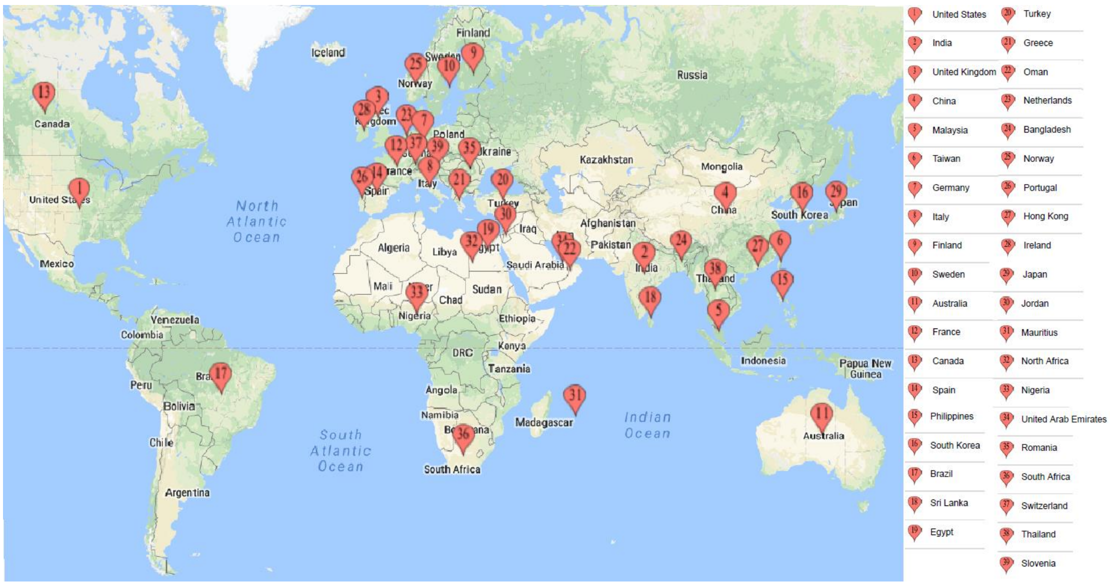


Figure 2.6 Representation of SLR articles on global map with rankings

- No assessment (N): conceptual theory building articles without sustainability assessment.
- Partial assessment (P): articles considering either one dimension or two dimensions of sustainability for the assessment.
- Full assessment (F) : articles considering all the three dimensions of sustainability for the assessment.

Most of the research does not consider the three sustainability dimensions for the assessment. Some articles (seven) in the last phase have taken all the three dimensions. Most of the researchers consider environmental assessment as sustainable assessment. The importance of the social sustainability dimensions in a manufacturing environment has been emphasized recently. Only a few articles have taken social sustainability. Even during the last phase (2012-2018) most of the articles (115 articles) are conceptual theory building or doing an assessment with one or two dimensions (58 articles) as shown in Figure 2.7.

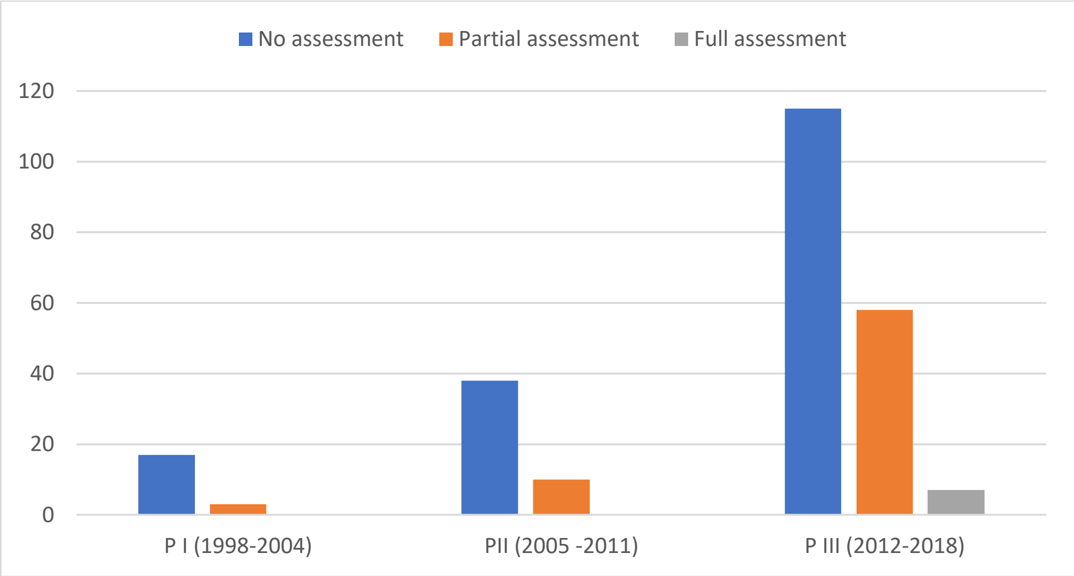


Figure 2.7 Phase wise distribution of articles based on levels of assessment

2.5.2 Elements of Sustainability

Manufacturing is an input-output process. It requires resources (tangible and non-tangible) to be converted into products for the customers. These products are then transported to the users (end user or intermediate user) to fulfill their requirements. The users use these products and dispose-off after the use. There are economic, environmental and social consequences of getting resources (pre-manufacturing), converting resources into products (manufacturing), transportation, use and dispose-off (post-manufacturing). The economic, environmental and social consequences of these activities depend on the organizational policies. Therefore, any pragmatic sustainability assessment must consider the product, process, policy, life cycle, and resources for the assessment. Figure 2.8 shows the phase-wise distribution of the articles based on these elements. It shows that the researchers are considering product and process for the assessment. However, many of the researchers have not yet started considering life cycle aspect of the product. There may be two reasons for this. One, it is difficult to get the data for the life cycle assessment. Two, the organizations may be doing sustainability trade-off and therefore do not want to consider the life cycle into the assessment. This is quite possible as in many developing countries the environmental laws are not stringent and organizations may outsource their dirty manufacturing (environmentally and socially harmful manufacturing activities) to the developing countries. These days, many of the organizations are considering sustainability as a core business objective and, therefore, have developed policies for sustainability improvement. The present study also strengthens the statement that the sustainability in manufacturing was introduced to conserve resources and make products greener.

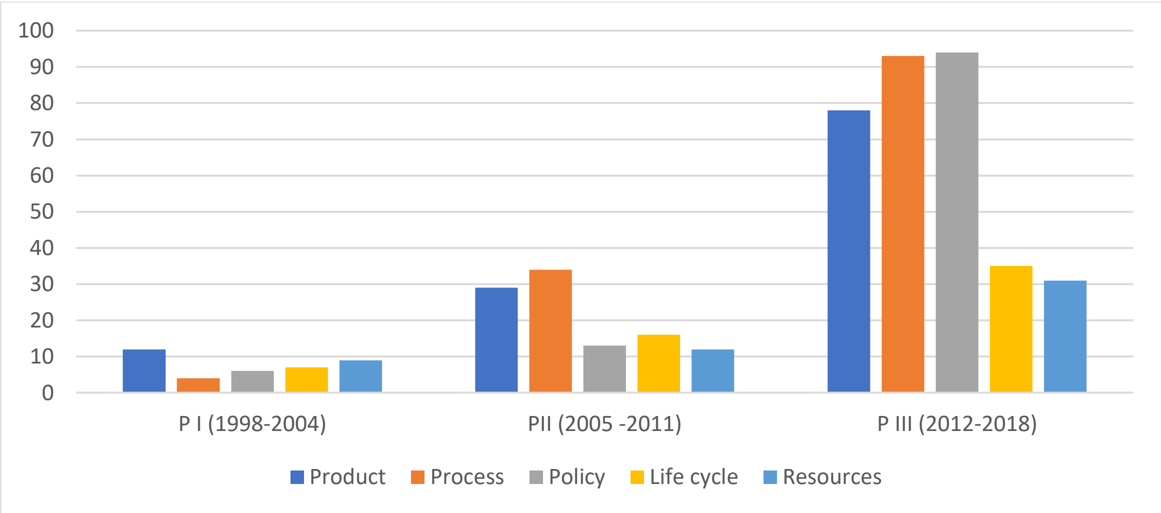


Figure 2.8 Phase wise distribution of SLR articles on the basis of sustainability elements

A maximum number of articles in the first phase 12 (out of 38) considered product and 9 (out of 38) considered resources (articles address at least three resources) in their research.

In contrast, only 9.5% of last phase articles have emphasized on resources. Table 2.3 provides an overview of main references, in which these elements/resources has been addressed for sustainability assessment and improvement.

The elements of sustainability identified from the review are verified for their reliability. The reliability can be checked by using various tools like Cronbach alpha, Fleiss Kappa, Cohen Kappa, etc. The present study uses the Cohen Kappa for inter-coder reliability measurement of the identified sustainability elements (product, process, policy, life cycle, and resources). The inter-coder reliability has been assessed using SPSS 20 (Statistical Package for the Social Sciences) software tool. The inter-coder reliability is a commonly used method for assessing the level of agreement in the contemporary research (Goyal and Chanda, 2017). Cohen Kappa assesses inter-coder reliability by the degree of consensus agreement. It is considered as a robust measure, due to its incorporation of inter-coder agreement even by coincidence (Cohen, 1960). If the value of Cohen Kappa is more than 0.4, it indicates fair to good agreement between the coders beyond chance (Cohen, 1960). The inter-coder reliability was checked for the identified elements and Cohen Kappa value was found to be 0.67 (at p=0.006). This shows that the identified elements are reliable measures of sustainability.

2.5.3 Research Methodologies Adopted in the Existing Literature

As expected, earlier research on the topic was conceptual even though in case, the aim of the research is green manufacturing or other similar aspects. During the early phase, most of the papers were conceptual papers with few review studies on environmental aspects of manufacturing, which was introduced earlier than sustainability.

Table 2.3 Main references related to identification of elements for manufacturing sustainability assessment

Manufacturing elements	Main references **(with keyword sustainability)**	Main references **(with keywords – GM, CM, ECM, ERM, and EBM)**
Product sustainability	Arivalagan and Sudhakar, 2005; Azapagic, 2004; Delai and Takahashi, 2011; Garetti and Taisch, 2012; Hong, 2012; Jasinski *et al.*, 2016; Jayal *et al.*, 2010; Joung *et al.*, 2013; Jovane *et al.*, 2008; Liyanage, 2007; Lu *et al.*, 2011; Mani *et al.*, 2014; Ocampo *et al.*, 2016; Seliger *et al.*, 2008; Veleva and Ellenbecker, 2001; Westkämper, 2000; Esfahbodi *et al.*, 2017; Garbie, 2017; Abdul-Rashid *et al.*, 2017a	Bras *et al.*, 2006; Digalwar *et al.*, 2013; Govindan *et al.*, 2015; Hrovatin *et al.*, 2016; Ilgin and Gupta, 2010; Manley *et al.*, 2008; Meng *et al.*, 2016; Rehman *et al.*, 2016; Sangwan, 2011; Zhu and Deshmukh, 2003
Process sustainability	Shields *et al.* 2002; Parthasarathy *et al.* 2005; Labuschagne and Brent 2005; Marksberry and Jawahir 2008; Hicks and Matthews 2010; Jain and Kibira 2010; Gunasekaran and Spalanzani 2012; Yuan *et al.* 2012; Liu and Huang 2013; Herrmann *et al.* 2014; Dornfeld 2014; Shao *et al.* 2017; Koho *et al.* 2015; R. Dubey *et al.* 2015; Egilmez *et al.* 2016; Mannan *et al.* 2016; Winroth *et al.* 2016; Dunuwila *et al.* 2018a; Katiyar *et al.* 2017; Li and Mathiyazhagan 2018	Gungor and Gupta 1999; Pineda-henson and Culaba 2004; Fei *et al.* 2005; Yan *et al.* 2007; Siniawski and Bowman 2009; Shang, Lu, and Li 2010; Kung, Huang, and Cheng 2012; Tsai *et al.* 2013; Chuang and Yang 2014; Moreira *et al.* 2015; Guo *et al.* 2015; Rehman *et al.*, 2015; Routroy and Kumar 2016
Sustainability Policies	Bhanot *et al.*, 2016b; Delai and Takahashi, 2011; Dubey *et al.*, 2015; Garbie, 2013; Gaughran *et al.*, 2007; Gunasekaran and Spalanzani, 2012; Hall and Howe, 2010; Hallstedt *et al.*, 2015; Jasinski *et al.*, 2016; Joung *et al.*, 2013; Labuschagne *et al.*, 2005; Mani *et al.*, 2016; Pham and Thomas, 2012; Seliger *et al.*, 2008; Shields *et al.*, 2002; Spangenberg and Bonniot, 1998; Spiegel *et al.*, 2015; Sureeyatanapas *et al.*, 2015; Sutherland *et al.*, 2016; Wang and Yang, 2015; Peruzzini and Pellicciari, 2017	Azzone and Noci, 1998; Chung and Wee, 2008; Curkovic, 2003; Dey and Cheffi, 2013; Digalwar *et al.*, 2013; Dubey and Ali, 2015; Gabaldón-estevan *et al.*, 2014; Govindan *et al.*, 2016b, 2014; Hong *et al.*, 2009; Hrovatin *et al.*, 2016; Hua *et al.*, 2005; Li *et al.*, 2010; Mittal and Sangwan, 2014c, 2013b; Orji and Wei, 2015; Rehman *et al.*, 2016, 2014; Sarkis, 1999; Taylor *et al.*, 2014; Yang *et al.*, 2012; Zhai *et al.*, 2014

Table 2.3 Main references related to identification of elements for manufacturing sustainability assessment (Contd.)

Resources	Adams and Ghaly, 2006; Araujo and Gomes De Oliveira, 2012; Azapagic, 2004; Basu and Kumar, 2004; Bilge *et al.*, 2016; D. Chen *et al.*, 2014; Delai and Takahashi, 2011; Faulkner and Badurdeen, 2014; Garbie, 2013; Gaughran *et al.*, 2007; Harik *et al.*, 2015; IChemE, 2002; Jayakrishna *et al.*, 2016; Joung *et al.*, 2013; Lee *et al.*, 2012; Ocampo *et al.*, 2016; Paju *et al.*, 2010; Spangenberg and Bonniot, 1998; Strezov *et al.*, 2013; UNCSD, 2007, 2001; Veleva and Ellenbecker, 2001; Ziout *et al.*, 2013; Madan Shankar *et al.*, 2017; Park and Kremer, 2017	Azzone and Noci, 1998; Deif, 2011; Dey and Cheffi, 2013; Durham, 2002; Fei *et al.*, 2005; Gabaldón-estevan *et al.*, 2014; Govindan *et al.*, 2015; Guo *et al.*, 2015; Gutowski *et al.*, 2005; Mittal and Sangwan, 2014a; Pineda-henson and Culaba, 2004; Pirraglia and Saloni, 2012; Rehman and Shrivastava, 2013; Sangwan and Mittal, 2015; Subaı *et al.*, 2006; Tsai *et al.*, 2011; Yan *et al.*, 2007
Life cycle	Araujo and Gomes De Oliveira, 2012; Bilge *et al.*, 2016; Eastwood and Haapala, 2015; Egilmez *et al.*, 2013; Ford and Despeisse, 2016; Garbie, 2014; Garetti and Taisch, 2012; Govindan *et al.*, 2016a; Jayakrishna *et al.*, 2016; Journeault, 2016; Jovane *et al.*, 2008; Kumaraguru *et al.*, 2014; Labuschagne and Brent, 2005; Lu *et al.*, 2011; Mani *et al.*, 2014; Rashid *et al.*, 2013; Searcy, 2011b; Sutherland *et al.*, 2016; Westkämper, 2000; Abdul-Rashid *et al.*, 2017a; Caldera *et al.*, 2018; Chan *et al.*, 2017; Dunuwila *et al.*, 2018b; Li and Mathiyazhagan, 2018; Moldavska and Welo, 2017	Azzone and Noci, 1998; Baresel-bofinger *et al.*, 2011; Barreto *et al.*, 2010; Bras *et al.*, 2006; Deif, 2011; Gutowski *et al.*, 2005; Ilgin *et al.*, 2015; Ilgin and Gupta, 2010; Kung *et al.*, 2012; Li *et al.*, 2010; Madu *et al.*, 2002; Moreira *et al.*, 2015; Orji and Wei, 2016; Minhaj A A Rehman and Shrivastava, 2013; Sangwan and Mittal, 2015; Shang *et al.*, 2010; Zhang, 1999; Zhu and Deshmukh, 2003

Next phase produced more case studies mainly aiming at environmental aspects in addition to conceptual papers. The last phase has conceptual articles, case studies and empirical studies, and few review articles as shown in Figure 2.9. Most of the case studies have applied tools or techniques in a practical situation to assess partial or full sustainability. The empirical studies have validated or/and compared the benefits, the status of implementation, drivers, and life cycle thinking, etc. in the area of sustainable manufacturing. Few of the empirical studies have compared the sustainable manufacturing implementation status of different countries.

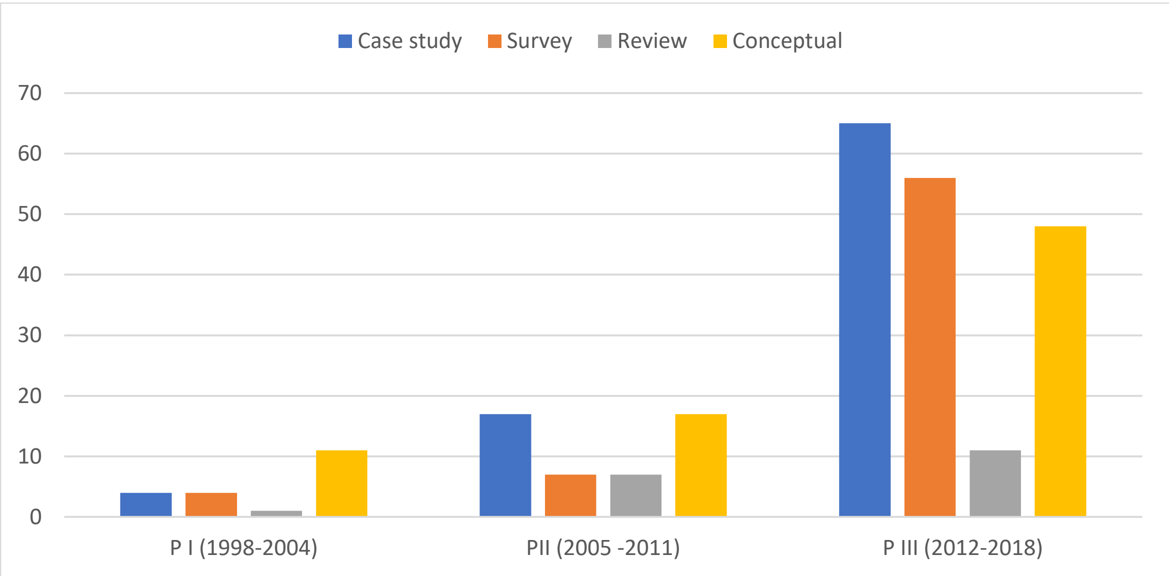


Figure 2.9 Classification of SLR articles on the basis of research methodologies used

2.6 CRITICAL OBSERVATIONS FROM SLR

Chronicle development of the literature is given in Table 2.4. Some of the critical observations from the review of the literature are:

- The research in manufacturing sustainability started with the aim of improving the material and energy utilization. However, many of the research articles do not focus on resource utilization improvement. Also, technical building services and human resources have not been researched from manufacturing sustainability perspective.

Further research in this area should focus on all the resources in an integrated way (throughout the supply chain).

- There is dire need to consider and develop indicators to measure the social and economic benefits of sustainable manufacturing. Manufacturing sustainability has qualitative and lagging economic indicators and is therefore difficult to measure. Further research is required to develop quantitative and easy to use (simple data acquisition) indicators particularly for social and economic dimensions.
- Few research articles support the inclusion of life cycle engineering for manufacturing sustainability. Meaningful manufacturing sustainability has to focus on the life cycle engineering otherwise the manufacturing sustainability can be easily traded off in the supply chain and unsustainable manufacturing can be outsourced to vendors in developing countries.
- Product life cycle, resources, product, process, and policy have not been integrated with sustainability indicators. Separate sustainability indicators should be developed to measure these elements so that the weak areas of sustainable performance can be easily identified and improved.

Resource consumptions by any manufacturing organizations mainly depends upon the products and processes. Therefore, product sustainability and process sustainability are two important aspects of sustainable manufacturing, which require policies to achieve sustainable development of manufacturing organizations. Lack of sustainability policies in an organization leads to poor decisions on product and process sustainability. Product sustainability, process sustainability, and sustainability policies should be combined together with resources across the product life cycle to achieve sustainability goals.

Table 2.4 Chronicle development of the literature on manufacturing sustainability

	Phase I (1998-2004)	Phase II (2005-2011)	Phase III (2012-2018)
Focus Area	Green product and resource utilization	Focus on product and process sustainability	Product and process sustainability focus with a significant gain in sustainability policy studies. Life cycle and resources gained importance
Type of studies	Origin of concept and theory building	Case studies and concept development. Few review studies approved	Case studies and concept development, empirical studies and review studies gained importance
Type of methodology	Mainly conceptual (no assessment)	Mainly conceptual and the start of environmental sustainability assessment	Mainly case studies and conceptual and the initiation of full sustainability assessment

2.7 SUMMARY

This chapter presents a systematic literature review of 248 articles addressing manufacturing sustainability. The descriptive and content analyses of the literature have been presented. The study has traced the growth of manufacturing sustainability literature in terms of levels of sustainability, elements of sustainability, types of research methodologies used, and focus areas. The main conclusions of the study can be summarized as:

- Most of the papers do not consider the three dimensions of sustainability simultaneously for sustainability assessment.
- All the resources used by the manufacturing organizations are not considered throughout pre-manufacturing, manufacturing, and post-manufacturing activities for sustainability assessment.
- Lack of social sustainability indicators from manufacturing perspective.

- Lack of manufacturing sustainability framework which considers the elements of manufacturing sustainability throughout the supply chain.
- Product sustainability, process sustainability, sustainability policies have not been considered simultaneously.
- The latest research articles (from last 2-3 years), mainly focus on assessing sustainable manufacturing practices and their influence on manufacturing organizations.

CHAPTER 3

DEVELOPMENT OF A CONCEPTUAL FRAMEWORK FOR SUSTAINABILITY ASSESSMENT

Existing sustainability frameworks are reviewed in this chapter to identify their characteristics. A conceptual framework is proposed for the assessment of sustainability of manufacturing organizations taking into consideration the strengths and weaknesses of the existing frameworks.

3.1 INTRODUCTION

It has been observed that all types of organizations, including non-profit organizations, public and private sector organizations try to overexploit the natural resources in the name of competitiveness, productivity, quality, or service. The sustainability concept has been accepted as a topic of mutual interest and often an essential part of man-made activities, yet there is little guidance about its practical implementation. In fact, sustainability is a highly complex issue with many dimensions and its implementation is highly challenging; requiring the attention of engineering community, social scientists, government officials, and political leadership. Sustainability assessment has been a core issue of ambiguity and many organizations use or misuse different indicators as per their suitability. However, it is certain, that more and more organizations are implementing various strategies and best practices for making their businesses bearable, equitable and viable.

In the year 1987, Brundtland commission defined sustainable development as: development that fulfills the needs of the current generation without compromising needs of the future generation (WCED, 1987). In the ensuing years, more than 100 definitions of sustainability have appeared (Lee and Lee, 2014). Sustainability has also been used as business sustainability, corporate sustainability or industrial sustainability. These definitions may differ in detail but all agree that sustainability aims at satisfying economic, social and environmental goals (Labuschagne *et al.*, 2005; MSA, 2008). It has been found that there is a lot of ambiguity in the use of these definitions. Sustainable manufacturing must be defined in a simple and general way as designing, manufacturing, delivering, and disposing of products that generate least negative impact on society and environment and are economically viable throughout their life cycle. This definition is used throughout the thesis to define the scope of sustainability in a manufacturing environment. The major problem with the sustainable manufacturing is sustainability assessment and the major problems with sustainability assessment are: (i) Who should assess sustainability? (external assessment or internal assessment) (ii) Which departments in the organization are responsible to capture the data for the assessment and in which format? (iii) Do the organizations have some pre-requisite before implementing sustainability improvement initiatives? Sustainability issues in the manufacturing environment have been addressed by the organizations primarily because of the external pressure from legislation (Mittal and Sangwan, 2014a). It is still the main driver for sustainability improvement initiatives in developing/emerging economies. The other important driver for sustainability initiatives in developing/emerging economies is supply chain pressure as a large percentage of their production consists of parts to be exported to developed countries. However, legislation and competitiveness are the major drivers for sustainability initiatives in developed countries (Mittal and Sangwan, 2014b).

Some of the existing assessment frameworks are exhaustive and complex demanding for rigorous quantitative data which might be challenging to assess. Furthermore, the information captured from the internal data (which is generally retrieved from the performance measurement systems) may be ill-fitted or inadequate for the external assessment. Governments require huge infrastructure, in term of manpower, money, and technology, to assess the sustainability of the organizations on a continuous basis. The better way to assess sustainability seems to be the internal assessment by the organizations on a set of standard metrics for which the data retrieval should be easy. Many organizations have reported that the sustainability improvement initiatives were short-lived in their organizations because the implementation is not linked to productivity and quality improvement techniques like TPM, TQM, JIT, lean, six-sigma, etc. and secondly data required for sustainability assessment is multi-faceted and the organizations were not prepared to capture and share the data in the required format. The sustainability improvement requires a cultural shift for which the organization should assess the readiness of people and adequacy of existing philosophies. Recently, Sutherland *et al.* (2016), also emphasized the lack of social indicators along manufacturing supply chains and highlighted the existence of challenges to internalize and operationalise societal sustainability, specifically in the manufacturing domain. Therefore, it is important for the adoptability of the sustainability frameworks that these frameworks should have indicators which are easy to understand and the data required to compute these indicators should be easily available to the internal people. Moreover, the KPIs should address the whole product life cycle (integrated supply chain) as well as the three dimensions of sustainability. No attempt has been made to assess the manufacturing sustainability through the integrated resource consumption along the product and process life cycle (integrated supply chain). This chapter proposes a sustainability assessment framework which provides the guidance strategies to the evaluators to improve sustainability in a manufacturing domain. Another uncharted area in sustainability assessment is readiness assessment of the organizations to assess their sustainability level. If the organizations are not capturing the data, required for sustainability assessment, through their performance measurement systems then it becomes preemptive to sustainability evaluation. Under such circumstances the employees have to spend a lot of their time, energy and efforts for data computation and the practice become unsustainable. Contrary to this, if the organizations are made ready for the sustainability assessment by easy and sustained efforts through the existing performance measurement systems then there are more chances that the sustainability assessment will be easier and sustained and employees can be engaged for sustainability improvement strategies. The organizational changes are must to achieve sustainability improvement. This view has also been endorsed by Lozano *et al.* (2016) while elucidating the relationship between sustainability reporting and organizational change management for sustainability.

This chapter proposes a conceptual framework for the assessment of manufacturing sustainability in the organizations along the integrated supply chain. A review of existing 23 frameworks has been done to understand the strengths and weaknesses of the current frameworks to leverage the strengths and mitigate the weaknesses in the proposed framework.

3.2 REVIEW OF SUSTAINABILITY ASSESSMENT FRAMEWORKS

23 frameworks, based on their suitability to the manufacturing environment and overall synergy with the aim of the study, are selected for the review. This section discusses these 23 frameworks to get an insight of the frameworks.

3.2.1 **Global Reporting Initiative (GRI) Framework** [GRI Guidelines, 2011; GRI Guidelines, 2015]

The GRI guidelines were first published in 2000 with an aim to assist organizations in preparing sustainability reports that put together social, economic and environmental aspects of the business. It is a hierarchically structured framework based on the three core aspects of sustainability as shown in Figure 3.1. The main aim of GRI framework is to enhance the quality, rigor, and utility of sustainability reporting for the whole organization. Organizations are required to provide organizational profile and structure. GRI guidelines contain 84 indicators of the economic, environmental and social aspects.

The guidelines suggest the indicators to be considered at different levels of hierarchy (i.e. project level or shop-floor level). Some of the indicators are difficult to evaluate. For example, ‘no. of IUCN red list species and national conservation list species with habitats in areas affected by operations’. Organizations can’t collect this information directly and are dependent upon multiple government agencies. Moreover, the list also depends on other organizations working in the area. Various GRI indicators are challenging to assess and a little direction is provided to the organizations on the selection of indicators (Adams and Ghaly, 2006). This framework is only a reporting mechanism and no guidelines are provided for sustainability innovation. The latest version of Global Reporting Initiative (2015) (version 4) has added 14 indicators, deleted six indicators, and amended 12 indicators to reflect supplier environmental assessment and ISO 14064 standards for greenhouse gas emissions.

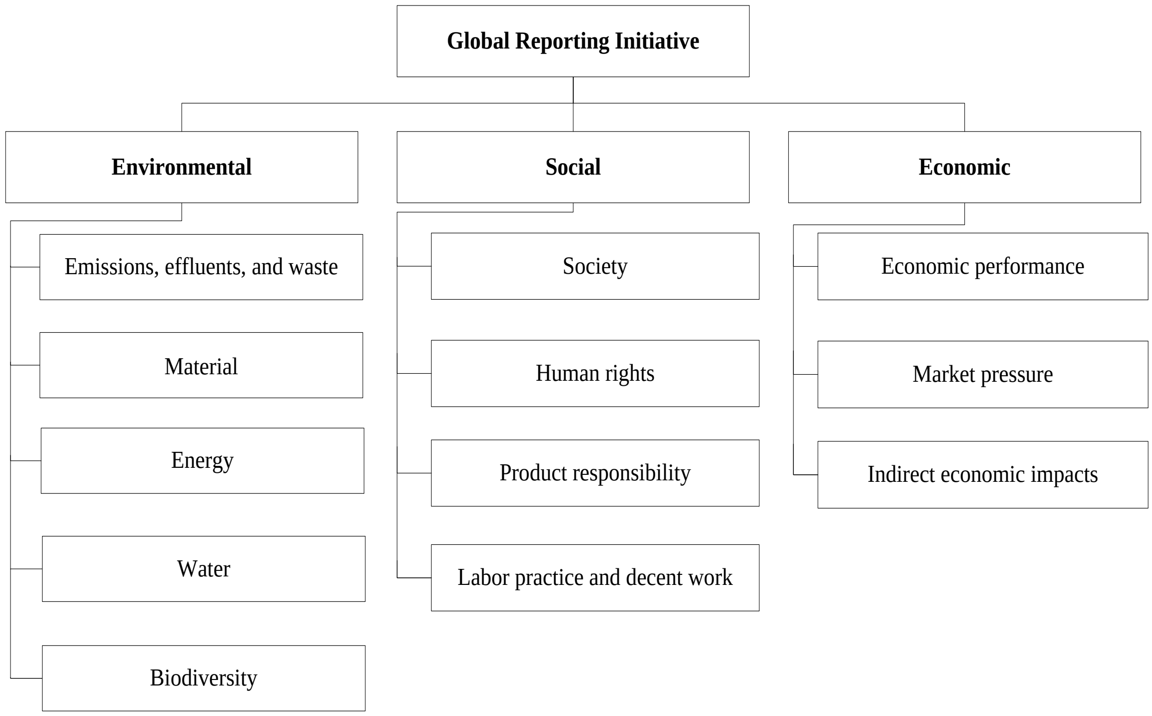


Figure 3.1. GRI Framework (Source: GRI Guidelines, 2011)

3.2.2 The Reference Model For Proactive Action (RMfPA) for Competitive Sustainable Manufacturing (CSM) (Jovane *et al.*, 2008)

This is a reference model for proactive action for competitive sustainable manufacturing. This model consists of environmental, economic, societal, and technological issues in the product, process, and innovation. The schematic diagram of the reference model for proactive action is shown in Figure 3.2. The key challenges for sustainability are globalization, climate change, public health, an aging population, loss of biodiversity, poverty and social exclusion, transport congestion, and soil and declining fertility.

The model recommends various methods, tools, and technologies for sustainability. The model relates sustainability and its importance at the global level. The study also discusses, briefly, the role of International Academy for Production Engineering (CIRP) research community towards sustainability and production.

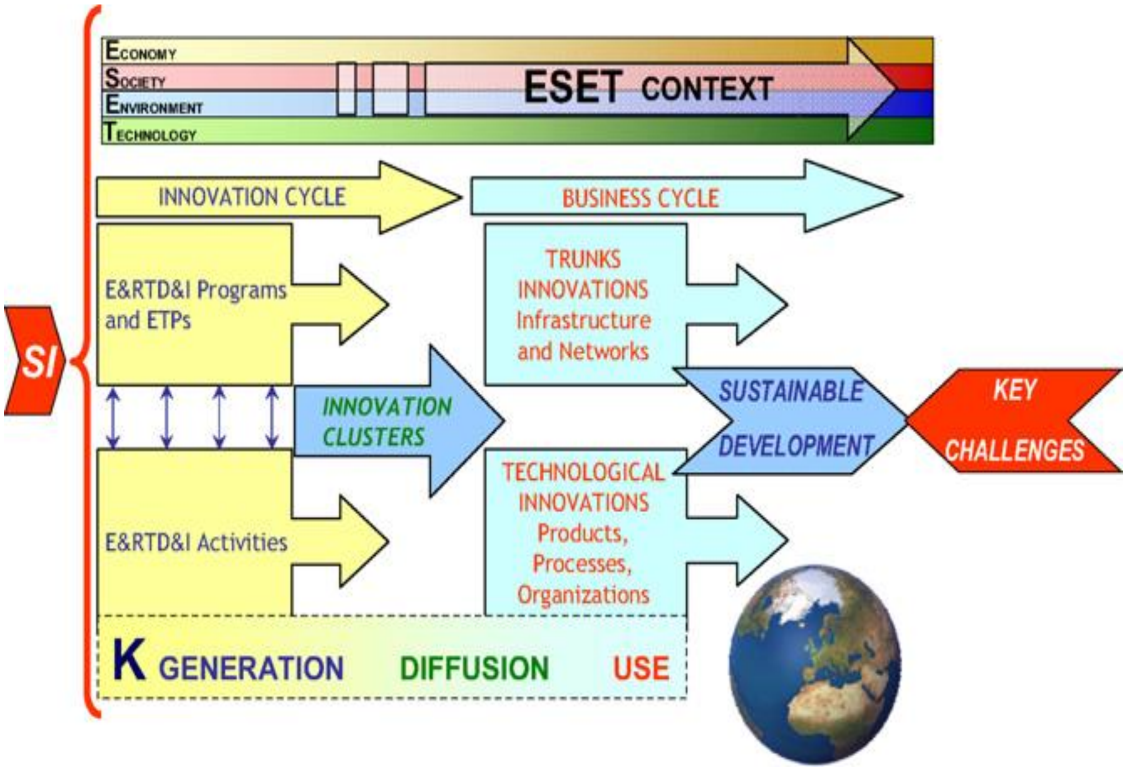


Figure 3.2 The proposed reference model for proactive action to pursue CSM (Source: Jovane *et al.*, 2008)

3.2.3 Wuppertal Sustainability Indicator Framework (Spangenberg and Bonniot, 1998)

Wuppertal Institute presented a four-dimension framework – economic, environmental, social, and institutional – as per the UNCSD framework. This framework provides interlinkage indicators among these four dimensions as shown in Figure 3.3. This framework can be used at the macro (industry) as well micro (project) levels (Labuschagne *et al.*, 2005). A framework aims at improving the energy and resource consumption relationship with the social condition by allowing the integration of technical innovation (Kuhndt *et al.*, 2002). Human development index (HDI) is adapted from United Nations Development Programme (UNDP) to develop a corporate human development index.

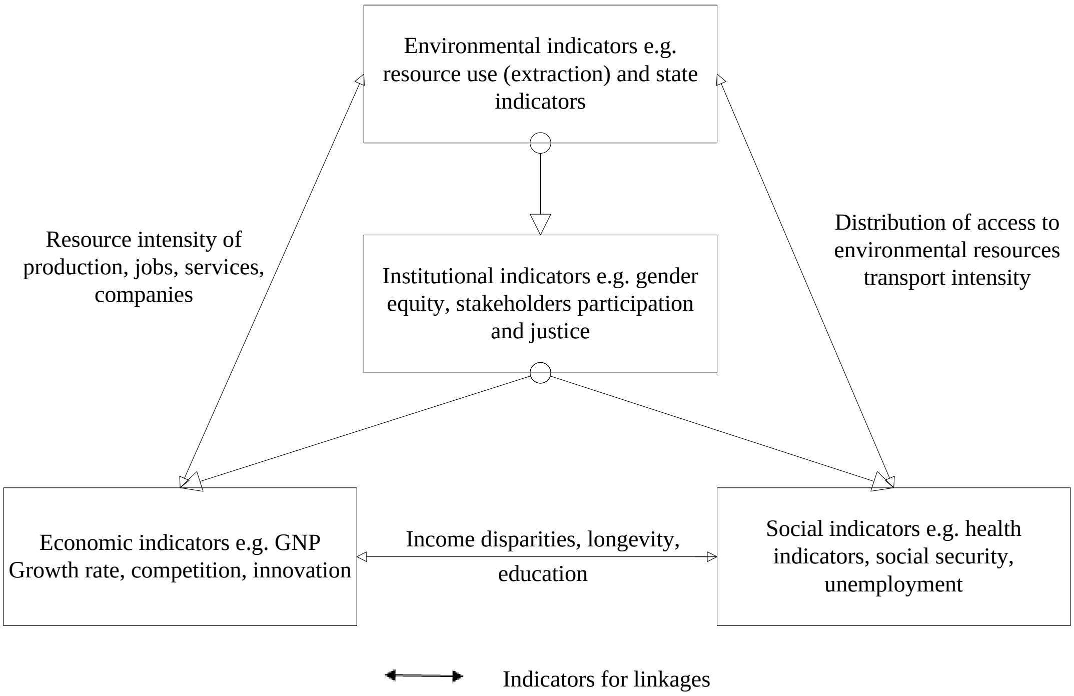


Figure 3.3 Wuppertal framework (Source: Spangenberg and Bonniot, 1998)

3.2.4 Labuschagne *et al.* Framework (Labuschagne *et al.*, 2005)

This framework was proposed to assess the sustainability of operations, projects, technologies, and overall sustainability of organizations in the manufacturing sector. However, this framework is more suitable to evaluate the sustainability at operational level. The indicators used in this framework provide the foundation for companies to report sustainability (Adams and Ghaly, 2006). This framework considers institutional sustainability (Figure 3.4) as a prerequisite for the sustainability. It is good to have institutional framework and capacity defined earlier as a prerequisite for sustainable operations assessment of an organization. Some researchers (Rauch and Newman, 2009) (Ivar Stål, 2015) feel that this framework does not provide customary end-of-pipe solutions. It only provides broad deliberations about resources and energy efficiency.

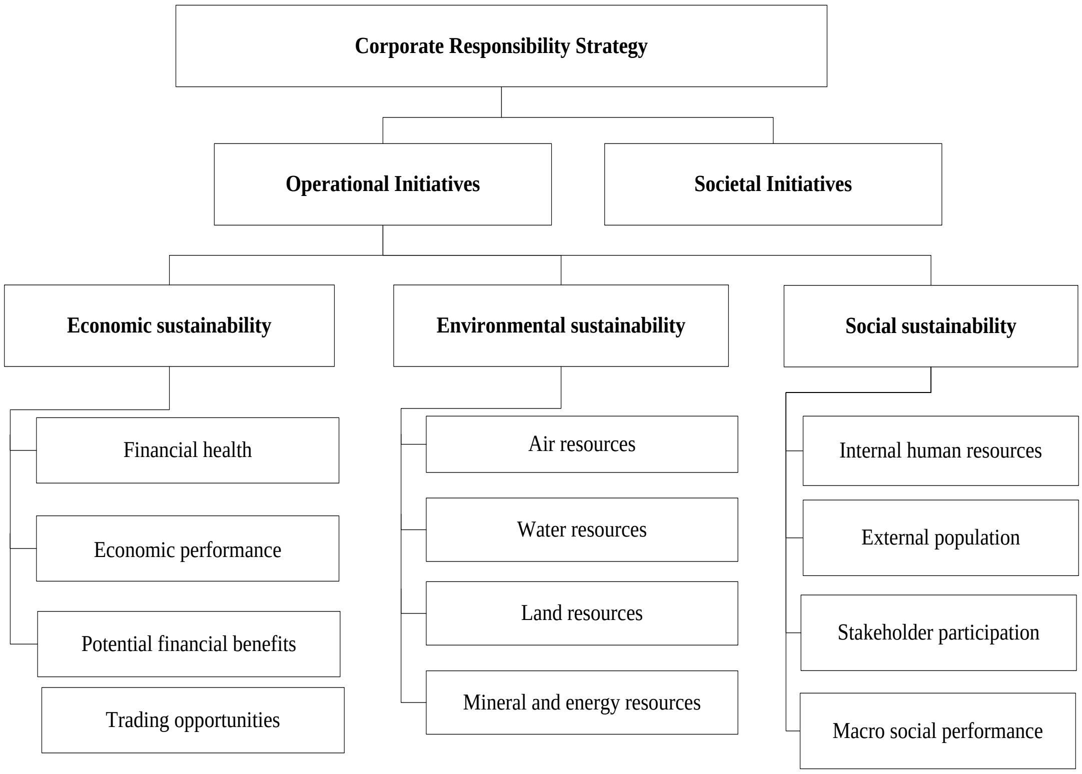


Figure 3.4 Labuschagne *et al.* framework (Source: Labuschagne *et al.*, 2005)

3.2.5 **Lowell Center for Sustainable Production (LCSP) Framework** (Veleva and Ellenbecker, 2001)

The LCSP framework is oriented towards health, safety and environmental aspects of sustainable production. It is a five-level framework with separate indicators for each level as shown in Figure 3.5. It highlights six aspects of sustainable production – natural environment, material and energy use, economic performance, workers, social justice and community development, and products. This framework provides flexibility to industry to develop their own indicators and also encourages participation of both workers and managers in indicator development. The framework is more inclined towards environmental sustainability and intended to provide an end-of-pipe solution. This framework lacks new innovations in sustainability indicators (Adams and Ghaly, 2006). Indicators belonging to level five are difficult to use or implement. This framework was intended to be implemented in large organizations. It proposes qualitative and quantitative indicators but does not provide guidelines for the selection of the indicators.

3.2.6 Indicator Framework for Sustainable Manufacturing (Joung *et al.*, 2013)

The framework represents a conceptual idea of sustainability assessment indicators. This framework suggests a set of sustainability indicators suitable for manufacturing. The study reviewed eleven models and frameworks that are publicly available. The framework provides evaluation and classification criteria for indicators. The proposed set of indicators contains 'technology advancement' and 'performance measurement' indicators in addition to the traditional social, economic and environmental indicators as shown in Figure 3.6. The study aims to establish an integrated repository of sustainability indicators to enhance the knowledge of contemporary indicators and sustainability measures.

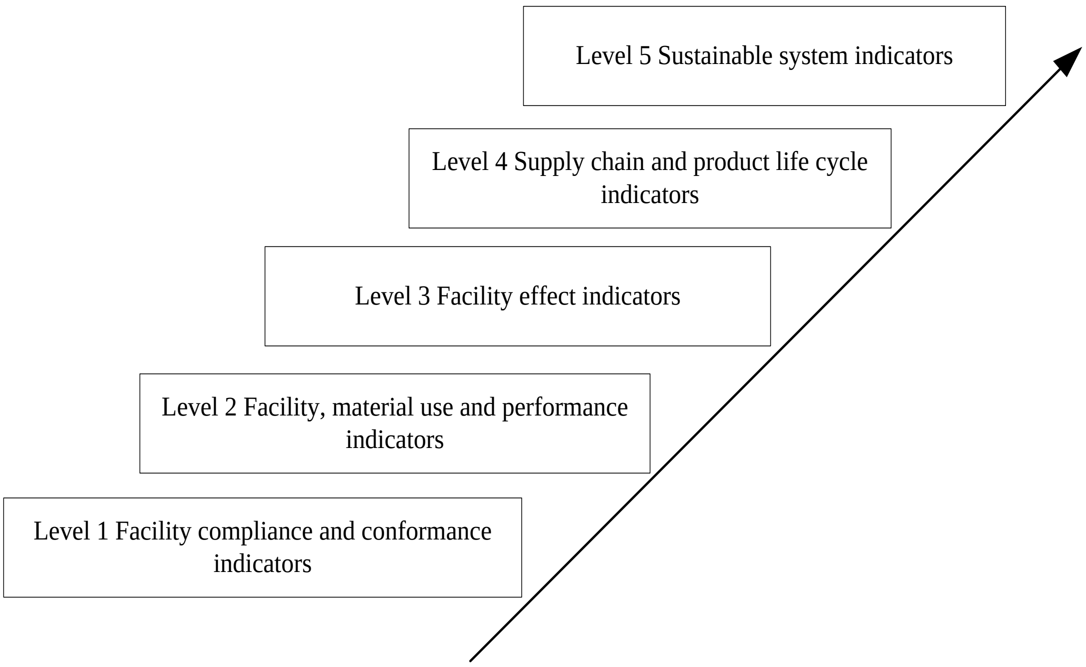


Figure 3.5 LCPS framework (Source: Veleva and Ellenbecker, 2001)

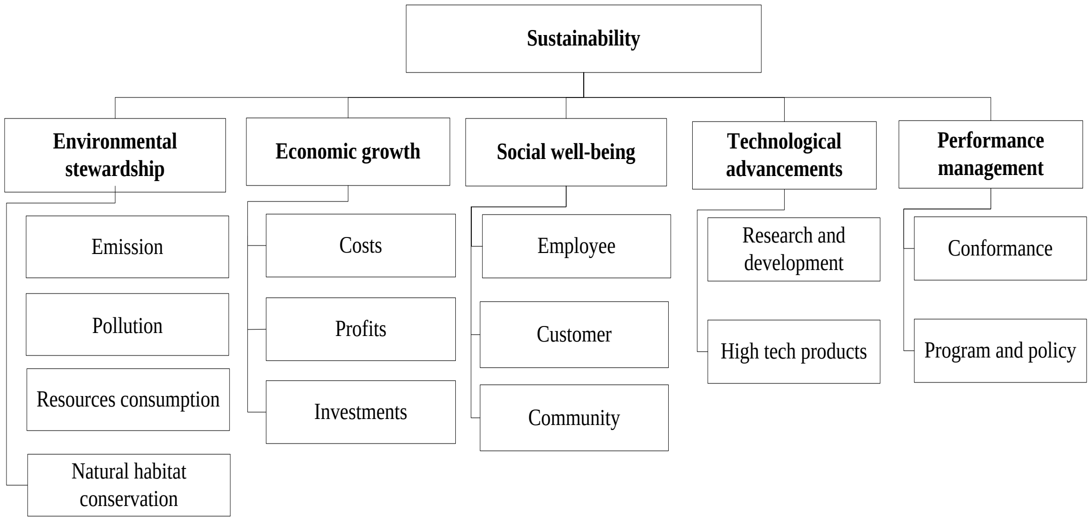


Figure 3.6 Framework of indicators for sustainable manufacturing (Source: Joung *et al.*, 2013)

3.2.7 Product, Process, and System Level Indicators for Sustainable Manufacturing (Jayal *et al.*, 2010)

This article aims at addressing sustainability in the manufacturing industry, including supply chain and product life cycle. The study provides model, metrics and optimization techniques at the product, process and system levels. The main focus of the model is manufacturing process and provides product evaluation during life cycle phases for dry, near dry and cryogenic machining. Six factors – environmental friendliness, machining cost, power consumption, waste management, operational safety, and personnel health – have been proposed to evaluate the sustainable machining. The framework also provides the relationship between the 6R and the supply chain to achieve the closed loop flow for sustainability. The study critically analyses the interrelationship of product sustainability in terms of triple bottom line and life cycle stages.

3.2.8 Framework for Sustainable Development Indicators for Mining and Minerals Industry (Azapagic, 2004)

This framework aims at developing the indicators for industrial minerals, metallic, and construction industry. This framework consists of social, economic, environmental, and integrated indicators. It discusses the stakeholders and issues relevant to different industries for the development of the indicators. It also favors the inclusion of life cycle stages of mineral production for the sustainability assessment. The proposed indicators include GRI indicators and few new indicators. This work is not aimed to assess the sustainability of small industries. This work is limited to triple bottom line sustainability. Further, it does not include guidelines or methodology for implementation.

3.2.9 World Class Sustainable Manufacturing Framework (Dubey *et al.*, 2015)

This framework divides sustainable manufacturing practices into two parts – hard practices and soft practices. The framework uses institutional theory, behavioral theory, relationship with the supplier, RMS (reconfigurable manufacturing system), and manufacturing strategies for the evaluation of environmental, social, and economic performance. Size of the organization and time have been used as control variables to account for differences amongst organizations as shown in Figure 3.7. The framework also provides the mediating influences of regulatory pressure, leadership, employee involvement, supplier relationship management, reconfigurable manufacturing, agile manufacturing, and lean production on the three dimensions of sustainability.

3.2.10 UN Commission on Sustainable Development framework (UNCSD, 2001; UNCSD, 2007)

United Nations Council on sustainable development (SD) approved a programme to work on indicators of SD after the call of Agenda 21. Many governments, international organizations, academic institutions, non-governmental organizations, and individual experts worked to develop this framework to measure sustainable development at national level.

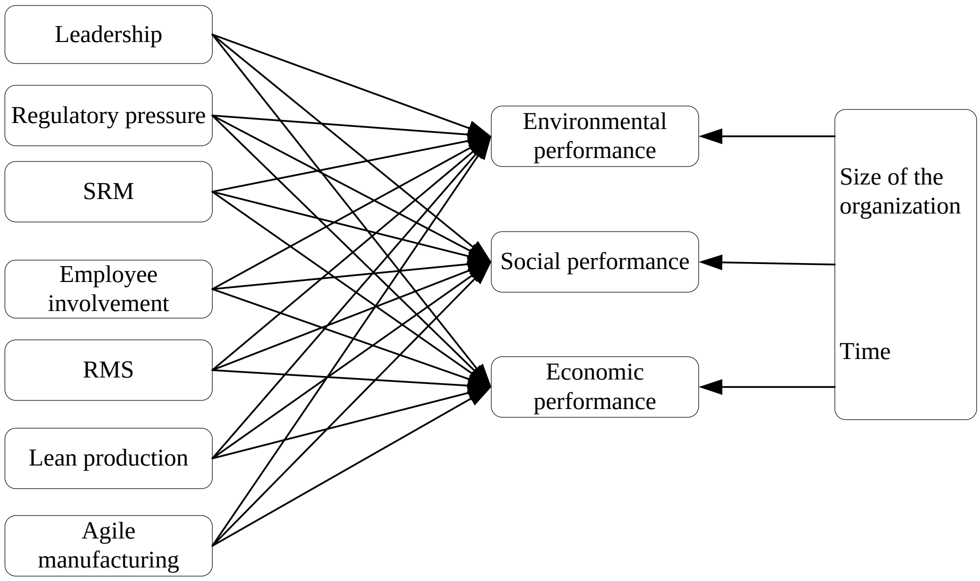


Figure 3.7 World class sustainable manufacturing framework (Source: Dubey *et al.*, 2015)

The aim of this framework is to offer indicators with definitions and explanations to decision makers for national capacity building and training programs. It adjoins institutional aspect to the triple bottom line aspects of sustainability, primarily to assess the "capacity building" at the national level, as shown in Figure 3.8. This framework evaluates the sustainability of government progress (Adams and Ghaly, 2006). This framework uses 38 sub-indicators under 15 main indicators. It has been developed, on the basis of a pressure state response (PSR) methodology, which incorporates only the linear relationship found in a system and neglects the interdependencies between the casual relationships (Spangenberg, 2002).

This framework has limited applicability at company and project levels but somehow provides direction to the organizations to orient their sustainability improvement efforts to amalgamate at the national level. A new version of this framework has been published online in 2007 (UNCSD, 2007). The main amendment found in this version is that the newer one does not categorize the themes according to the three dimensions of sustainability.

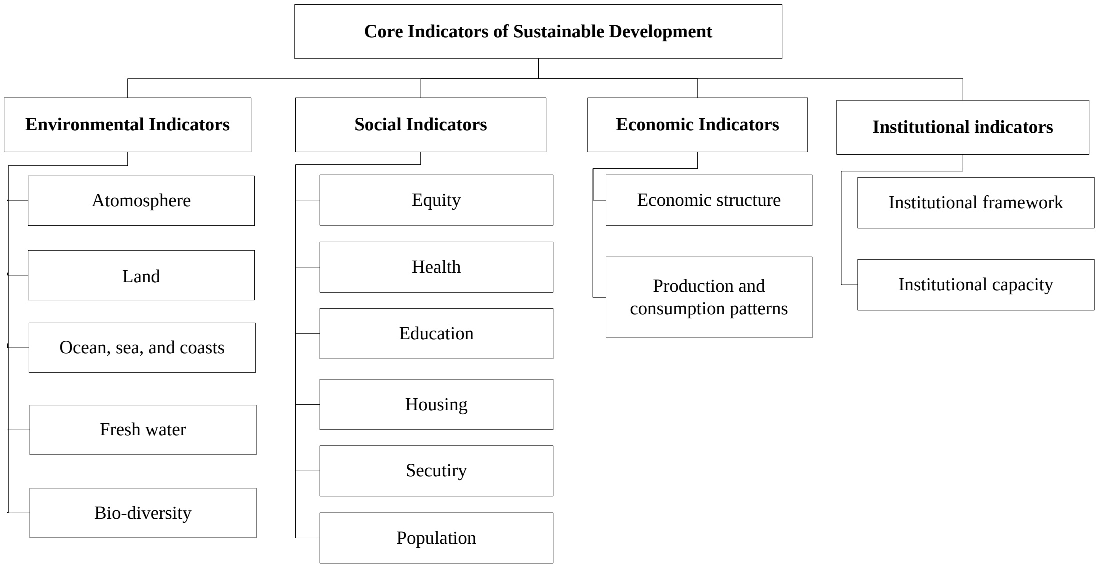


Figure 3.8 UNCSD Framework (Source: UNCSD, 2001)

It is also found that some of the themes, sub-themes, and indicators are modified or replaced. The modified themes are poverty instead of equity, whereas housing, security, population, institutional framework, and institutional capacity are replaced with four new themes: governance, demographics, natural hazards, and global economic partnership. The remaining themes are kept as it is. It is observed that the earlier version of the framework was more organized to address the sustainable development across the three dimensions of sustainability. The newer version of the framework is more influenced with MDG project (millennium development goals) of United Nations (United Nations, 2006), in which the main aim is to address the poverty, education, gender equality, child mortality, diseases, environmental sustainability, and global partnership. The latest version in this sequence addressed the three aspects people, planet, and prosperity with the main aim towards eradication of poverty globally (UN, 2015).

3.2.11 IChemE Framework (IChemE, 2002)

This framework is suggested by Institution of Chemical Engineers in 2002 and it is oriented towards the measurement of sustainability in process industry (Figure 3.9). This framework provides measurable indicators to enable the organizations to assess and set targets towards sustainability improvement. This framework aims to encourage the organizations to report their progress to show their pledge towards sustainability. This framework is profoundly focused towards environmental sustainability (Adams and Ghaly, 2006). It uses one-dimension and does not incorporate system interdependencies (Sikdar, 2003). It is an impact-oriented simple framework (Labuschagne *et al.*, 2005; Delai and Takahashi, 2011).

3.2.12 Performance Management Framework for Sustainability in Mining and Mineral Industry (Basu and Kumar, 2004)

The framework is proposed with an emphasis towards the new innovation and technology, to address the needs for innovation and technology in mines and mineral industry as shown in Figure 3.10. The framework defines sustainability with emphasis on engineering design. This framework focuses on innovation, technology, and governance to enable sustainability performance at sites.

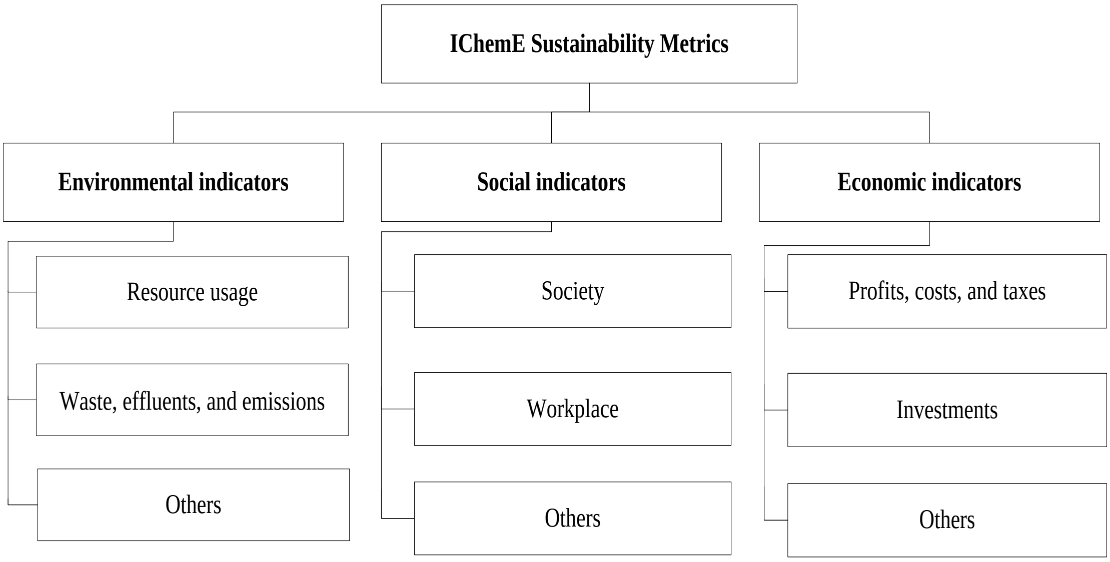


Figure 3.9 IChemE Framework (Source: IChemE, 2002)

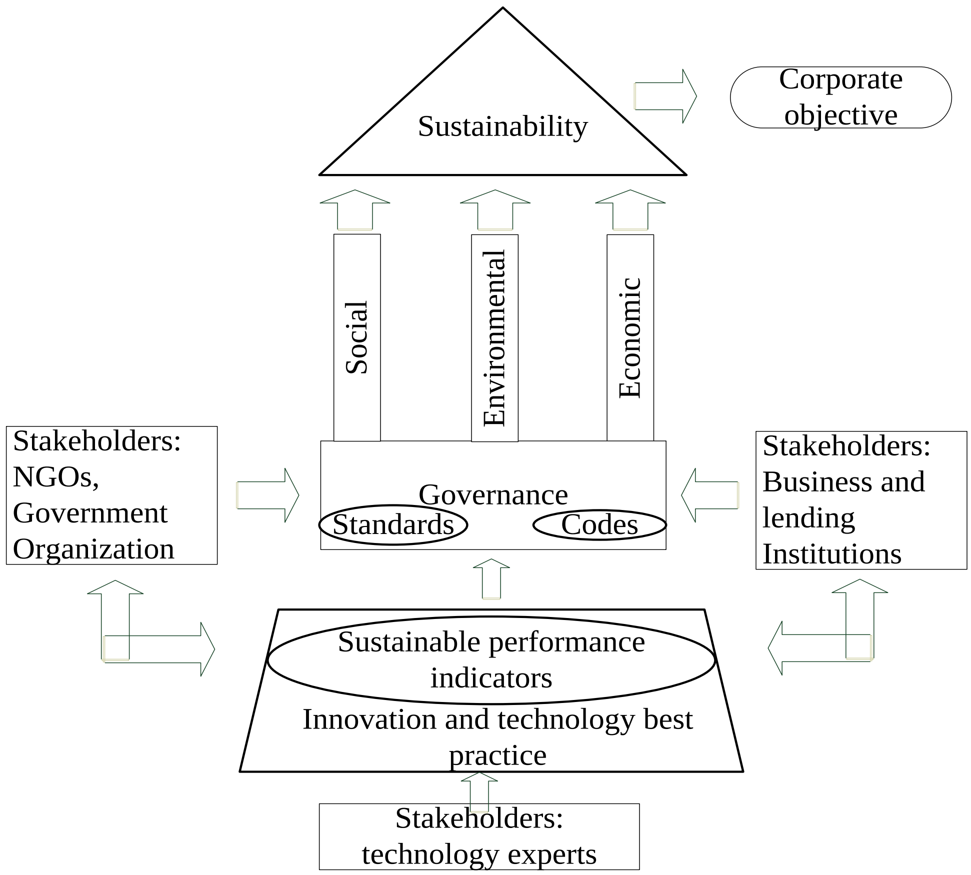


Figure 3.10 sustainability performance management frameworks for mining and mineral industry (source: Basu & Kumar, 2004)

It is a conceptual framework in nature and defines foundation to support sustainability goals (Fonseca *et al.*, 2013). According to Fonseca (2010), this framework considers integration as well as stakeholder engagement for sustainability in mines and mineral industry. Economy, health, and safety are taken as major drivers for technology. It discusses the sustainability indexes with an emphasis on information sharing for the sustainability. It opines that sustainability performance management is a road towards corporate sustainability.

3.2.13 Integral Framework for Sustainability Assessment (Adams and Ghaly, 2006)

This framework is developed for sustainability assessment of Costa Rican Coffee industry. The framework first highlights the issue of sustainability and then discusses the current sustainability of the industrial system by reviewing and evaluating the current frameworks on sustainability. The framework integrates the idea of industrial ecology, cleaner production, environmental management system, and social justice. A five-step methodology – industry-specific data collection, stakeholder communication and input, analysis of other relevant frameworks, prepare indicators set, and measure and analysis the data – has been developed for the evaluation of the Costa Rican coffee industry. The framework is based on the hypothesis that macro system sustainability (national/global) can only be achieved if the micro and meso systems within it are also sustainable.

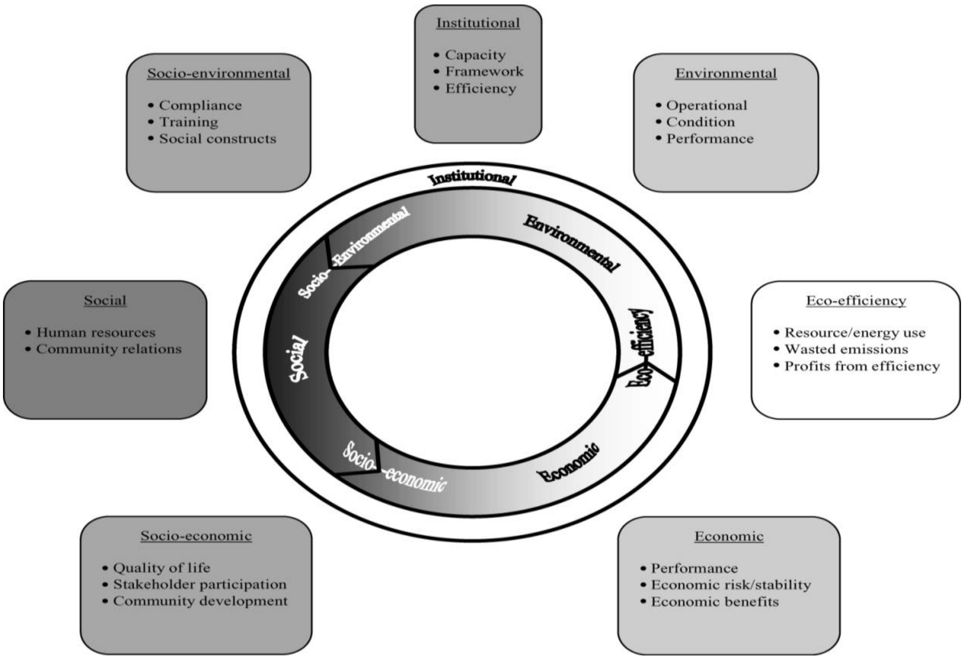


Figure 3.11 framework for sustainability assessment in Costa Rican industry (Source: Adams and Ghaly, 2006)

This study suggests a multi-dimensional consideration of sustainability including economic, social, environmental, socio-economic, socio-environmental, eco-efficiency, and institutional indicators. These seven different dimensions of the framework create an overlap in the indicators as shown in Figure 3.11. Stakeholder participation has been observed as an important aspect of sustainability. It indicates that the eco-efficiency can be a major aspect to develop employment and economic returns that can benefit the regional system through value addition (Adams, 2006).

3.2.14 Sustainability Measurement System Reference Model (Delai and Takahashi, 2011)

A reference model to integrate corporate sustainability measurement of organizations with the current performance measurement systems. According to Aida and Abdul (2015), indicators of sustainability can be developed through various methods and these methods change with the business process. The study attempts to address the corporate sustainability of business enterprises and it provides a schematic idea for the development of the sustainability indicators. Initially, eight well-known performance measurement systems were reviewed and the strengths of these systems have been incorporated into the model development. The developed model describes four steps – a starting point, content, process, the capacity of continuous sustainability assessment. Each step is delineated at abstraction level to understand the construct 'who', and 'how' indicators and performance measures should be selected and measured. The study argues that sustainability measurement can be a driving force for process selection and decision making (Salvado *et al.*, 2015). Performance measures used in the study are mainly oriented for corporate sustainability assessment.

3.2.15 Dow Jones Sustainability World Index (DJSI) (DJSI, 2011)

The objective of DJSI is to monitor the performance of the organizations in the field of corporate sustainability. In this framework, a family of indices is introduced on a world platform and the organizational stock performance is measured in the context of social, economic, and environmental criteria. The Dow Jones indices can be a benchmark for stakeholders and investors who can incorporate sustainability considerations into their portfolios. The DJSI indices are formulated with the help of organizational performance in socio-economic, governance, and technology criteria (Basu and Kumar, 2004). According to Delai and Takahashi (2011), the sustainability vision of these indices is to provide value for shareholders by benefiting from the opportunities and handling the risk from social, environmental and economic development. The fiscal return on stocks is positively associated with the graphical representation of these indices, which is found a mission in the report. There are different indices for global, European, North American, Asia Pacific, and Korean industries. However, most of the indicators are qualitative in nature and assessment is based on the data gathered from the company filled questionnaire; company documents; media and stakeholders; and companies. Some of the information used is from publicly available sources.

3.2.16 Sustainability Analysis of Iron and Steel Production (Strezov *et al.*, 2013)

The study assessed the sustainability of three iron and steel making technologies: basic oxygen steelmaking (BF/BOF), electric arc furnace (EAF) and direct reduced iron (Midrex) (Yazdi, 2014). This framework also emphasizes challenge of the steel industry to manage trade-off between high energy prices, changing demands and the green economy (Magro *et al.*, 2015). It suggests indicators of sustainability performance for all three dimensions (economic, environmental, and social) for the steel industry, especially for the environmental dimensions (Varvara *et al.*, 2015). This work assesses the steel and iron making on the basis of five major indicators – economic parameters, greenhouse gas emissions, freshwater consumption, land use, and air pollution. These indicators are similar to some of the sustainability indicators of world steel association (Yazdi, 2014). The study concludes that the social impacts are difficult to quantify and no indicator of social impact is seen in the work. The electric arc furnace steel making was found to have the best sustainability performance, closely followed by Midrex. The blast furnace has the lowest ranking, although it's performance was found to be significantly above that of coal fired power stations.

3.2.17 Framework for Multi-Resolution Modeling of Sustainable Manufacturing (Jain and Kibira, 2010)

The multi-resolution framework represents sustainable manufacturing as interaction of four complex dimensions of environment, finance, social, and manufacturing as shown in Figure 3.12. In this framework, multi-resolution modeling is proposed using the simulation software incorporating system dynamics. The benefits of multi-resolution modeling is that it is capable of modeling sustainable manufacturing from the regional level to the global level. The modeling can be done at two different levels – high resolution and low resolution by replacing detailed representation with an approximation. It provides a more elaborative idea of the respective domains. The framework can serve as a basis for the organizations to model the sustainable manufacturing. However, the modeling requires special skills and also the basic unit of measurement is not clearly defined.

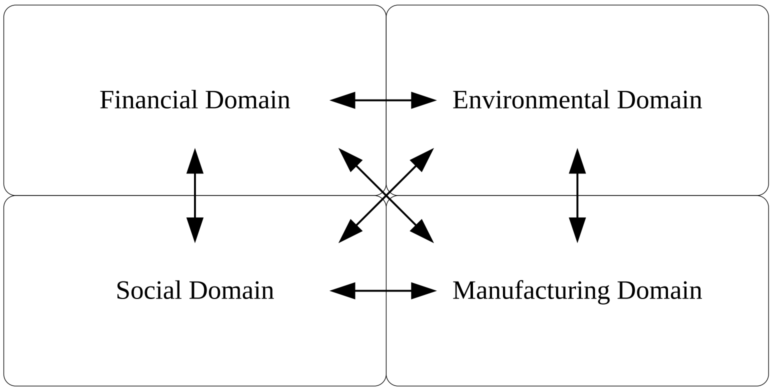


Figure 3.12 Framework for multi-resolution modeling of sustainable manufacturing (Source: Jain and Kibira, 2010)

3.2.18 Sustainability Manufacturing Mapping Methodology Framework (Paju *et al.*, 2010)

The framework introduced and illustrated the application of VSM (value stream mapping) for the sustainability assessment, which is named as sustainable manufacturing mapping methodology (SMM). SMM incorporates LCA and discrete event simulation with value stream mapping. The framework focuses on environmental sustainability and the main output are material and energy balances to achieve the strategic goals. The working with simulation gives benefits of creating an artificial history of the system and it measures the process variability and interdependencies. The sustainable manufacturing mapping methodology classifies seven categories for assessment: energy, materials, emissions, production, logistics, costs, and social. These categories are further divided into sub categories. The metrics and units have been defined for each sub category. It measures the process variability and interdependencies.

3.2.19 Product and Process Metrics Framework for Sustainable Manufacturing (Lu *et al.*, 2011)

The study presents a framework for the product and process metrics for sustainable manufacturing. The examples from machining process and machined products are used to demonstrate the applicability of framework. This study considers the life cycle engineering approach, and 6R (reduce, reuse, recycle, recover, redesign, and remanufacture) is a prerequisite for the product and process analysis. The product metrics defined for sustainable manufacturing are: residues; energy use and efficiency; product EOL management; material use and efficiency; water use and efficiency; cost; innovation; profitability; product quality; education; customer satisfaction; and product safety and societal well-being. The process metrics defined for sustainable manufacturing are:

environmental impact, energy consumption, cost, operator safety, personal health, and waste management. The process metrics are differentiated at three hierarchical levels – manufacturing system level, workstation level, and operational level. The study advocates optimizing the process sustainability over the product sustainability to achieve overall sustainability. The framework is a good basis for the sustainability assessment of organizations.

3.2.20 An Analytical Technique to Model and Assess Sustainable Development Index in Manufacturing Enterprises (Garbie, 2014)

The sustainability is described at two levels – macro level and micro level. Here, macro level refers to cities and countries, whereas micro level considers manufacturing enterprise, and its relative areas (Ding *et al.*, 2015). The study focuses mainly on micro level sustainability, with an aim to model the components of sustainability in manufacturing enterprises. The study identifies the some of the important research gaps like - weak sustainability, complexity of issues for economic, social, and environmental dimensions (no clear consensus), difference between sustainability and SD, lack of identifying indicators, etc.. It answers six direct questions to model the sustainability index using a program. All the indicators for three dimensions are modeled and discussed (Dubey *et al.*, 2015). Each indicator is defined/measured using a quantitative metric or in percentage. The study also includes life cycle engineering/assessment as an important factor for sustainable manufacturing.

After the analytical modeling, the study presents a case study of the aluminium industry. The study limits itself to micro level sustainability and a clarity on eco-system goals is not provided (Garbie, 2014).

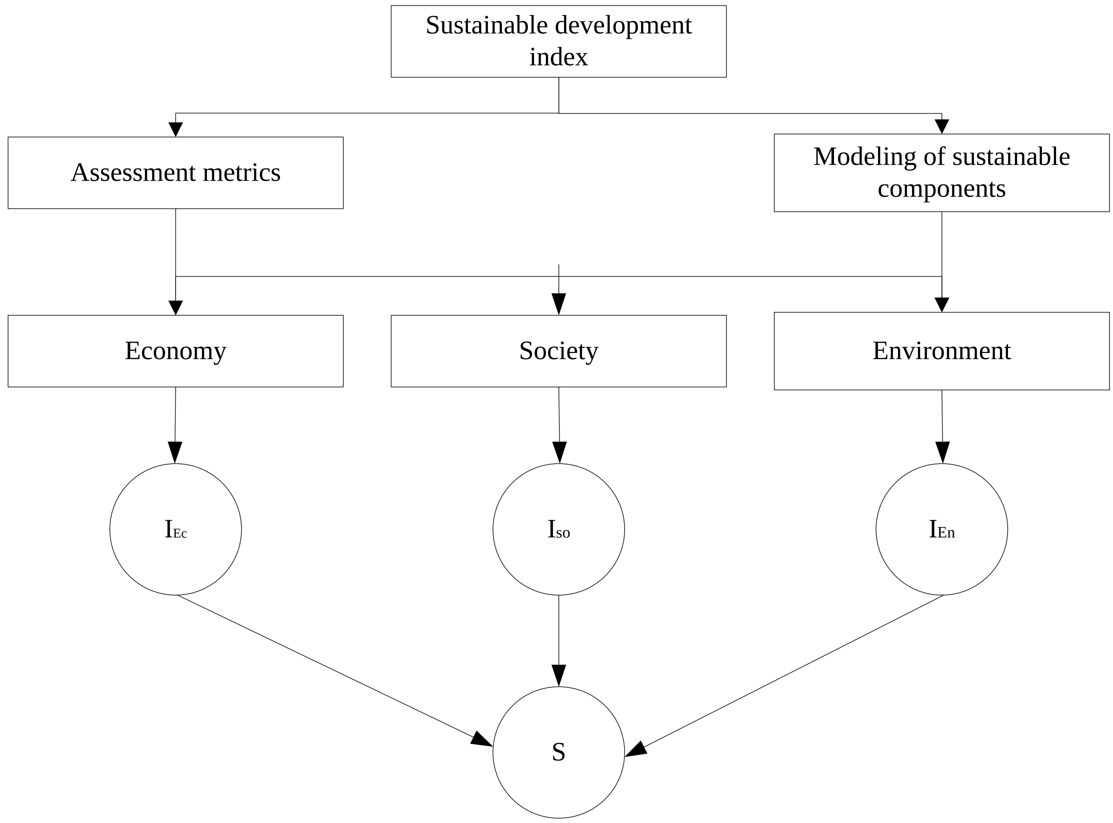


Figure 3.13 The Sustainable development index model (Source: Garbie, 2014)

3.2.21 **Corporate Sustainability Performance Measurement System** (Searcy, 2011)

The system presents an approach for guiding the evolution of a corporate sustainability performance measurement system (SPMS). The SPMS uses three phases of planning, performing and follow-up as shown in Figure 3.14 for the evaluation of corporate sustainability measurement system. Key issues to be addressed in each phase are provided. The framework is helpful in guiding decision makers through the process of reviewing and updating their corporate SPMS.

The framework is conceptual for generalized sustainability performance measurement system. The framework correlates the necessary aspects of sustainability assessment to integrate into existing goals and strategies of performance measurement. However, the framework does not provide indicators for the assessment.

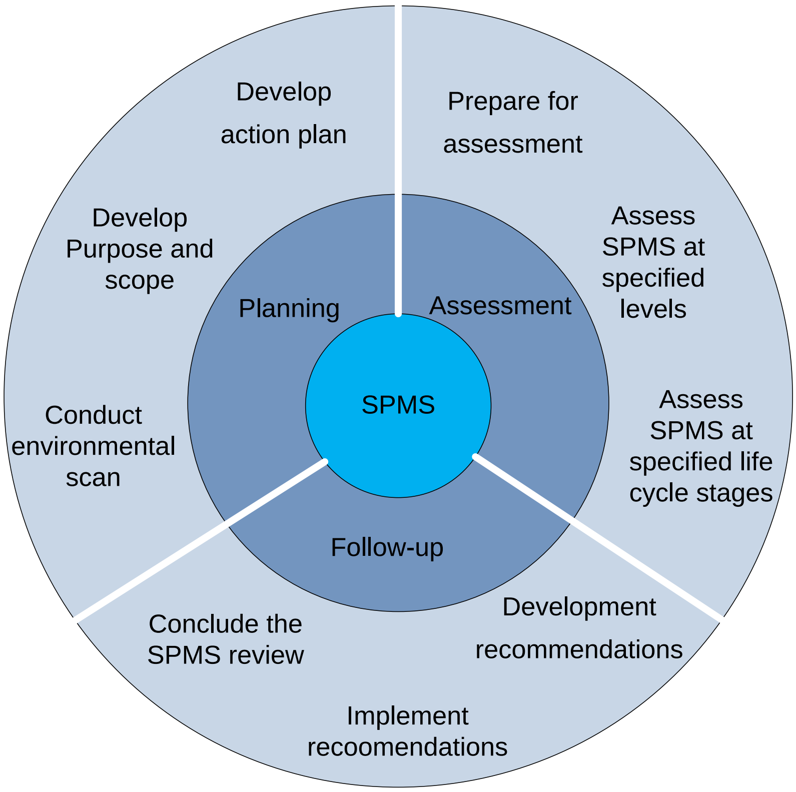


Figure 3.14 Framework for structuring the evolution of a corporate SPMS (source: Searcy, 2011)

3.2.22 The Role of Values and Objectives in Communicating Indicators of Sustainability (Shields *et al.*, 2002)

The study aims to provide a reasonable justification of effectiveness of sustainability indicators for social learning and information to the consumers. A general view of the sustainability and its indicators regarding their values and objectives has been discussed. The roles and objectives of these sustainability indicators are conferred in terms of values, society, decisions, actions, and impacts. This study also reflects about the hierarchy of information and controls, and defines the values, definitions society, decisions, actions, etc. in a hierarchical structure. The study argue that sustainability indicators can be more effective if they deliver social learning. The sustainability indicators can also influence the change in mindset of decision makers, which can effect decisions and behavior.

Development of sustainability indicators is a continuous learning process. The study claims that the overlap between policy, science, and publics' value and objectives cannot be ignored and sustainable policies are value driven. The study deals with generalized sustainability irrespective of any specific sector; describes the indicators, their values and objectives along with their interrelationship to achieve sustainability.

3.2.23 Framework for Sustainable Performance Assessment of Supply Chain Management Practices (Chardine-Baumann and Botta-Genoulaz, 2014)

The framework is used to characterize a company's sustainable performance in economic, environmental, and social aspects. It discusses the various aspects of best practices as defined by APQC (APQC, 2015). The study addresses the characterization model for sustainable performance by discussing the sustainability dimensions, performance measures and indicators for the three dimensions. It states that the social performance measures are generally defined at the organizational level in order to assess management practices (Kannegiesser *et al.*, 2015). The study favors the sustainable development of supply chain management to improve the performance and sustainable development of supply chain also impacts the firm's competitiveness (Su *et al.* 2016). The framework addresses the issue of sustainability performance by covering all SCM sustainability performance indicators in a systematic manner.

3.3 CHARACTERIZATION OF SUSTAINABILITY ASSESSMENT FRAMEWORKS

The review of 23 frameworks/models/systems is summarized in Table 3.1. The characterization of sustainability initiative frameworks has been performed on the basis of eight criteria. These criteria have been developed by closely observing the research work on sustainability [Calabrese *et al.*, 2016; Yuan *et al.*, 2012; Searcy *et al.*, 2008; Veleva and

Ellenbecker, 2001, etc.] and also from the working knowledge of other production engineering areas like TQM, TPM, benchmarking, product development, etc. The definitions of the selected criteria are:

i. *Comprehensiveness*: Comprehensiveness is defined in term of the life cycle coverage given in the framework. If the framework covers 'cradle to cradle' then it is highly comprehensive, if 'cradle to gate' then it has medium comprehensiveness and if 'gate to gate' then it has low comprehensiveness.

ii. *Level of sustainability:* Level of sustainability is in term of triple bottom line. If a framework incorporates all the three dimensions of sustainability (economic, environmental and social) then the level of sustainability is high, if any two dimensions then medium and if only one dimension then low.

iii. *Level of clarity:* If the framework provides information about (i) elements of sustainability, (ii) interrelationship among elements and (iii) methodology to incorporate the elements then the level of clarity is considered high and if any two of the above-mentioned information is provided then level of clarity is medium, and if only one information is discussed then level of clarity is low.

iv. *Focus of indicators:* This classification divides the frameworks into three categories: manufacturing, governance, and mixed (i.e. both governance and manufacturing) frameworks.

v. *Type of approach:* Whether the framework assesses the compliance or the overall system. The frameworks either follow a system approach or compliance approach.

vi. *Level of specificity:* In this classification frameworks are divided by two criteria: either industry specific framework or generalized framework for any industry/organization.

vii. *Number of indicators:* This classification captures the number of indicators of sustainability considered in the framework. If the number of indicators is less then 20 framework have a low number of indicators, if between 20 and 50 then medium, if more than 50 then high.

viii. *Level of implementability:* The frameworks are categorized as having a high level of implementability if indicators address the operational level of the sustainability, medium level of implementability if indicators address the overall system sustainability and low level of implementability if it can be used only for reporting sustainability.

The 23 frameworks were categorized based on the above eight criteria (see Table 3.1). For some of the frameworks, it was not possible to categorize on some criteria as shown in Table 3.1. It has been observed that most of the frameworks address the three dimensions (environmental, economic and social) and are generalized in nature. The major problem with the existing frameworks is lack of sustainability assessment methodology.

The only exception is the Veleva and Ellenbecker (2001) framework, which provides methodology. However, in this framework, the proposed indicators or metrics are difficult to assess. Some of these 23 frameworks are not related to the manufacturing domain yet they have been included for the review as these frameworks propose indicators which are important for the manufacturing industries also. For example, UNCSD framework provides social indicators. Recently, the need for social indicators in the manufacturing frameworks has been pointed by Sutherland *et al.* (2016).

Table 3.1 Categorization of sustainability measurement initiative frameworks

Framework	Type of approach	Comprehensive-ness	Level of sustainability	Level of clarity	Level of specificity	Number of indicators	Level of implementability	Indicator focus
✓ **(Spangenberg and Bonniot, 1998)**	System	Low	High	High	Generalized	-	Medium	Governance
✓ **(UNCSD, 2001)**	Compliance	High	High	High	Generalized	High	High	Governance
✓ **(Veleva and Ellenbecker, 2001)**	System	High	High	Medium	Generalized	High	High	Mixed
✓ **(IChemE, 2002)**	System	High	High	Medium	Industry	High	High	Mixed
✓ **(Shields *et al.*, 2002)**	System	Low	High	Medium	Generalized	Low	-	Governance
✓ **(Azapagic, 2004)**	Compliance	High	High	High	Industry	High	Low	Mixed
✓ **(Basu and Kumar, 2004)**	System	Low	High	Medium	Industry	-	Medium	Manufacturing
✓ **(Labuschagne *et al.*, 2005)**	System	Medium	High	Medium	Industry	High	Medium	Mixed
✓ **(Adams and Ghaly, 2006)**	System	High	High	Medium	Industry	Low	Low	Mixed
✓ **(Paju *et al.*, 2010)**	System	Low	High	Low	Generalized	Medium	Low	Manufacturing
✓ **(Jain and Kibira, 2010)**	System	Low	High	High	Generalized	Medium	High	Mixed
✓ **(GRI Guidelines, 2011)**	Compliance	Medium	High	High	Generalized	High	Low	Mixed
✓ **(Delai and Takahashi, 2011)**	System	High	High	Medium	Generalized	Medium	High	Mixed
✓ **(Lu *et al.*, 2011)**	System	High	High	High	Generalized	Low	High	Manufacturing
✓ **(Baumann and Genoulaz, 2014)**	System	High	High	High	Generalized	High	Medium	Mixed
✓ **(Searcy, 2011)**	System	Low	High	Medium	Generalized	Low	-	-
✓ **(Jayal *et al.*, 2010)**	System	High	High	Medium	Generalized	Medium	High	Manufacturing
✓ **(Jovane *et al.*, 2008)**	Compliance	High	High	Medium	Generalized	-	-	Manufacturing
✓ **(Joung *et al.*, 2013)**	System	High	High	Medium	Generalized	-	Medium	Mixed
✓ **(Strezov *et al.*, 2013)**	Compliance	Low	Medium	Low	Industry	Low	Low	Manufacturing
✓ **(DJSI, 2011)**	System	Medium	High	Low	Generalized	High	Low	Mixed
✓ **(Garbie, 2014)**	System	Medium	High	Medium	Generalized	High	Medium	Mixed
✓ **(Dubey *et al.*, 2015)**	System	Low	High	High	Generalized	Medium	High	Mixed

3.4 PROPOSED CONCEPTUAL FRAMEWORK FOR MANUFACTURING SUSTAINABILITY ASSESSMENT

This section presents a conceptual framework for manufacturing sustainability assessment. Research community has attempted to achieve sustainability through the integration of the philosophies like knowledge management (Dassisti *et al.*, 2012), continuous learning (Davies, 2012), continuous improvement (Glover *et al.*, 2014) with product and process sustainability (Lu *et al.*, 2011; Jayal *et al.*, 2010), people management (Ehnert *et al.*, 2013), supply chain and supplier management (Baskaran *et al.*, 2012), and stakeholders participation (Nordheim and Barrasso, 2007). But, as far as author's knowledge, there is no research or framework which assesses the sustainability through the integrated resource consumption throughout the life cycle of products and processes of the organization in other words through the integrated supply chain. The proposed a framework has three phases: pre-implementation or sustainability readiness assessment phase, post-implementation or sustainability assessment phase, and sustainability reporting phase as shown in Figure 3.15. In the first phase, the organizational readiness for sustainability assessment is assessed by self-assessing the organizational sustainability policies, product sustainability, and process sustainability. This phase should be implemented by using a cross-functional internal team at the middle hierarchy. An exhaustive list of questions, which are qualitative in nature are to be developed for the self-assessment. The self-assessment questions are related to the assessment of sustainability policies of the organization, the assessment of the product sustainability and process sustainability as mentioned above. Care should be taken to develop questions related to all the resources (people, money, material, energy, infrastructure, water, and air) and all the three dimensions of the sustainability. Mind mapping technique is used to develop these questions. Mind mapping is a powerful tool which simply translates the thoughts into a visual picture which can be used later to sort out the details and interrelations for further improvement (Davies, 2011). Mind maps for ‘product sustainability’, ‘process sustainability’, and ‘sustainability policies’ are shown in Figures 3.16, 3.17, and 3.18 respectively.

Minimum qualifying scores are fixed for the individual readiness and the overall readiness of the organization. If the organization fails to score the minimum qualifying score then the team looks for the improvement area(s), make the improvements and re-assess. It should be understood at this point that the sustainability assessment is done to improve the sustainability of the organization and not just to measure the sustainability. The readiness assessment helps the organization to focus on the sustained improvement in the next phase. For example, if there is no written policy on sustainability or sustainability has not been integrated with the business policy or managerial staff is not involved in setting sustainability targets, etc; then improve these policies before sustainability assessment. If the organization goes directly for the sustainability assessment then it may prove counterproductive. This phase helps the organization in establishing the basic infrastructure for the data capturing and assessment. If the organization is ready at this stage then employees will be looking forward to the next phase. Details of the readiness assessment phase are in chapter 4. In the next phase – the organization implements the new initiatives to improve its sustainability. Initially, the readiness self-assessment model will provide enough hints to recognize the areas of improvement. Later, the assessment of resources, critical factors, and the triple bottom line will be used to guide and develop strategies for improvement as shown in Figure 3.15. The details of assessment model are in chapter 5. Next, the assessment should be reported in an unbiased and unambiguous manner. Indicators, their units an scope play an important role in sustainability improvement. These reports are used by the decision makers to take policy decisions.

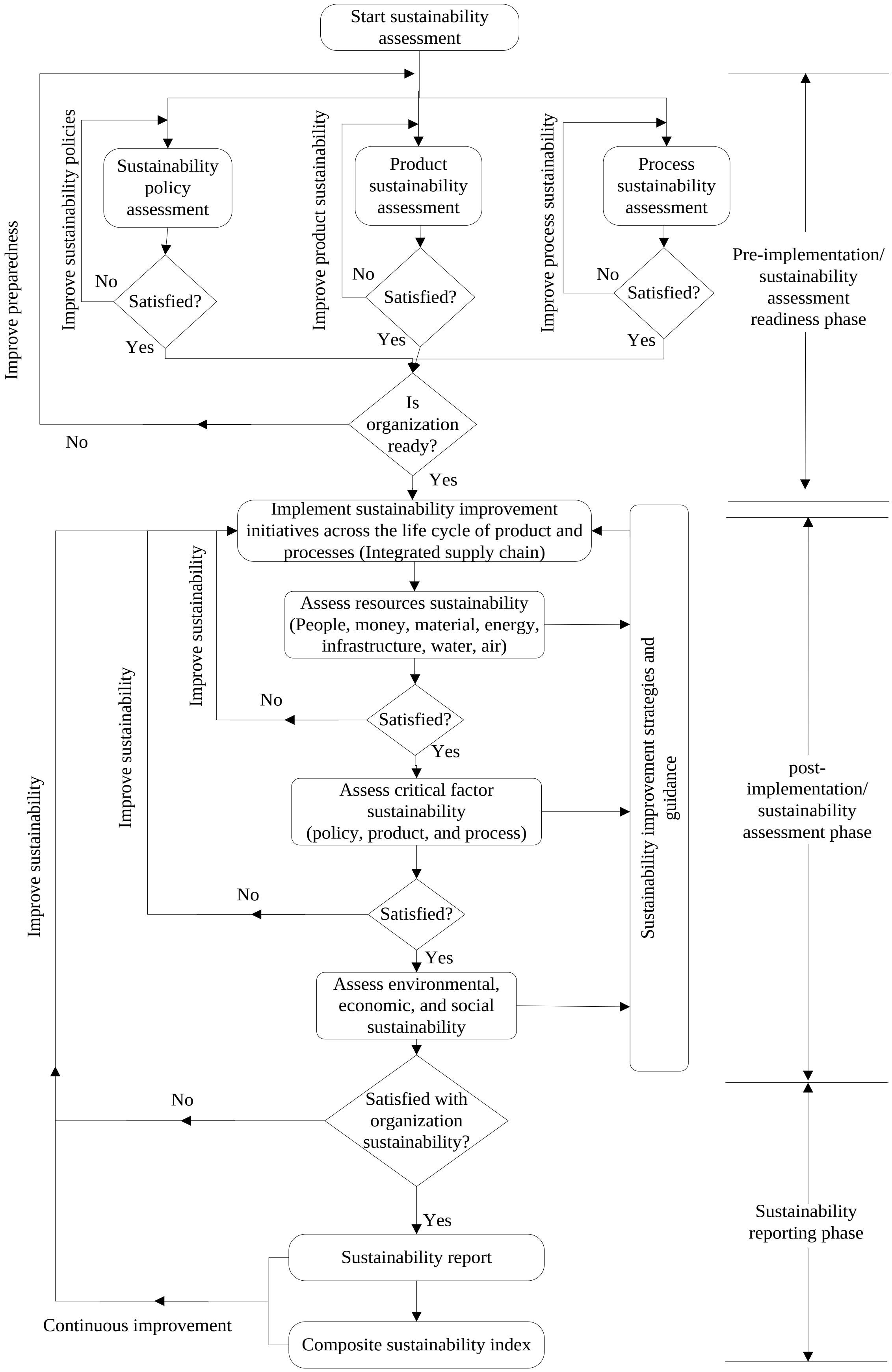


Figure 3.15 Proposed conceptual framework for manufacturing sustainability assessment

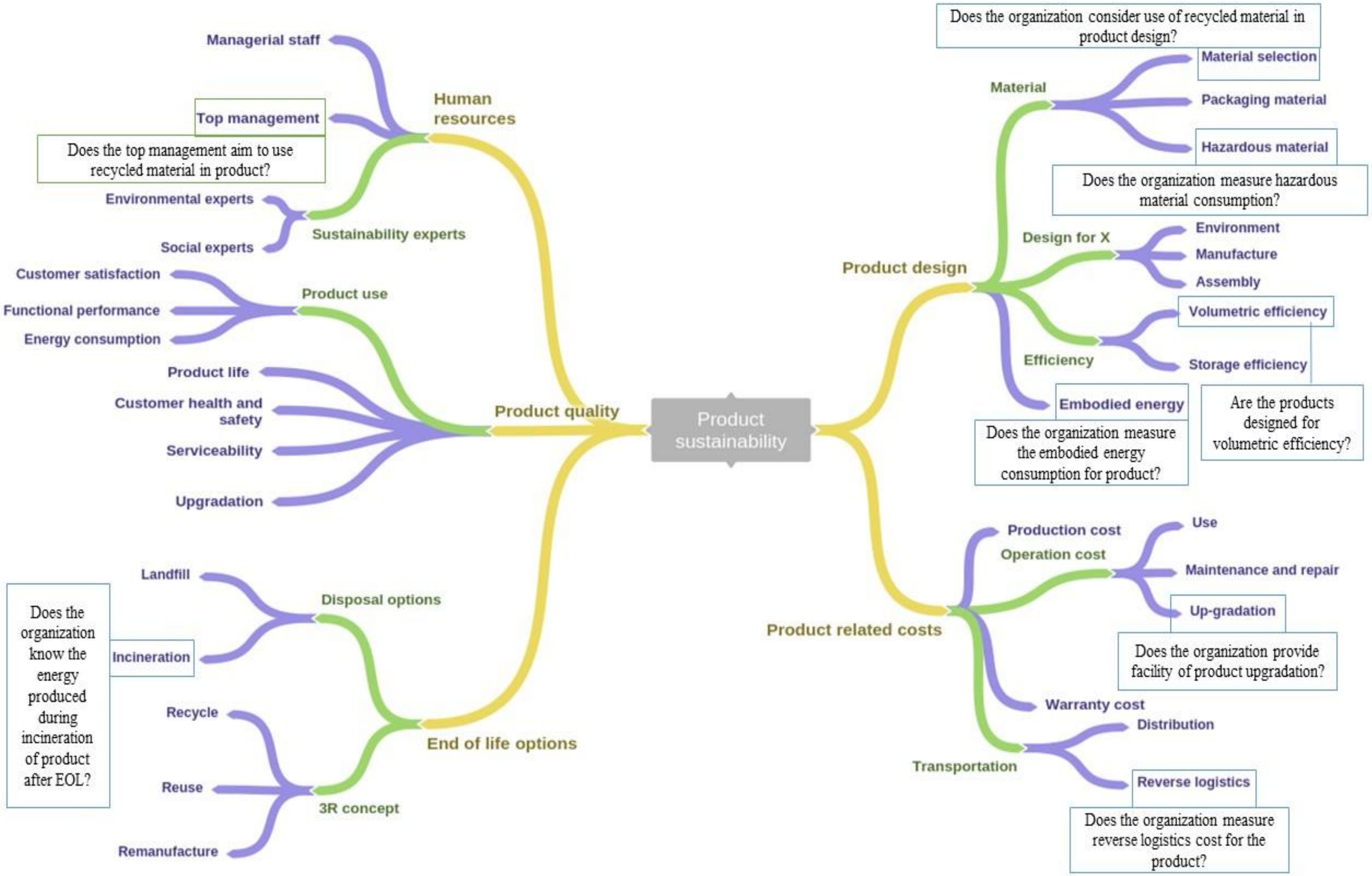


Figure 3.16 Mind map to develop product sustainability readiness self-assessment questionnaire

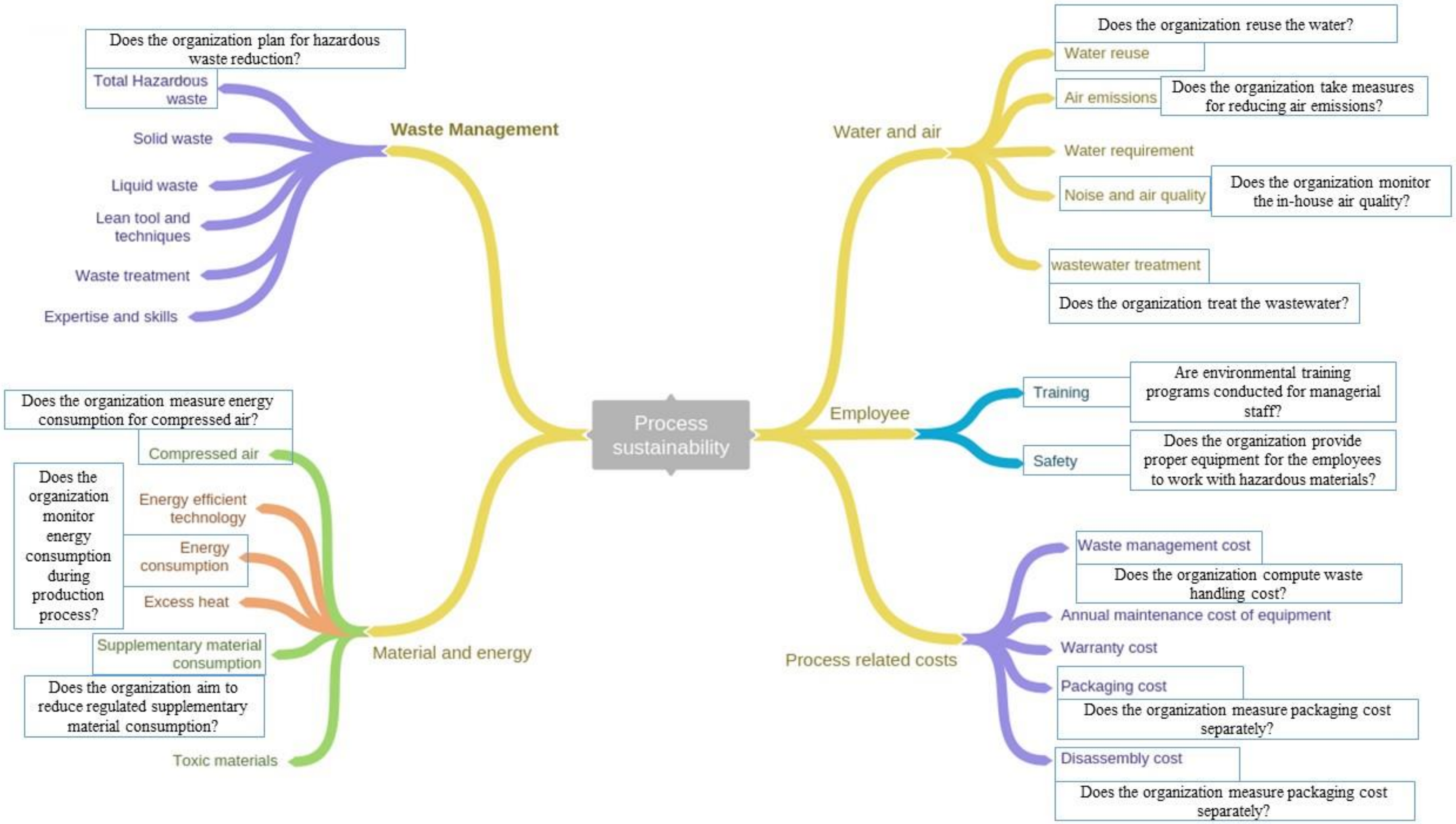


Figure 3.17 Mind map to develop process sustainability readiness self-assessment questionnaire

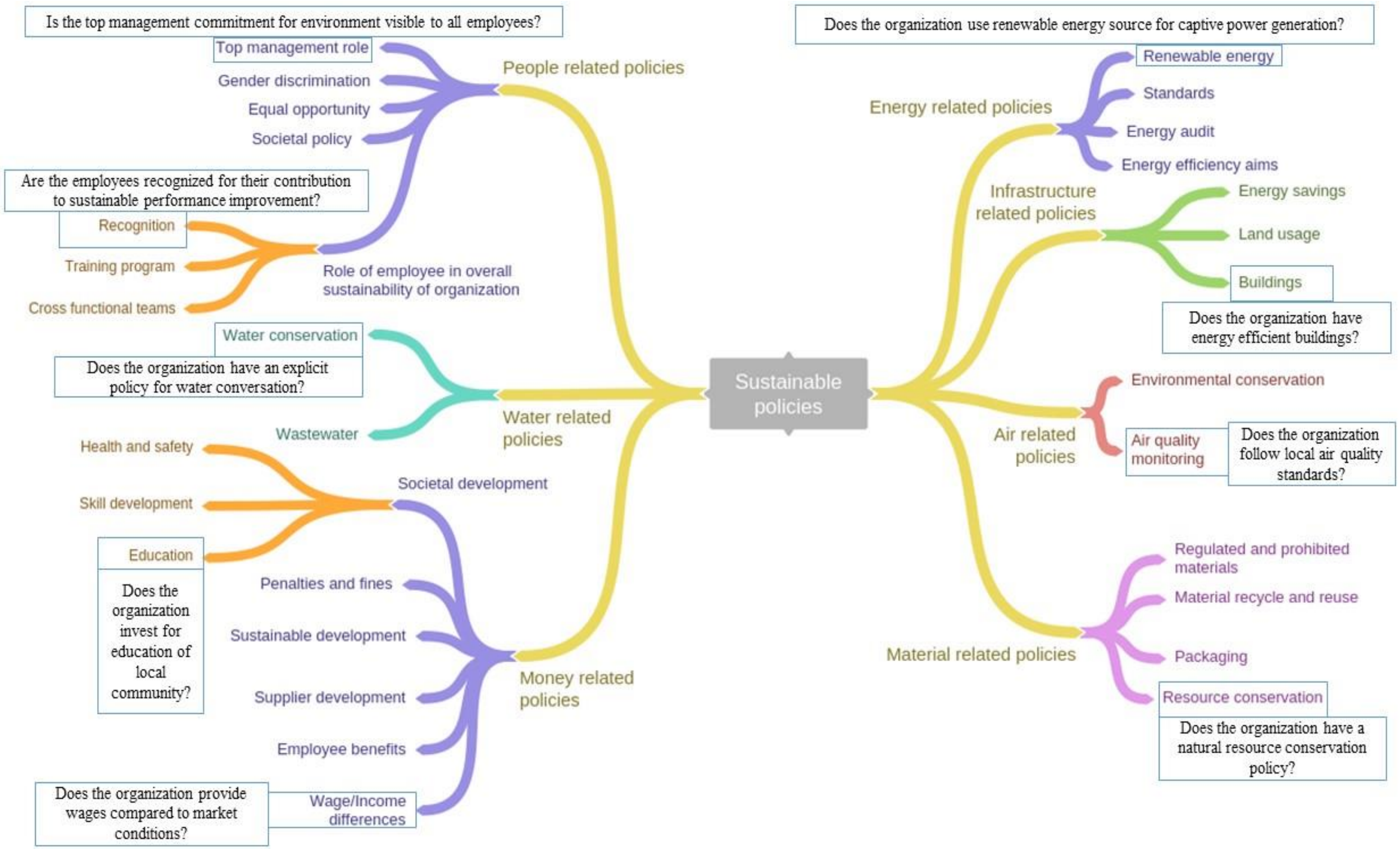


Figure 3.18 Mind map to develop sustainability policies readiness self-assessment questionnaire

3.5 SUMMARY

Manufacturing sustainability is becoming increasingly important for industry and the current study proposes a multi-level conceptual framework for measuring sustainability in manufacturing organizations. The proposed framework consists of three phases – pre-implementation or sustainability readiness self-assessment phase, post-implementation or sustainability assessment phase, and sustainability reporting phase. The novelties of the proposed framework are:

- A readiness self-assessment model is introduced for the first time for sustainability assessment of manufacturing organizations. This provides a direction to the leadership to understand the current strengths and weaknesses of the organization on sustainability performance. It also lowers the resistance to change later during implementation.
- Sustainability linked to all the resources – people, money, material, energy, infrastructure, water, and air.
- Sustainability associated with organizational policies, products, and processes.

In addition to the above three novelties, the linkages of sustainability to three dimensions (environment, social and economic) as well as the life cycle stages have also been included in the proposed framework. The proposed framework also provides flexibility to managers and decisions maker to develop their own indicators thereby encouraging the stakeholder participation.

CHAPTER 4
DEVELOPMENT OF A
SUSTAINABILITY READINESS SELF-ASSESSMENT MODEL

This chapter proposes a self-assessment model to assess the readiness of a manufacturing organization for sustainability assessment and improvement.

4.1 INTRODUCTION

An important first step when embarking on the sustainability improvement journey is readiness assessment. Measuring readiness assessment is a systematic analysis of an organizations' ability to undertake the potential sustainability improvement initiatives. Readiness assessment identifies the weak areas of the organization and helps to mitigate or close these weak areas before the implementation of sustainability improvement initiatives. However, there is no readiness assessment model for assessing organizational preparedness for sustainability assessment and improvement. This chapter aims to: (i) develop a sustainability readiness self-assessment model and (ii) validate the model by using two case studies from Indian manufacturing organizations.

Selection of an appropriate sustainability assessment tool is important for sustainability assessment and improvement. It is observed that selection of sustainability assessment tool is generally made by analyst(s), without incorporating the cultural, economic, and political context of assessment (Gasparatos and Scolobig, 2012). The need for consensus on sustainability and its measurement system creates some difficulties in the implementation of sustainability when put into practical situation (Delai and Takahashi, 2011). According to Garbie (2014) to know the sustainable development (SD) status of a manufacturing organization, the entire choice of best practices, dimensions, aspects, indicators, and performance measures should be addressed. A systematic approach named Design for Sustainable Manufacturing Enterprise (DFSME) was presented by Garbie (2013) to incorporate assessment procedure to analyze the current situation of organization in terms of social, economic, and environmental aspects.

According to Neely *et al.* (2005) performance measurement/assessment is always a topic of discussion but it is not well defined. It defines performance measurement as a process of quantifying actions, measurement as the process of quantification, and performance is the results of actions. Neely *et al.* (2005) also claims that when you are able to measure what you talk about and express it in quantitative terms, than you can claim your knowledge about it, otherwise your knowledge is insufficient and unsatisfactory in nature. Similarly, in case of sustainability assessment and improvement, when organization is not aware of its level of sustainability implementation, it is difficult to claim the assessed sustainability performance. A sustainability readiness self-assessment model is required for manufacturing industry to support management in assessing sustainability readiness and effective decision making on policies, products, and processes for sustainability improvements. Readiness self-assessment model/framework are often seen in research work of other manufacturing philosophies like six sigma (Lee *et al.*, 2011), total productive maintenance (Chandra and Kodali, 2000), continuous improvement (Ali *et al.*, 2013), etc.

A systematic literature review (SLR) has been carried out for manufacturing sustainability (Chapter 2) to identify the elements of manufacturing sustainability. For readiness self-assessment model critical factors (policy, product, and process) and resources (money, material, energy, infrastructure, people, air, and water) are used to develop the model. A through discussion on these critical elements and resources is provided later in this chapter and chapter 5 respectively.

4.2 EXISTING RESEARCH ON SELF-ASSESSMENT MODELS

The research has overlooked the important aspect of organizational readiness for sustainability assessment of manufacturing organizations. A study by Voss *et al.* (1994) tested benchmarking and self-assessment frameworks for manufacturing. The study observed that benchmarking and self-assessment approaches are different from other performance evaluation approaches, because these approaches use instructive way to examine different perspectives. The readiness self-assessment model also follows the same approach to examine important aspects of manufacturing value chain to improve upon them. The readiness assessment model has been used for green IT implementation (Muladi and Surendro, 2014). Sustainable development commission of UK has also provided a self-assessment guide for business sectors for addressing regional sustainable development strategies (sustainable development commission, 2002). Conti (1999) enticed attention towards improvement oriented self-assessment in his book on self-assessment for organizations. Chanyagorn and Kungwannarongkum (2011) presented a readiness assessment model for public and private organization in context of developing countries with an aim of information and communication technology. The work of Lee *et al.* (2011) developed a readiness self-assessment model for six sigma implementation in Chinese enterprises. Ali *et al.* (2013) investigated impact of organizational self-assessment for six variables: strategic focus, monitoring continuous improvement, integrating continuous improvement, involvement and learning, and knowledge sharing for sustainability of continuous improvement. The study by Chandra and Kodali (2000) used self-assessment model for total productive maintenance. The readiness of an organization can be assessed using simple self-assessment tools, which need not be based on the key performance indicators of sustainability. This chapter presents a sustainability readiness self-assessment model for manufacturing organizations.

4.3 DEVELOPMENT OF A SUSTAINABILITY READINESS SELF-ASSESSMENT MODEL

The readiness self-assessment model revolves around the assessment of the resources under three critical factors of manufacturing sustainability as shown in Figure 4.1. This three layered cake model shows that each critical factor should be assessed for all resources. Figure 4.1 describes a sample list of questions developed for the material sustainability requirement from manufacturing process perspective. Similar questions have been developed for the remaining interactions of resources and critical factors. The list of 229 questions developed for sustainability readiness self-assessment model is given in Table 4.1.

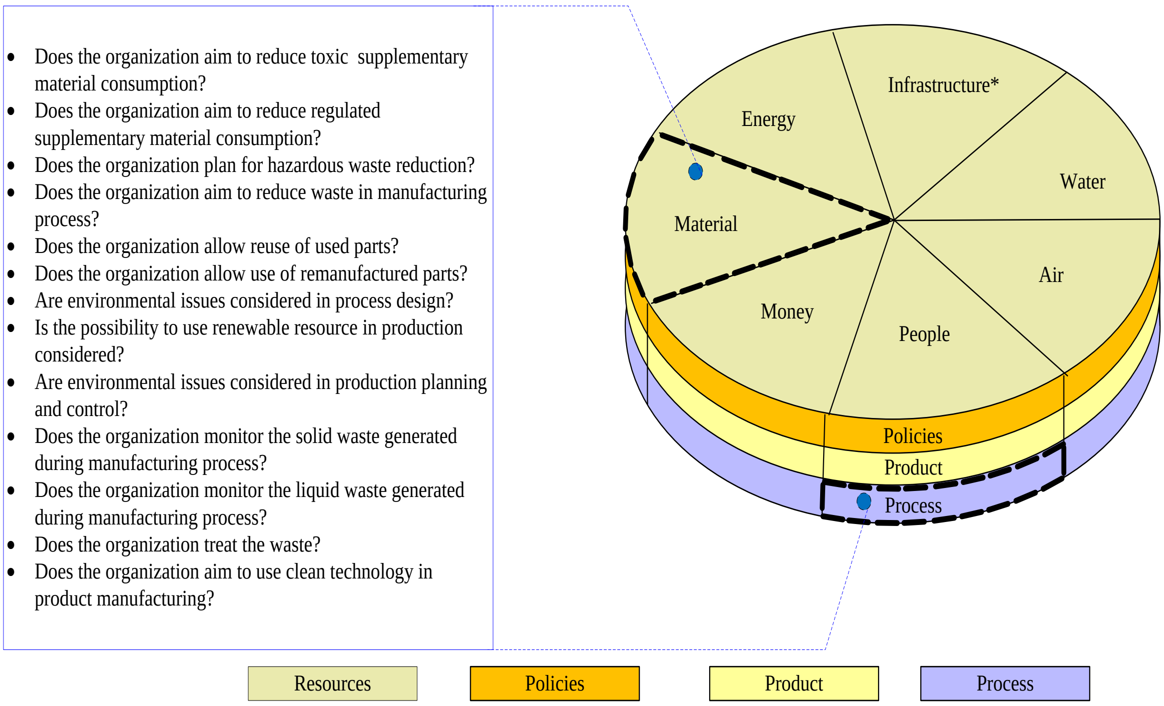


Figure 4.1 The guiding structure for the development of questions for the proposed sustainability readiness self-assessment model (Infrastructure* includes land, equipment, and technical building services)

4.3.1 Critical Factors of Manufacturing Sustainability

4.3.1.1 Sustainability policies

In the current scenario, research community has explored a variety of policies for the development of the organizational sustainability. Important policies are related to knowledge management (Dassisti *et al.*, 2012), continuous improvement (Glover *et al.*, 2014), and continuous learning (Davies, 2012). But, there are other areas in which policies are required to guide the organizational sustainability. These policies are related to environmental sustainability, human resource management (including employee, customer, supplier, and stakeholders), technology and innovation, investments, emissions, infrastructure, social sustainability, corporate social responsibility, and energy. According to Abbasi and Nilsson (2012), policies and research models can deal with the complex issue of sustainability in an efficient manner. But, these policies should be converted into determined activities for the sustainable transformation. Li and Lin (2016) presented a study on energy conservation policies to improve the green productivity of Chinese manufacturing sector. Performance oriented green growth is an important aspect for the future economy and social change (Choi *et al.*, 2016). The self-assessment questions for the organizational polices are constructed to cover stakeholders of organization, governance system, policies for resources consumption, technological advancement, product use and end-of-life, cost, revenue, investment, and community development. List of questions related to policy and seven resources are:

Self-assessment questions for Policy – People interaction

- Are the organizational environmental policies written and displayed to guide the employees?

- Does the organization have a written strategy to guide organization to achieve social vision?
- Does the organization involve employees in environmental and social policy making process?
- Does the organization prohibit child labour?
- Does the organization provide minimum wages?
- Does the organization have a strong policy against sexual harassment?
- Does the organization provide equal opportunity to women employees?
- Does the organization have a provision for paternity and maternity leave?
- Does the organization have a documented corporate social responsibility policy?
- Does the top management monitor the progress of employee through performance appraisal?
- Is the top management commitment for environment visible to all employees?
- Is the top management commitment for society visible to all employees?
- Does the organization have an explicit social policy?
- Are social issues addressed as business issues?
- Does the top management monitor the progress of social projects?
- Does the top management monitor the progress of environmental projects?
- Is managerial staff involved in environmental policy development?
- Is the managerial staff involved in social policy development?
- Are the environmental goals clear to managerial staff?
- Are the social goals clear to managerial staff?
- Does the organization conduct sustainability awareness/training/competence programs regularly?
- Does the organization document the social lessons learned?

- Are employees involved in process of determining environmental goals?
- Are employees involved in process of determining social goals?
- Are in-house employees involved in environmental and social project implementation?
- Are social competence programs conducted for managerial staff?
- Does the organization have a separate team to tackle social issues?
- Does the organization have a separate team to tackle environmental issues?
- Are the employees authorized to handle environmental problems?
- Are the employees encouraged to provide suggestion on environmental performance improvement?
- Are the employees encouraged to provide suggestion on social performance?
- Are the employees recognized for their contribution to sustainable performance improvement?
- Does the organization regularly review the environmental and social training programs?
- Does the organization have enough internal sustainability experts?
- Does the organization employ external environmental experts?
- Does the organization involve environmental experts in technology development/procurement?
- Does the organization involve social experts in technology development/procurement?
- Does the organization have a policy to receive complaints from local community?
- Does the organization conduct periodic environmental audits?
- Does the organization conduct periodic social audits?

Self-assessment questions for Policy – Energy interaction

- Does the organization have an explicit energy policy?
- Is the energy policy documented to guide the managerial staff?
- Does the organization include environmental issues in developing energy policy?
- Does the organization use renewable energy source for captive power generation?
- Does the organization purchase energy efficient technologies?
- Does the organization follow the energy management standards (i.e. ISO 50004:2014)?
- Does the organization produce energy through cogeneration?
- Are the energy audits conducted regularly?
- Is energy efficiency a criterion for supplier selection?

Self-assessment questions for Policy – Money interaction

- Does the organization have an explicit economic policy related to social and environmental issues?
- Does the organization monitor the environmental penalties?
- Does the organization allocate financial resources regularly for sustainable development?
- Are environmental issues addressed as business issues?
- Does the organization invest for supplier development?
- Is the organization involved in philanthropy activities?
- Does the organization has an explicit policy for environmental investments?
- Does the organization consider the environmental risks in its financial policies?
- Does the organization invest in employee development?

- Does the organization invest for environmental responsibility?
- Does the organization provide pension benefits to the employees?
- Does the organization provide health benefits to the employees?
- Does the organization provide wages compared to market conditions?
- Does the organization invest in social development in nearby areas?
- Does the organization avoid income discrepancy for male and female employees?
- Does the organization conduct program for skill development of local community?
- Does the organization invest for education of local community?
- Does the organization invest for health of local community?
- Does the organization check the environmental standards of the product?
- Does the organization allocate budget for environment improvement?

Self-assessment questions for Policy – Material interaction

- Does the organization have an explicit material policy?
- Does the organization monitor its regulated material consumption?
- Does the organization monitor its prohibited material consumption?
- Does the organization promote use of non-toxic/ non-polluting material?
- Does the top management promote recycling of materials?
- Does the organization have a natural resource conservation policy?
- Does the organization have collection center(s) for product recycling?
- Does the organization promote use of environment friendly material?
- Does the organization have a plan to reclaim packaging?
- Does the organization plan for packaging material disposal?
- Does the organization use recycle material for packaging?

- Does the organization use lean tool and techniques?
- Does the organization aim to reduce waste in end-of-life of product?
- Does the organization reduce the use of packaging?

Self-assessment questions for Policy – Infrastructure interaction

- Does the organization have an explicit infrastructure policy?
- Does the organization have an explicit policy for land usage?
- Does the organization have separate corporate social responsibility department?
- Does the organization have energy efficient buildings?
- Does the organization use sunlight for illumination?
- Is the organization building used for rain water harvesting?
- Does the organization monitor asset utilization?

Self-assessment questions for Policy – Water interaction

- Does the organization have an explicit policy for water conversation?
- Does the organization treat the wastewater?
- Does the organization have knowledge about depletion of different water resources in local area?
- Does the organization harvest rainwater?

Self-assessment questions for Policy – Air interaction

- Does the organization have an explicit policy for air quality?
- Does the organization follow local air quality standards?
- Does the organization launch environment conservation program regularly to improve ambient air quality?
- Does the organization measure annual ozone level?

4.3.1.2 Product sustainability

Product sustainability is one of the important factors for organizational sustainability. According to Fawcett *et al.* (2016), some important criteria for product sustainability are: sustainable materials, manufactured in a sustainable way, sourced in a sustainable way, delivered in a sustainable way, used in a sustainable way, sustainably collected, and can be reused, remanufactured, recycled. Herrmann *et al.* (2008) claims that total life cycle management is an integrated approach for sustainability. The product design factors have been considered on the basis of Hauschild (2004), Lu *et al.* (2011) and Singh *et al.* (2013), which discuss sustainable product design aspects. EOL strategies for a product and related factors are given in Lu *et al.* (2011) and Jawahir *et al.* (2005). According to Veleva *et al.* (2003), data availability is observed as a barrier for assessing product life cycle and supply chain sustainability. The various aspects covered by the self-assessment questions on product sustainability include material, product life span, energy, disassembly, customer, repair and maintenance, product upgrade, use, end-of-life options, resources, waste, emissions, etc. List of self-assessment questions related to product and seven resources are:

Self-assessment questions for Product – People interaction

- Does the organization provide details of environmental emissions of the product to the customer?
- Does the organization involve cross functional team in product design?
- Is the top management committed for environmentally sustainable products?
- Does the organization have an explicit policy for product return?
- Does the organization recycle the products after customer use?

- Does the top management aim to recycle the product in environment friendly manner?
- Does the organization involve environmental expert in product design?
- Does the organization involve social experts in product design?
- Does top management aim to use recycled material in product?

Self-assessment questions for Product – Energy interaction

- Does the organization measure the embodied energy consumption for product?
- Does the organization design the product for less energy consumption during operation?
- Does the organization design the product for less energy consumption during maintenance and repair?
- Does the organization provide product upgradation for low energy consumption?
- Does the organization measure fossil fuel consumption during operation?
- Does the product design give possibilities to use renewable resources during use phase?
- Does the organization monitor energy consumption during distribution phase?
- Does the organization monitor the energy consumption during reverse logistics?
- Does the organization know the energy requirement for EoL treatment (i.e. recycle, landfill, etc.)?
- Does the organization know the energy produced during incineration of product after EoL?

Self-assessment questions for Product – Money interaction

- Does the organization measure the product operation cost separately?

- Does the organization measure the product maintenance and repair cost separately?
- Does the organization invest for marketing of sustainable products?
- Does the organization allocate budget for the expenditure on warranty of product?
- Does the organization allow replacement of faulty product/components?
- Does the organization provide facility of product upgradation?
- Does the product lead in market?
- Does the top management aim to innovate in product development?
- Does the organization have eco-labels for its products?
- Does the organization aim to dispose-of the products in environment friendly manner?
- Does the organization measure distribution cost?
- Does the organization measure reverse logistic cost for the product?

Self-assessment questions for Product – Material interaction

- Does the organization measure the total material consumption for a product?
- Does the organization consider use of recycled material in product design?
- Does the organization aim to reduce regulated material consumption?
- Does the organization aim to reduce waste in product maintenance and repair?
- Does the organization assess product durability during design?
- Does the design team estimate quantity of packaging material required?
- Does the organization measure hazardous material consumption in product?
- Are the quality standards available for raw material selection?

- Does the organization document the environmental lessons learned from the products?
- Does the product design allow ease of disassembly?
- Does the product design eliminate secondary processes (i.e. painting/polishing/buffing etc.)?
- Are the products designed for volumetric efficiency?
- Are the products designed for weight efficiency?
- Does the organization monitor the solid/liquid waste generated per product?
- Does the organization measure the regulated/hazardous material consumption in outsourced components?
- Is the design team aware of newer materials?

Self-assessment questions for Product – Infrastructure interaction

- Does the organization measure land requirement for the product?
- Does the organization measure land requirement for the raw material consumption?
- Does the organization measure land requirement for the auxiliary material consumption?
- Are the products designed for storage efficiency?

Self-assessment questions for Product – Water interaction

- Does the organization monitor water consumed (by type) for one product?
- Does the organization monitor water consumed (by volume) for one product?
- Does the organization consider the water consumed during use phase of the product?

- Is the organization aware of water requirement for service/maintenance/repair of product?

Self-assessment questions for Product – air interaction

- Does the organization monitor the air emissions due to raw material used in the product?
- Does the organization estimate air emissions of the product use phase?
- Does the organization measure air emission during service/maintenance/repair of product?
- Does the organization measure air emission during distribution of product?
- Does the organization measure air emission during disposal of product?

4.3.1.3 Process sustainability

From the perspective of process sustainability, researchers have discussed the topic of overall equipment efficiency (OEE), manufacturing flexibility and responsiveness along with waste elimination methods. Jaegler and Burlat (2014) discussed the issue of manufacturing capability using OEE. According to Gunasekaran (1998), agile manufacturing can support the flexibility and responsiveness in production processes. Waste elimination is considered as an important part to support sustainability through process improvement. Verrier *et al.* (2014) and Chiarini (2014) identified various practices for waste elimination techniques through lean and green manufacturing. Hong (2012) benchmarked the sustainability practices for manufacturing organizations. Aguado *et al.* (2013) developed an approach to harmonize efficiency and sustainability in a lean production system. Jurado and Fuentes (2013) presented a literature review on lean management, supply chain management and sustainability. Verrier *et al.* (2014)

attempted to combine organizational performance with sustainable development and addressed the lean and green project benchmarking repository. Readiness self-assessment questions have been designed by considering social aspects, environmental aspects, cost, personnel involvement, operational safety, energy, waste management, financial ability, expertise and skills, etc. List of questions related to process and seven resources are:

Self-assessment questions for Process – People interaction

- Does the production process incorporate employee suggestions?
- Does the organization provide proper equipment for the employees to work with hazardous materials?
- Are the employees trained to incorporate customization in production process?
- Does the organization provide a written methodology for sustainability implementation?
- Are environmental awareness programs conducted for managerial staff?
- Are social awareness programs conducted for managerial staff?
- Are environmental training programs conducted for managerial staff?
- Are social training programs conducted for managerial staff?
- Are environment competence programs conducted for managerial staff?
- Does the organization have requisite knowledge of sustainability implementation?

Self-assessment questions for Process – Energy interaction

- Does the organization monitor energy consumption during production process?
- Does the organization aim to use renewable energy during production process?

- Does the organization conduct training program for energy efficiency in production?
- Is operational staff capable to reduce energy consumption during ideal time of equipment and machinery?
- Is operational staff capable to reduce energy consumption during actual production process?
- Does the organization measure energy consumption for compressed air?
- Does the organization compute the energy requirement for waste treatment?
- Does the organization compute the energy requirement for water treatment?
- Does the organization compute the energy requirement for water used?
- Does the organization use energy efficient vehicles for distribution?
- Is the excess heat generated in production process utilized?

Self-assessment questions for Process – Money interaction

- Does the organization invest in green technology?
- Does the organization invest in employee health and safety?
- Does the organization measure man hour lost due to accident/incidents?
- Does the organization measure the cost of annual maintenance for equipment and machinery?
- Does the organization invest in new process development?
- Does the organization provide overtime to employees?
- Does the organization compute waste handling cost?
- Does the organization compute waste categorization cost?
- Does the organization compute solid waste treatment cost?
- Does the organization compute liquid waste treatment cost?

- Does the organization measure the average disassembly cost?
- Does the managerial staff target for cost effective production?
- Does the organization invest for water recycling?
- Does the organization invest in environment friendly packaging?
- Does the organization measure packaging cost separately?
- Does the organization purchase energy efficient technology?
- Does the organization invest for land restoration?
- Does the organization make revenue out of waste?

Self-assessment questions for Process – Material interaction

- Does the organization aim to reduce toxic supplementary material consumption?
- Does the organization aim to reduce regulated supplementary material consumption?
- Does the organization plan for hazardous waste reduction?
- Does the organization aim to reduce waste in manufacturing process?
- Does the organization allow reuse of used parts?
- Does the organization allow use of remanufactured parts?
- Are environmental issues considered in process design?
- Is the possibility to use renewable resource in production considered?
- Are environmental issues considered in production planning and control?
- Does the organization monitor the solid waste generated during manufacturing process?
- Does the organization monitor the liquid waste generated during manufacturing process?
- Does the organization treat the waste?

- Does the organization aim to use clean technology in product manufacturing?

Self-assessment questions for Process – Infrastructure interaction

- Does the organization monitor the landfill area requirement for process waste?
- Does the organization treat the waste before landfill?
- Does the organization perform land restoration?
- Does the organization conduct plantation drives regularly?
- Does the organization aim for conservation of bio-diversity?
- Does the organization have monitor plant/machinery utilization targets?

Self-assessment questions for Process – Water interaction

- Does the organization monitor utilization of water during production process?
- Does the organization reuse the water?
- Does the organization measure water pollution?
- Does the organization measure PH level of water discarded?
- Does the organization measure heavy metal content in water discarded?
- Does the organization measure dissolved oxygen in water discarded?
- Does the organization measure suspended and dissolved impurities in water discarded?

Self-assessment questions for Process – Air interaction

- Does the organization measure the process related air emissions?
- Does the organization monitor the in-house air quality?
- Does the organization take measures for reducing air emissions?
- Does the organization measure annual level of particulate matters?

- Does the organization measure annual level of volatile organic compounds (VOC)?
- Does the organization measure annual level of NOx emission?
- Does the organization measure annual greenhouse gas emission?
- Does the organization use enclosure for noise control?

4.3.2 The Proposed Sustainability Readiness Self-Assessment Methodology

The methodology for self-assessment of the organizational readiness is as:

Step I. Develop a cross functional team to answer the self-assessment questions.

Step II. Answer questions and assign a score of 1 (if the evidence strongly favors the compliance) or 0 (if the evidence is partial or not present).

Step III. Repeat Step II till all questions for each resource (*i*) and each critical factor (*j*) are answered.

Step IV. Total Point Obtained for each resource (TPO_i) is computed and tabulated in the form of a matrix 'Z' (size n x m) as shown in Table 4.1. Where 'n' is the number of resources, and 'm' is the number of critical factors.

$$TPO_i = \sum_{j=1}^{m} Z_{ij} \qquad \forall \ j \quad (4.1)$$

Step V. If the score obtained for any combination of resource and critical factor (qualifying score - Qs) is less than 50% of its maximum score than terminate the assessment process and examine the weak area(s) for improvement. Re-assess after improvement of the weak area(s).

$$Qs_{ij} \geq 0.5 * Z_{ij} \qquad (4.2)$$

Step VI. If the score obtained for any critical factor is less than 70% of its maximum score then terminate the assessment process and examine the weak critical factor for improvement. Re-assess after improvement.

$$Qs_j \geq 0.7 * Z_{ij} \tag{4.3}$$

Step VII. For an organization to qualify the assessment the gross qualifying score should be at least 75% of the maximum score.

$$GQs_i = \sum_{j=1}^{m} Qs_{ij} \quad \forall \text{ j } (4.4)$$

The values of gross qualifying score (75%), critical factor score (70%), and resource and critical factor qualifying score (50%) can be varied by the management of the organization depending upon organizations' level of sustainability.

4.3.3 Testing of the Sustainability Readiness Self-Assessment Model

Use and content testing of the proposed readiness assessment model has been done through two case studies. These two case studies have been performed in two Indian manufacturing organizations. The first organization is an automotive manufacturing organization located in the national capital region of India and second one is a cement manufacturing organization having plants and operations at various locations in India.

4.3.3.1 Case study of an automotive manufacturing company

The case company is a two-wheeler manufacturing company located in the national capital region of India. This organization was established in 1999. It is spread over 32 hectares with 107640 square feet covered area. It is one of the leading two-wheeler manufacturing company in India producing around 1.5 million two wheelers annually. Personal visits were made to the company to record responses to the questions. Initially, visits were made to the various departments of the company to understand their nature of work. Finally, a combined meeting of people from purchase, logistics, quality control, human resource, CSR, environment, production, product development, research & development, and estate management departments was called. The survey questionnaire for the self-assessment is provided in Appendix – A. The respondents were at the level of managers or senior managers having minimum of three years of experience. Care was taken to have competent people in the meeting. For example, the presence of person from the painting section, compressed air and energy monitoring section, and environmental quality section was ensured. Most of the questions were answered without much effort. The language of some questions was changed, on the advice of the team, to improve content validity. The author was also open to add or delete the questions but no need was felt to delete or add questions during the meeting. The results of the case study are given in Table 4.1. Radar charts (Figure 4.2) for the case company show, at a glance, the overall readiness and the preparedness under the critical factors.

Table 4.1 Summary of readiness self-assessment scores for the automotive manufacturing organization

S. No.	**Resource**	**Critical factor**			**No. of questions = Max. points (MAXP)**	**Total points obtained (TPO)**	**Qualifying score (Q_S = 0.7MAXP)**			**Gross Qualifying score (GQS = 0.75 MAXP)**
		Policy	**Product**	**Process**			**Policy**	**Product**	**Process**	
1.	People	40	9	10	**59**	30	28	7	7	***45***
2.	Money	20	12	18	**50**	42	14	9	13	***38***
3.	Material	13	16	13	**42**	30	10	12	10	***32***
4.	Energy	9	10	11	**30**	26	7	7	8	***23***
5.	Infrastructure	7	4	6	**17**	8	5	3	5	***13***
6.	Water	4	4	7	**15**	8	3	3	5	***11***
7.	Air	4	4	8	**16**	10	3	3	6	***12***
	Total	***97***	***59***	***73***	**229**		***70***	***44***	***54***	***172***

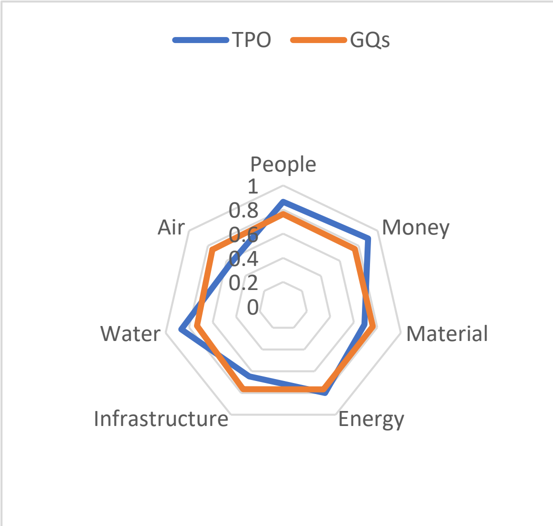
The radar chart shows that the case organization is prepared to assess the people, money, energy, and water resources but has to improve its preparedness for assessing material, infrastructure and air resources. Some of the changes suggested for improvement were cost sensitive as these require re-layout of facilities. The low score for the material resource is attributed to all the three critical factors. The main problem areas are packaging, non-promotion of non-polluting/non-toxic materials, and lack of reverse logistic facilities.

Similarly, the low score for air resource is due to the non-assessment of product related emissions during the service, distribution and disposal of the products. Figure 4.2 (b-d) show that the case company has sustainability policies and processes but needs to improve product sustainability. This is primarily because the company does not focus on the distribution, use and end of life phases of the products from sustainability perspective.

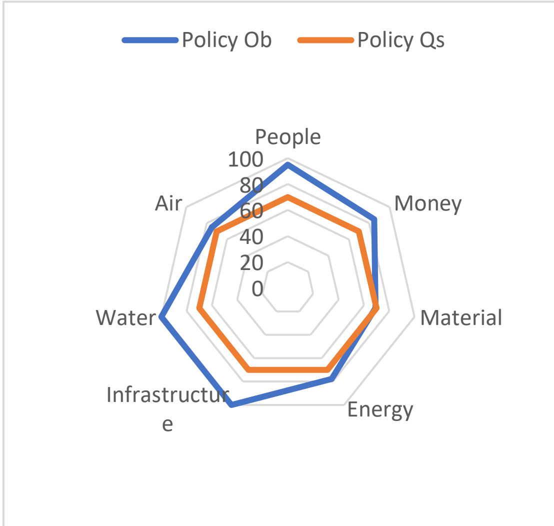
4.3.3.2 Case study of a cement manufacturing organization

The case organization is a leading manufacturer of portland cement and ready mix concrete (RMC) in India. Company has 93 million tonnes per annum capacity for portland cement. The company has 18 integrated plants for cement manufacturing. Company also has 35 RMC plants at various locations in India. The company assesses their carbon footprint across businesses every year.

To assess and validate the sustainability readiness self-assessment model, personal visits were made to 12 different plants to collect data through semi-structured interviews. The respondents comprise engineers, senior engineers, production officers, managers, and assistant managers, having minimum experience of 10 years and a maximum of 23 years.

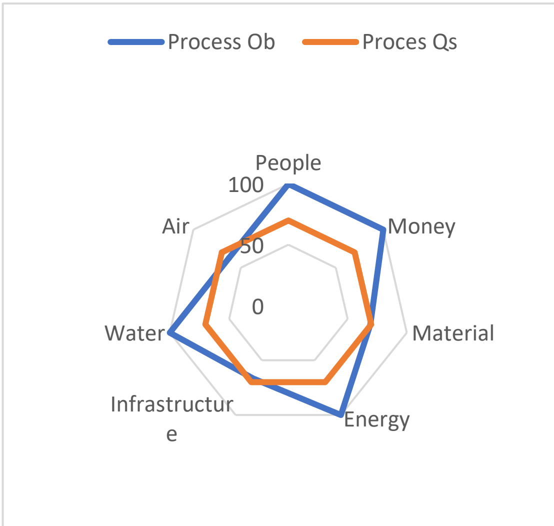


4.2 a) Overall readiness of the case organization



4.2 b) Sustainability policy readiness

4.2 c) Product sustainability readiness



4.2 d) Process sustainability readiness

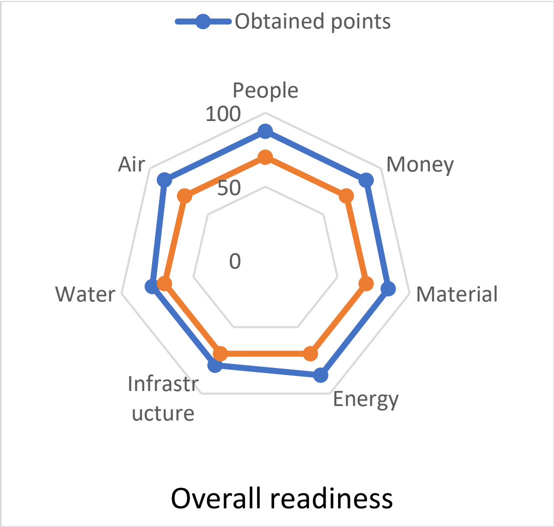
Figure 4.2 (a-d) Readiness assessment results for the automotive manufacturing organization (Q_s - qualifying score, O_b-score obtained)

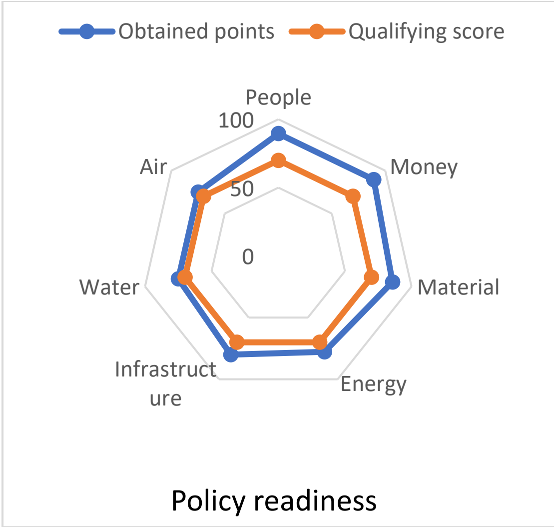
The duration of semi-structured interviews varied between 30 minutes to an hour. Different departments of participants includes: processes, business excellence, mechanical, thermal power plant, electrical, technical services, production, electrical and instrumentation (E&I), human resources, etc. Special care has been taken to involve competent people from these departments. As the author was open for any suggestion to delete, add, or modify the self-assessment questions. Some of questions suggested as ‘not applicable' for cement industry has been removed and few questions suggested by participants were discussed but not incorporated in current assessment due to lack of consensus among participants. During discussion with respondents, out of 229 questions, 12 questions were found not suitable for cement industry and hence, deleted.

Data was collected for 217 questions of the modified readiness self-assessment instrument. The data has been recorded on the interaction of three critical factors with resources as described in the model. The summary of readiness self-assessment score is given in Table 4.2. The results of the study are prepared using the methodology explained in section 4.3.2. The radar charts for the overall policy, product, and process readiness are shown in Figure 4.3 (a-d). The radar chart shows that the cement organization is prepared to assess all the seven resources across the three critical factors. The cement organization is proactively working for the sustainability improvement through its businesses. It also has its sustainability report on the website. In comparison, the automotive manufacturing organization is not well prepared for sustainability assessment.

Table 4.2 Summary of readiness self-assessment scores for the cement manufacturing organization

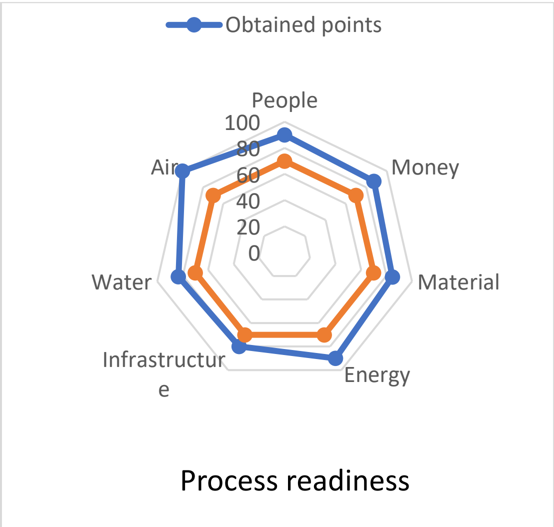
S. No.	**Resource**	**Critical factor**			**No. of questions = Max. points (MAXP)**	**Total points obtained (TPO)**	**Qualifying score (Q_S = 0.7MAXP)**			**Gross Qualifying score (GQS = 0.75 MAXP)**
		Policy	**Product**	**Process**			**Policy**	**Product**	**Process**	
1	People	38	8	10	**56**	49	27	6	7	***42***
2	Money	19	12	16	**47**	41	13	8	11	***35***
3	Material	14	14	13	**41**	35	10	10	9	***32***
4	Energy	9	10	10	**29**	25	6	7	7	***22***
5	Infrastructure	5	4	5	**14**	11	4	3	4	***11***
6	Water	4	4	6	**14**	11	3	3	4	***11***
7	Air	4	5	7	**16**	14	3	4	5	***12***
	Total	***93***	***57***	***67***	**217**	186	***66***	***40***	***47***	***164***

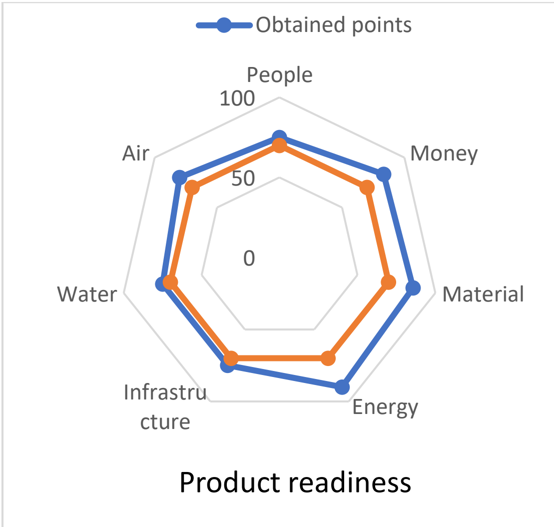




4.3 a) Overall readiness of the case organization

4.3 b) Sustainability policy readiness





4.3 c) Product sustainability readiness

4.3 d) Process sustainability readiness

Figure 4.3 (a-d) Readiness assessment results for the cement manufacturing organization (Q_s -qualifying score, O_b-score obtained)

4.4 SUMMARY

This chapter proposes a sustainability readiness self-assessment model for assessing the organizational preparedness for sustainability assessment and improvement using resource based theory. A list of 229 questions has been developed for the readiness self-assessment of three critical factors of product sustainability, process sustainability and sustainability polices. Readiness of each critical factor is assessed under different categories of resources. The proposed model is tested in two organizations – an automotive manufacturing organization and a cement manufacturing organization. The proposed model is simple and easy to use yet very effective to identify the weak areas of sustainability for improvement.

CHAPTER 5

DEVELOPMENT OF A MANUFACTURING SUSTAINABILITY ASSESSMENT MODEL AND INDICATORS

This chapter presents a sustainability assessment model; sustainability indicators for manufacturing organizations; and an empirical study of Indian cement industry is also presented.

5.1 INTRODUCTION

Sustainability assessment has been an important area in sustainability research. Some organizations and researchers have developed models for the sustainability assessment which are too diverse in coverage and depth, some have narrow focus and some are too generalized, some are country specific and others are industry specific. There is a lack of assigning the indicators to all the resources consumed/affected by the organization. Also, the indicators should be able to measure the product and process sustainability as well as the policies related to sustainability.

Various resources – materials, energy, money, water, infrastructure, air, and people – are required to design, produce and deliver a product. If a manufacturing organization aims at incorporating the sustainability holistically, then it has to focus on all the resources required to design, produce and deliver the products to the customer. But, before the design begins, designers should know the goals to be achieved by the product. In other words, the design team should know the organizational policies. The major difficulties in sustainability assessment as per Moon (2016) are: vast scope of sustainability (temporal and geographical); and multiple non-deterministic, dynamic and non-monotonic interactions among social, economic, and environmental dimensions. Dijk *et al.* (2017) also opine that sustainability assessment consists of complex and interlinked factors.

Therefore, sustainability assessment requires introduction of some new techniques/methods/tools. And, if the organization is not prepared for these changes then there is little chance for the sustainability improvement.

Next, indicators or key performance indicators (KPIs) are required to measure the sustainability. Indicators should be developed to measure the performance of an organization with respect to all the resources and throughout the product life cycle of products and processes (integrated supply chain). The indicators should be able to assess the three critical factors of sustainability (policies, product and process) and the three dimensions of the sustainability (economic, environmental and social). It is essential for an organization to be fully aware of its policies, products and processes, which can influence the sustainability of an organization directly or indirectly. According to Dijk *et al.* (2017), sustainability assessment is a common term used to cover numerous approaches aimed at decision making in operational sustainability. These approaches have a common aim of integrating various perspectives and diverse knowledge. Similarly, sustainability assessment without structured knowledge of critical sustainability factors and exhaustive indicators means looking organizational sustainability from local optima. Some companies do report sustainability performance but are not clear about the relevance of assorted sustainability indicators. According to Northey *et al.* (2013), companies providing general information in their sustainability reports lacks analysis of indicators for improving performance. Another article by Kumar *et al.* (2015) opines that companies are providing incomplete information in their sustainability reports and they rely on external agencies for sustainability reporting. This chapter proposes a model for manufacturing sustainability assessment and the required indicators for the sustainability assessment. The internal teams can easily assess sustainability using this model.

5.2 DEVELOPMENT OF A MANUFACTURING SUSTAINABILITY ASSESSMENT MODEL

This section proposes a sustainability assessment model for manufacturing organizations. This model has four important levels – life cycle assessment (integrated supply chain elements), resources, critical factors, and sustainability dimensions – as shown in Figure 5.1. Any meaningful sustainability assessment must include all the phases of the product life cycle or in other words the assessment must include the integrated supply chain (forward and backward supply chains).

The proposed model explicitly relates the sustainability indicators in terms of sustainability dimensions, three critical factors, seven resources, and product life cycle phases. This classification provides clarity for applicability of the indicator, dimension addressed by the indicator, and how it can affect the sustainability assessment. This simple classification provides useful guidance for the improvement of weak sustainability areas of the organization. This model is the detailed phase II of the manufacturing sustainability assessment framework given in chapter 3. Various levels of the model are explained next.

5.2.1 Level I: Product Life Cycle Phase

The first step is to develop a repository consisting various products (manufactured) and processes (used by the organization) with all the resources consumed by the organization, suppliers, customers, and EOL handlers. This repository is continuously updated as and when the changes happen in the organization. This provides a kaleidoscopic view during the indicator identification and ensures that no part of the sustainability measurement is left out.

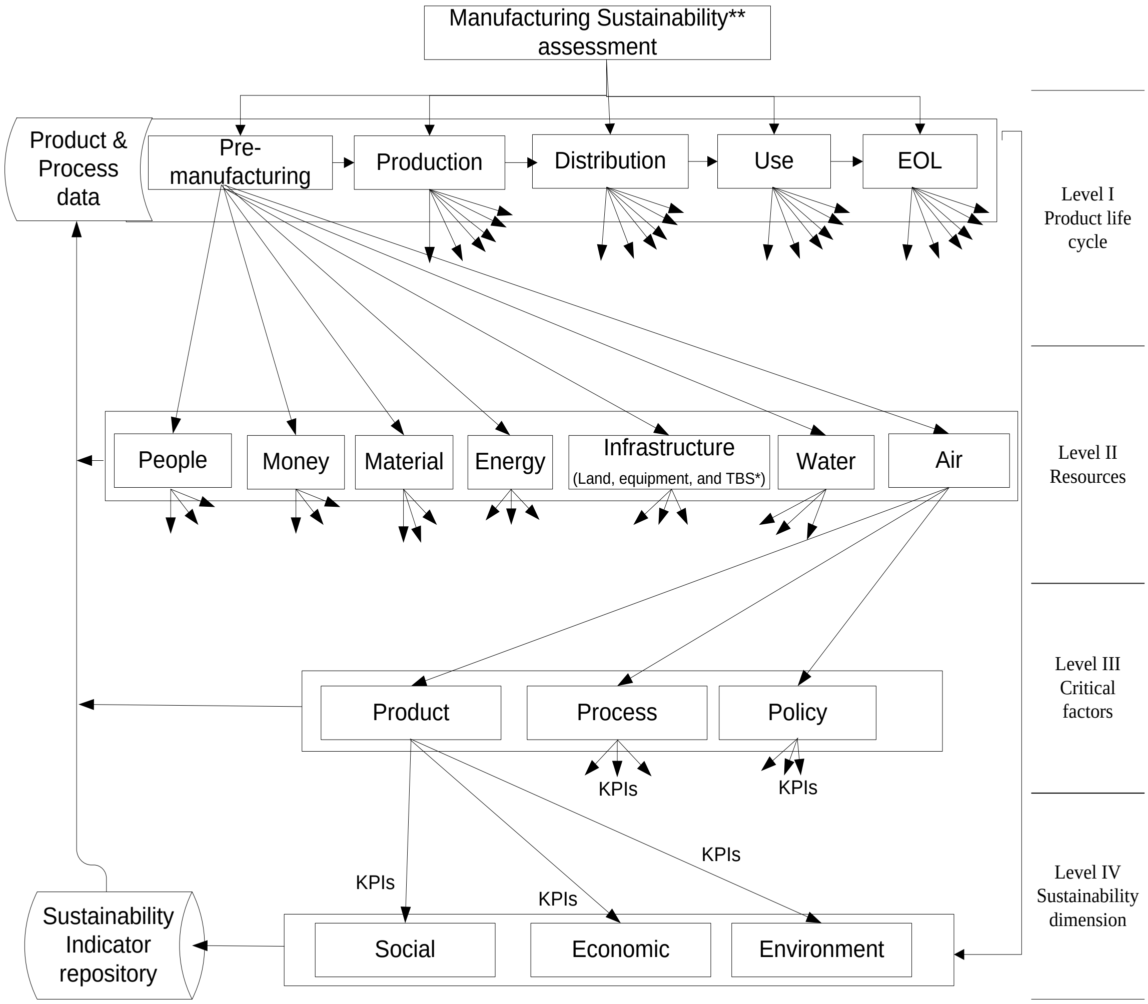


Figure 5.1. Proposed sustainability assessment model

* TBS – Technical building services

** Cradle to cradle process

5.2.2 Level II: Resources

Sustainability is about resource consumption and resource pollution. The efficient use of resources like material, energy, money, water, infrastructure, etc. makes an organization sustainable. Similarly, the non-pollution of air, water, land, etc. makes an organization sustainable. This level provides a comprehensive list of resources, which organizations either consume or affect along their integrated supply chain.

5.2.2.1 People

Every organization has internal and external people who are related directly or indirectly to the organization. These people include supply chain partners, stakeholders, shareholders, customers, employees, politicians, consultants, local community, etc. The proposed model proposes sustainability indicators for assessing the influence of organizational activities on these people and vice versa. This study considers the people as a mandatory resource for manufacturing organizations. The sustainable development and sustainability in manufacturing is directly and/or indirectly affecting the growing needs of people. Daily and Su (2001) discussed the factors like top management support, environmental training, employee empowerment, teamwork, and rewards to achieve sustainability. Nordheim and Barrasso (2007) discussed a study on development of sustainability indicators for European aluminium industry with a focus on internal and external stakeholders. Baskaran *et al.* (2012) assessed sustainability of suppliers of textile industry. Luo and Bhattacharya (2014) discussed a conceptual framework to test the effect of customer satisfaction on corporate social responsibility and market value. Saratun (2016) stated that the proper employee management is an important factor for corporate sustainability. Some of the aspects for which indicators have been identified in this study are: policies for people management, employee involvement, cost associated to employees, organizational investment for providing better working environment to employees, employee development and support, equal opportunity, health and safety aspects of employee and customer, customer management, local community, supplier development, stakeholders involvement, etc.

5.2.2.2 Money

Money is an essential resource for performing any operation, starting from the raw material extraction to the end-of-life treatment. The three important elements for an economically successful organization are: value creation, business model for value creation using both supplier and customer integration, and revenue policy of the organization (Boons *et al.*, 2013). Organizations generally generate revenue from sales of products but in case of sustainable manufacturing the reuse, remanufacturing, material recovery, overall equipment efficiency improvement, energy savings, etc. are feasible solutions for saving money and increasing profit. The organizations are also investing some part of their earnings for social upliftment, community development, eco-system improvement via planting trees, conserving water, and other CSR practices. Generating least environmental impact with higher economic gains is a new manufacturing paradigm (Mittal and Sangwan, 2014d). Egilmez *et al.* (2013) has also proposed a new method for integrating economic and environmental aspects to assess the sustainability of U.S. manufacturing sector. The various aspects of money included in the proposed model are eco-efficiency (the ratio of total financial output to environmental impact generated), the economic gains and losses (including revenue, taxes, costs, etc.), green technology investment, transportation, supplier, breakdown and accidental losses, environmental investments, fines and penalties, social investment, product responsibility, social responsibility, environmental responsibility, etc.

5.2.2.3 Materials

The natural resource depletion is one of the major threats to the society and manufacturing organizations play an important role in it, as manufacturing is an input-output process.

Manufacturing revolves around the material consumption. Reduction in material consumption and increase in use of recycled material can decrease the environmental impacts and reduce the rate of natural resource depletion. Material consumption and recycling of used material are also associated with the economic and social criteria of sustainability. Improving material efficiency (Meyer *et al.*, 2007) and developing strategies for materials management (Lindahl *et al.*, 2014) are important aspects of manufacturing sustainability. The hazardous materials and the related policies are important factors to reduce the social and environmental impacts. Material selection policies need to focus not only during the manufacturing but also during the other life cycle phases, particularly during end-of-life and use phases. Herrmann *et al.* (2014) suggested incorporating EOL strategies early in the design phase. Waste generation also has a significant impact on the productivity, resource efficiency and material efficiency. Researchers have favoured the concept of 6R (reduce, reuse, recycle, recover, redesign, and remanufacture) (Dassisti *et al.*, 2012; Joshi *et al.*, 2006) to improve material sustainability. The indicators have been identified to address the issue of material consumption, hazardous material consumption, waste policies, end-of-life options, use phase materials, fossil resources, maintenance and repair, etc.

5.2.2.4 Energy

Manufacturing processes and production systems require energy and it is a crucial part in any manufacturing value chain. Mostly, electricity is used for providing the operating supply to the equipment and machines. Energy is also required indirectly in the form of compressed air. Fossil fuels (coal, oil, gas, etc.) are commonly used for providing the energy to the manufacturing processes or equipment. Different sources of energy generate different environmental impacts. According to Kant and Sangwan (2014), the industrial sector accounts approximately half of the world's total energy requirement and the rate of consumption has doubled over last 60 years. The environmental emissions associated with electricity generation can be reduced by using renewable energy sources. Energy, in addition to the core production process requirement, is also required during product distribution, use and EoL phases. A lot of research is being done these days to reduce the energy consumption in transportation (Pressley *et al.*, 2014; Sweeting and Winfield, 2012). The indicators addressed under this category are energy consumption for production (both conventional and non-conventional), energy required for operation of product, energy cost, energy for distribution, reverse logistics, etc.

5.2.2.5 Infrastructure

Infrastructure is considered as a resource and it consists of technical building services (TBS), land and equipment. This is because every manufacturing process chain requires some enclosures or attachments to provide the required environment for working. TBS provides the essential services like cooling and heating, illumination, amenities required for employees and workers, process specific supplies (compressed air, exhaust systems, etc.), communication system, etc. According to Hesselbach *et al.* (2008), the function of TBS is to provide required production conditions in terms of moisture, temperature, conditioning of air, and purity through heating/cooling. The organizations are looking for energy efficient buildings (Russell-Smith *et al.*, 2015) which lead to reduction in overall energy consumption. Utilization of total sunlight is also increasing in the industry. Secondly, the land is required for construction, storage of inventory and finished products, waste disposal, etc. (Castellini *et al.*, 2012; Labuschagne *et al.*, 2005). Land is an essential element of infrastructure because the development of infrastructure completely varies with quality of land (protected area, brown field, barren, etc.). The infrastructure also covers the equipment required to carry out the production processes. The equipment, in the manufacturing value chain, consumes major part of the energy. The proper selection of plant layout can reduce the unnecessary man and material movement, along with reduction in energy consumption (Hesselbach *et al.*, 2008). Indicators addressed under this resource category are land requirement, waste land and energy consumption.

5.2.2.6 Air

The maintenance of healthy work environment is essential from social perspective. The manufacturing processes generate emissions in various forms (gases, particulates, fumes, etc.), degrade the quality of air, and create noise. Discharge of harmful gases, particulate matter and noise are generally considered under air emission. This discharge is due to the use of equipment, machines, energy, and chemicals during the pre-manufacturing, manufacturing, and post- manufacturing activities. Kyoto protocol (Grubb *et al.*, 1999) and Intergovernmental Panel on Climate Change (IPCC, 2007) define air emissions in terms of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), per-fluorocarbons (PFCs), Nitrogen tri-fluoride (NF_3), particulate matter, and sulphur hexafluoride (SF_6). The air quality monitoring and air emissions are addressed in contemporary research frequently (Mani *et al.*, 2014; Rachuri *et al.*, 2011; Yin *et al.*, 2014). The reduction in air emissions can improve the sustainability of an organization. The associated outcomes of air emissions have led to serious phenomena like global warming and ozone depletion. The indicators for air cover air quality, noise emissions, concentration of air pollutants, compressed air, permissible limit of air emissions, etc.

5.2.2.7 Water

Water is a key element for maintaining ecosystem and favourable environment to support and sustain all forms of life. Quantifying the water usage and its associated measures provides understanding of potential environmental impacts and also the effect on the stakeholders at regional or global level (GRI Guidelines, 2011). Some studies assessed the water footprint of individuals and organizations to account the related environmental impacts (Bhakar *et al.*, 2015; Ene *et al.*, 2013; Li and Chen, 2014). The problems of water quality and availability are well known to the world. The polluted water discharge from the industry has rendered the water resources unusable and aqua life damaged. The possible solution for these problems is to recycle the used water or reuse the water by creating a closed loop. The water resource indicators cover water treatment cost, fresh and potable water consumption, discharge water quality, water recycled, etc.

5.2.3 Level III: Critical Factors

Initial sustainable activities attempted to reduce the use of energy and resources in production processes. Next, the aim of sustainability in manufacturing shifted towards product sustainability (Seliger *et al.*, 2008). It is well known that unless there are policies in the organization, which promote sustainability culture, it will be impossible to improve sustainability. Sustainability policies should be integrated with the business policies for the development of organizational goals. The addition of sustainable policies as constraints makes the sustainability as monster in the eyes of organizations. Pintér *et al.* (2012) argued, based on experiences from European Union and OECD countries, that decision made on the basis of sustainable development principles and triple bottom line are inadequate and unsuccessful. Therefore, these three critical factors have been developed to make sustainability assessment versatile and inclusive. Detailed description of these three critical factors is given in chapter 4.

5.2.4 Level IV: Sustainability Dimensions

The assessment of sustainability is inadequate if it is measured only for the three dimensions. However, the assessment of sustainability for the three dimensions is a necessary condition if not the sufficient condition. The final goal should be the assessment of environmental, social and economic sustainability. The assessment of resource sustainability and critical factors only helps the decision makers to develop a comprehensive and versatile repository of sustainability indicators from different perspectives in a guided manner. The triple bottom line assessment has been covered in the literature very well. The proposed model assesses and checks that the three dimensions are adequately addressed. 26 indicators have been identified for the economic assessment, 65 for the environmental assessment and 30 for the social assessment.

5.3 IDENTIFICATION OF SUSTAINABILITY ASSESSMENT INDICATORS

OECD (2001) defines indicator as a parameter or a value derived from parameters, which provides information about a phenomenon. Azapagic (2004) stated that indicators can translate sustainability issues into quantifiable measures of economic, environmental and social performance. Indicators can be classified as internal or external; stand-alone or aggregated; individual or composite; absolute or ratio; qualitative or quantitative. According to Jia *et al.* (2016), indicators are becoming an influential tool for policy making and public communication. The organizations can assess the sustainability within and beyond the organizational boundary. Indicator should be able to translate the internal as well as the external performance of an organization in terms of sustainability (Azapagic, 2004). According to Veleva and Ellenbecker (2001), the main objectives of an indicator are to raise awareness, provide useful information to decision makers, and assess the progress towards the pre-defined goals. According to UNCSD (2001), development and testing of indicators is a continuous process. The process of indicator development should be carried out to fine-tune the indicators over the time to face the new challenges of sustainability. The proposed model not only provides scope for the continuous improvement but also provides guided strategies for the continuous improvement.

The indicators have been selected from the contemporary literature. Many researchers believe that choosing proper indicators among a large number of sustainability indicators needs a proper guidance, which is lacking in the existing studies (Long *et al.*, 2016; Veleva & Ellenbecker, 2001). The following criteria have been considered for the selection of suitable indicators for sustainability assessment:

- Relevance: an indicator should be related to an aspect of sustainability. It should be meaningful and must serve a purpose.
- Accessibility: information/data about an indicator should be easy to identify/compute /process within a reasonable time frame.
- Measurability: it should be simple to measure an indicator qualitatively or preferably quantitatively
- Reliability: an indicator should reflect the same meaning under same conditions
- Understandability: it should be easy for stakeholders to interpret an indicator

Marnika *et al.* (2015) suggested 36 indicators (30 environmental, 4 social, 2 economic) for sustainability assessment of mining sites in protected areas. These 36 indicators were further divided into 7 major groups. Five of these groups were dedicated towards the environmental indicators, one group contains social indicators, and another group contains economic indicators.

Amrina and Vilsi (2015) conferred 13 key performance indicators (5 economic, 8 environmental, 6 social) to address sustainable manufacturing in cement industry. The managers and senior managers of cement industry were asked to rate the KPIs of cement industry on a scale of 1 to 9 to assess the sustainability performance.

Sureeyatanapas *et al.* (2015) developed a framework for the corporate assessment of Thai sugar industry along with 30 indicators of sustainability (7 environmental, 9 economic, 8 social, 6 quality). This study focuses on environmental impacts, resources, environmental management, profitability, cost and investment, fines and penalties, external society, internal society, international business standards, internal quality, external quality, and quality management as sustainability performance dimensions.

Rahdari and Rostamy (2015) designed a general set of 70 sustainability indicators (12 environmental, 23 social, 35 economic) for corporate sustainability. The study reviews the existing indexes, guidelines and rating systems of sustainability.

Efroymson and Dale (2015) suggested 16 indicators (15 environmental, 1 productivity) for environmental sustainability of bio-fuel production. These environmental sustainability indicators have six major categories *viz.* soil quality, water quality, greenhouse gases, bio-diversity, air quality, and productivity.

Tseng (2013) modeled the sustainability indicators (10 environmental, 11 social) using linguistic preferences for assessment of production processes. Further, these indicators were applied in a printed circuit board manufacturing unit to assess sustainability.

However, indicators are not categorized into sustainability dimensions or performance measures.

Nordheim and Barrasso (2007) provided a set of sustainability indicators for European aluminum industry and proposed 33 sustainability indicators. These 33 indicators are under 11 sustainability performance dimensions (policy and management efforts, production, competitiveness, revenues and payments, employee conditions and relations, community relationship, health and safety, resource use global, resource use European, emissions, and product life cycle).

Afgan *et al.* (2000) provided a set of indicators to assess the sustainability of energy systems for an island and in this regard, 14 sustainability indicators (4 resources, 4 environmental, 3 social, 3 economic) were identified. These indicators were then assessed to represent the sustainability of solar, wind, bio-mass, and oil-based energy generation systems to select the most appropriate energy system for the study area.

Searcy *et al.* (2005) suggested an approach for the development of a set of sustainability indicators for the energy industry. In this study, 122 indicators of sustainability were incorporated (93 newly developed and 23 existing indicators) to assess the sustainability of a energy utility company.

Hemdi *et al.* (2013) suggested a sustainability evaluation method using 28 sustainability parameters to develop a sustainability index. This study can be used by decision makers for sustainability assessment.

Corbire-Nicollier *et al.* (2011) compared the bio-ethanol supply chain for locally prepared and imported bio-ethanol using sustainability indicators. In this study, 18 sustainability indicators (8 environmental, 5 economic, 5 social) are compared for both scenarios of bio-ethanol production (locally prepared and imported).

Graedel and Allenby (2002) discussed about the environmental performance of the industry in terms of hierarchical metrics for sustainability. 10 environmental sustainability indicators are discussed under the scope of 4 performance dimensions (materials, resource consumption in processing, residuals and emissions, and operations).

Staniškis and Arbačiauskas (2009) presented a set of indicators for carrying out the sustainability performance assessment in an industrial enterprise. The study does not present full list of indicators and discusses only 8 indicators (2 economic, 4 environmental, 2 social).

Chardine-Baumann and Botta-Genoulaz (2014) presented a study for the sustainability assessment of supply chain management practices. In this study, 66 sustainability indicators (26 economic, 20 environmental, 20 social) under 15 performance measures have been considered.

Moldan *et al.* (2012) discussed various approaches and indicators which were developed to analyze the environmental sustainability indicators and also discussed the existing indicators from sustainability initiatives assessment programme. This study is limited to the discussion on environmental sustainability and does not discuss any particular list of indicators.

Kuhndt *et al.* (2002) opined that indicators are important for sectoral and sustainable business development. The study examined the stakeholder's participation and developed indicators for the generalized industry sector. However, it does not provide a list of indicators.

Henri and Journeault (2008) presented a study to address the environmental sustainability indicators for Canadian manufacturing firms. This study discusses 31 indicators of environmental sustainability in terms of use, strategy, and importance of measurement.

GRI Guidelines (2011) provided a generalized framework for sustainability reporting of industries on a voluntary basis. In this framework, along with guidelines, a list of 87 indicators (10 economic, 47 social, 30 environmental) is provided. An organization can choose the indicators for reporting sustainability.

Institute of chemical engineers (IChemE) (2002) provided the sustainability progress development metrics/indicators for process industries. This report provided a list of 54 sustainability indicators (14 economic, 14 social, 26 environmental) for sustainability assessment of industry.

Dow Jones sustainability indexes (DJSI) (2011) are the sustainability indexes of organizations based on the social, economic and environmental investments. These indexes were provided globally by the Dow Jones group and RebcoSAM company. In this report, 54 sustainability criteria (24 economic, 21 social, 9 environmental) have been discussed for assessment of sustainability index of an organization.

Sikdar (2003) discussed sustainability development and sustainability metrics for the chemical industry in quantitative terms. Author of the article believes that a small list of sustainability metrics/indicators will not be sufficient to address the sustainability comprehensively. The study does not provide a list of sustainability indicators but some examples are discussed.

United Nations commissions on sustainable development (UNCSD) (2001) provided framework and guidelines for sustainable development of countries in 2001. A list of 52 sustainability indicators (14 economic, 19 social, 19 environmental) is provided for assessing the sustainable development.

Joung *et al.* (2013) presented a study on the categorization of indicators for sustainable manufacturing and reviewed the publicly available indicators. This study provides a repository of 200 indicators and also discusses some indicators with the performance measures and examples.

Krajnc and Glavic (2003) provided the sustainability indicator set for measuring the environmental sustainability. It aims to address the sustainability in manufacturing organizations with a set of 89 indicators (16 economic, 10 social, 63 environmental). This sustainability indicator set is aimed to be applied at the strategic level.

Lowell center for sustainable production (LCSP) in the year 2001 provided framework and methodology for sustainable production in terms of sustainability indicators (Veleva and Ellenbecker, 2001). A list of 68 sustainability indicators (16 economic, 32 social, 20 environmental) is developed. The framework for sustainable production suggests indicators at five levels.

Li *et al.* (2012) presented a new method for development of composite sustainability indicators. In this study, principal component analysis (PCA) has been applied and a survey was conducted to find out the most suitable sustainable manufacturing indicators. A list of 33 sustainability indicators (11 economic, 10 social, 12 environmental) has been presented for the sustainability assessment.

Mani *et al.* (2014) provided an overview of elements to evaluate the performance of sustainable manufacturing. This study mainly focuses on environmental impacts and discusses LCA as an important aspect in manufacturing. The social and economic aspects are not covered in the scope of the study. This study selected only seven environmental sustainability indicators (energy, energy efficiency, embodied energy, carbon dioxide, waste, water, and emissions).

Delai and Takahashi (2011) presented a reference model for the sustainable measurement system. This study aims to develop a model for measurement of corporate sustainability and integrate measures with current performance management system. This study proposed a set of 47 sustainability indicators (6 economic, 20 social, 21 environmental) on the basis of literature review.

Ziout *et al.* (2013) presented a study to discuss the possibility of manufacturing system re-use using a multi-criteria decision-making approach. 12 sustainability indicators (6 economic, 3 social, 6 environmental) are used to develop the model and assess the manufacturing system re-use.

Singh *et al.* (2014) discussed the utilization of fuzzy for sustainability assessment of SMEs. To demonstrate the sustainability assessment of SMEs a set of 21 sustainability indicators (4 economic, 5 social, 12 environmental) are proposed.

Paju *et al.* (2010) developed a new manufacturing mapping methodology for sustainability assessment using the extension of value stream mapping (VSM) and named it as sustainable manufacturing mapping (SMM). In this study, a total 27 sustainability indicators (5 economic, 3 social, 13 environmental, 6 others) are proposed for the assessment.

Lu *et al.* (2011) proposed a framework of product and process indicators for sustainable manufacturing. This study discussed a 20 product and process metrics/indicators (5 economic, 6 social, 9 environmental) for sustainability assessment with their inter-relationship.

Jain and Kibira (2010) described a new concept of multi-resolution modeling for system dynamics in sustainable manufacturing. This study basically presented four domains for system dynamics modeling, *viz.* financial, environmental, social, and manufacturing. It provided a list of 48 elements/indicators (17 manufacturing, 12 economic, 7 social, 12 environmental) for sustainable manufacturing.

Dubey *et al.* (2015) presented a conceptual framework for world-class sustainable manufacturing using a structured questionnaire. This study incorporates the concept of leadership, regulatory pressure, supplier relationship management (SRM), employee involvement, reconfigurable manufacturing system (RMS), lean production, and agile manufacturing. This study proposes a list of elements in form of questions (7 leadership, 4 regulatory pressures, 5 SRM, 3 employee involvement, 7 RMS, 5 lean, 5 environmental, 6 agile, 3 social, 4 economic) for addressing sustainability in a world-class manufacturing organization.

Garbie (2014) developed an analytical technique to address the sustainability in supply chain practices with help of a composite index. In this study, a set of 79 sustainability indicators (43 economic, 19 social, 17 environmental) has been developed and utilized to define the composite index.

Azapagic (2004) offered a framework for mines and mineral industry inspired from the Mining, Minerals, and Sustainable Development (MMSD) project. This study provided a set of 130 sustainability indicators (26 economic, 46 social, 59 environmental) for assessment.

Singh *et al.* (2007) presented a study for the development of composite sustainability index for steel industry using fuzzy logic. This study addresses 60 sustainability indicators (12 organizational governance, 14 technical, 5 economic, 15 environmental, 14 social) for the steel industry. Strezov *et al.* (2013) discussed the important parameters for defining the role of steelmaking process in sustainable development. This study described a small set of environmental sustainability indicators for assessment of three different iron and steel making processes. Long *et al.* (2016) presented a sustainability assessment system for steel and iron industry of China. In the study, 7 economic indicators, 4 social indicators, and 5 environmental indicators are used.

Clarke-Sather *et al.* (2011) developed a set of sustainability indicators for the textile industry. In this study, 34 indicators (8 social, 7 economic, 3 environmental) are proposed for the three dimensions of the sustainability.

Jia *et al.* (2016) presented an integrated sustainability assessment of ethanol production process in terms on both qualitative and quantitative indicators. The study has incoroporated economic, environmental, and safety indicators. The economic indicators are mainly based on three aspects of raw material cost, operations cost, and capital cost. There are eight environmental indicators mainly assessing the environmental impacts in quantitative terms. Nine indicators measure the aspects of safety and security.

Winroth *et al.* (2016) developed a list of sustainable production indicators, which are useful for the production managers. Literature review and survey based methodology has been utilized and a list of 27 indicators is proposed. It consists 15 environmental indicators, 4 economic indicators, and 8 social indicators. Table 5.1 provides the list articles proposing/using more than 50 indicators. This table also provides the focus area of these articles.

Table 5.1 List of articles with large number of sustainability assessment indicators

S. No.	Title	Focus	No. of indicators
1.	(Joung *et al.*, 2013)	Manufacturing	200
2.	(Azapagic, 2004)	Mines and mineral	130
3.	(Searcy *et al.*, 2005)	Energy	122
4.	(Krajnc and Glavic, 2003)	Manufacturing	89
5.	(GRI Guidelines, 2011)	Generalized	87
6.	(Garbie, 2014)	Manufacturing	79
7.	(Rahdari and Rostamy, 2015)	Corporate sustainability	70
8.	(Veleva and Ellenbecker, 2001)	Manufacturing	68
9.	(Baumann and Genoulaz, 2014)	Generalized	66
10.	(Singh *et al.*, 2007)	Steel	60
11.	(IChemE, 2002)	Generalized	54
12.	(DJSI, 2011)	Generalized	54
13.	(UNCSD, 2001)	Governance	52
14.	(Winroth *et al.*, 2016)	Manufacturing	52

The proposed sustainability indicators are identified from the review of contemporary literature on sustainability assessment and the discussion held with industry professional. Table 5.2 shows the literature source(s) of the identified indicators. The list of indicators consists of total 121 indicators out of which, 37 are policy assessment indicators, 33 are product sustainability indicators, and 51 are process sustainability indicators. The list has 26 economic indicators, 65 environmental indicators and 30 social indicators. The review of current literature for sustainability assessment provides an impression of diversified nature of work to address the set of sustainability indicators and assessment methods. The basic purpose of identified indicators is sustainability assessment. Therefore, the indicators should be able to measure resources consumed/affected across the integrated supply chain of the organization. These indicators can also be used to measure the critical factors of sustainability (sustainability policies, product sustainability and process sustainability) as well as the dimensions of the sustainability (environmental, economic, and social). The various resources compiled for the purpose are people, money, material, energy, infrastructure (technical building services, infrastructure and land), water, and air. The basic idea is that the sustainability is related to resource consumption. It is imperative that all the resources consumed/affected are understood and measured. The identified indicators are presented in Table 5.3 with the units. This table also shows the sustainability dimension, critical factor and resource(s) intended to be measured using the indicators.

Table 5.2 Identified sustainability assessment indicators and literature source

S. No.	Indicator	Important references
1.	Investment in employee training	Krajnc and Glavic (2003), IChemE (2002), Azapagic (2004), Sureeyatanapas *et al.* (2014)
2.	Labor productivity	Shen *et al.* (2011), Castellini *et al.* (2012), Singh *et al.* (2007)
3.	Penalties due to violation of rules	Veleva and Ellenbecker (2001), Azapagic (2004), Krajnc and Glavič (2005), Azapagic (2003), Sureeyatanapas *et al.* (2014)
4.	Technology and innovation cost	Delai and Takahashi (2011), Krajnc and Glavič (2005), Staniškis and Arbačiauskas (2009), Shen *et al.* (2011), Jasinski *et al.* (2016)
5.	Operational cost	Veleva and Ellenbecker (2001), Lu *et al.* (2011), Clarke-Sather *et al.* (2011), Bragança *et al.* (2010), Husgafvel *et al.* (2014), Jasinski *et al.* (2016)
6.	Transportation cost	UNCSD (2001- 2007), Clarke-Sather *et al.* (2011)
7.	Total cost	Veleva and Ellenbecker (2001), Singh *et al.* (2014), Heller and Keoleian (2000), Jasinski *et al.* (2016)
8.	Capital employed	Delai and Takahashi (2011), Ziout *et al.* (2013), Azapagic (2004), Krajnc and Glavič (2005), Shen *et al.* (2011), Azapagic (2003)
9.	Investment in new services and products	UNCSD (2001- 2007), Veleva and Ellenbecker (2001), Krajnc and Glavič (2005), Staniškis and Arbačiauskas (2009), Singh *et al.* (2007), Azapagic (2003)
10.	Fraction of production cost used for supplier development	Li *et al.* (2012), Jasinski *et al.* (2016), Sureeyatanapas *et al.* (2014)
11.	Average disassembly cost	Lu *et al.* (2011), Gunasekaran and Spalanzani (2012), Chung and Wee (2008), Paul *et al.* (2014), Gungor and Gupta (1999)

S. No.	Indicator	Important references
12.	Maintenance and improvement cost	Santoyo-Castelazo and Azapagic (2014), Liyanage (2007), Lu *et al.* (2011), Bragança *et al.* (2010), Winroth *et al.* (2016), Jasinski *et al.* (2016)
13.	Warranty cost	Lu *et al.* (2011), Jasinski *et al.* (2016), Batterham (2006), Jayaraman *et al.* (2012)
14.	Market share in percentage	Labuschagne *et al.* (2005), Veleva and Ellenbecker (2001), Azapagic (2004), Samuel *et al.* (2013), Kushwaha and Sharma (2015), Sureeyatanapas *et al.* (2014)
15.	Return on investment	IChemE (2002), Azapagic (2004), Heller and Keoleian (2000), Azapagic (2003), Chalmeta *et al.* (2012)
16.	Profit gained	Labuschagne *et al.* (2005), Delai and Takahashi (2011), Singh *et al.* (2007), Azapagic (2003), Chalmeta *et al.* (2012)
17.	Value addition in production	Krajnc and Glavic (2003), IChemE (2002),, Ziout *et al.* (2013), Azapagic (2004), Azapagic (2003)
18.	Income	Boggia and Cortina (2010), Adopted from (Warhurst, 2002), Singh *et al.* (2007), Castellini *et al.* (2012)
19.	Annual sales volume	IChemE (2002), Azapagic (2004), Krajnc and Glavič (2005), (Parthasarathy *et al.*, 2005), Zingales and Hockerts (2003)
20.	Customer satisfaction	GRI Guidelines (2011 - 2015), Delai and Takahashi (2011), Azapagic (2004), Singh *et al.* (2014), Li *et al.* (2012), Winroth *et al.* (2016), Sureeyatanapas *et al.* (2014)
21.	Energy taxes paid	OECD (2001), WRI (2004), Chuang and Yang (2014)
22.	Waste treatment cost	Krajnc and Glavic (2003), UNCSD (2001- 2007), Husgafvel *et al.* (2014), Jasinski *et al.* (2016), Sangwan (2013)
23.	Land used	Labuschagne *et al.* (2005), IChemE (2002), Singh *et al.* (2014), Castellini *et al.* (2012), Bragança *et al.* (2010), Jasinski *et al.* (2016), Winroth *et al.* (2016)
24.	Number of trees planted in the year	Azapagic (2004), UNCSD (2001- 2007), McDonald and Young (2012), Amini and Bienstock (2014)
25.	Land rehabilitation	GRI Guidelines (2011 - 2015), IChemE (2002), Azapagic (2004), Shen *et al.* (2011), Jasinski *et al.* (2016)
26.	Environmental liability cost	Krajnc and Glavic (2003), Azapagic (2004), Krajnc and Glavič (2005), Staniškis and Arbačiauskas (2009), Li *et al.* (2012), Sureeyatanapas *et al.* (2014)
27.	Packaging cost	Krajnc and Glavic (2003), Saikis (1998), Vinodh *et al.* (2012)
28.	Economical risk	Li *et al.* (2010), GRI Guidelines (2011 - 2015), Ziout *et al.* (2013), Adams and Ghaly (2006), Husgafvel *et al.* (2014)
29.	Noise emissions	Shen *et al.* (2011), Singh *et al.* (2007), Azapagic (2003)
30.	Wicked smell in air	OECD (2001), Ziout *et al.* (2013), Shen *et al.* (2011)

S. No.	Indicator	Important references
31.	Carbon dioxide (CO_2) emission	OECD (2001), Azapagic (2004), Lu *et al.* (2011), Krajnc and Glavič (2005), Boggia and Cortina (2010), Azapagic (2003), Winroth *et al.* (2016), Jasinski *et al.* (2016)
32.	Total hydrocarbon (THC)	Krajnc and Glavič (2005), Jasinski *et al.* (2016), Moran *et al.* (2014)
33.	NO_x emissions	OECD (2001), Azapagic (2004), Lu *et al.* (2011), Krajnc and Glavič (2005), Li *et al.* (2012), Azapagic (2003), Winroth *et al.* (2016), Jasinski *et al.* (2016)
34.	Particulate matter (PM)	GRI Guidelines (2011 - 2015), Ziout *et al.* (2013), UNCSD (2001- 2007), Veleva and Ellenbecker (2001), Li *et al.* (2012), Shen *et al.* (2011), Azapagic (2003), Singh *et al.* (2007), Jasinski *et al.* (2016), Sureeyatanapas *et al.* (2014)
35.	Water cost fraction	Krajnc and Glavic (2003), (Jia *et al.*, 2015), Taylor *et al.*, (2012)
36.	Potable water used	Boggia and Cortina (2010), Bragança *et al.* (2010), (Al-ayouty *et al.* (2016), Marshall and Toffel (2005)
37.	Water used	IChemE (2002),, Labuschagne *et al.* (2005), Lu *et al.* (2011), Ziout *et al.* (2013), Azapagic (2004), Krajnc and Glavič (2005), Singh *et al.* (2014), Li *et al.* (2012), Azapagic (2003), Shen *et al.* (2011), Harik *et al.* (2015), Winroth *et al.* (2016), Sureeyatanapas *et al.* (2014)
38.	Fraction of water recycled	GRI Guidelines (2011 - 2015), Azapagic (2004), Lu *et al.* (2011), Li *et al.* (2012), Winroth *et al.* (2016), Baumann and Genoulaz (2014)
39.	Fraction of water reused†	GRI Guidelines (2011 - 2015), Azapagic (2004), Li *et al.* (2012)
40.	Liters of BOD (bio-chemical oxygen demand)	UNCSD (2001- 2007), Veleva and Ellenbecker (2001), Delai and Takahashi (2011), Shen *et al.* (2011), Heller and Keoleian (2000)
41.	Liters of COD(chemical oxygen demand)	Delai and Takahashi (2011), Krajnc and Glavič (2005), Heller and Keoleian (2000)
42.	Total amount of energy used	GRI Guidelines (2011 - 2015), IChemE (2002), Ziout *et al.* (2013), Azapagic (2004), Krajnc and Glavič (2005), Staniškis and Arbačiauskas (2009), Heller and Keoleian (2000), Li *et al.* (2012), Azapagic (2003), Winroth *et al.* (2016), Jasinski *et al.* (2016)
43.	Fraction of renewable energy used	Krajnc and Glavic (2003), Labuschagne *et al.* (2005), Singh *et al.* (2014), Azapagic (2004), Heller and Keoleian (2000), Clarke-Sather *et al.* (2011), Li *et al.* (2012), Azapagic (2003), Winroth *et al.* (2016), Jasinski *et al.* (2016), Garbie (2014), Baumann and Genoulaz (2014)

S. No.	Indicator	Important references
44.	Energy required for material recycling	Krajnc and Glavic (2003), Lu *et al.* (2011)
45.	Energy utilized for maintenance and repair	Lu *et al.* (2011), Heller and Keoleian (2000)
46.	Amount of hazardous solid waste	Krajnc and Glavic (2003), Azapagic (2004), Winroth *et al.* (2016), IChemE (2002), Sureeyatanapas *et al.* (2014)
47.	Liquid waste generated	Krajnc and Glavic (2003), Ziout *et al.* (2013), Azapagic (2004)
48.	Amount of total solid waste	IChemE (2002), Krajnc and Glavic (2003), Azapagic (2004), Li *et al.* (2012), Clarke-Sather *et al.* (2011), Shen *et al.* (2011), Azapagic (2003), Winroth *et al.* (2016), Singh *et al.* (2007)
49.	Fraction of solid waste recycled	Staniškis and Arbačiauskas (2009), Shen *et al.* (2011), Singh *et al.* (2007), Harik *et al.* (2015)
50.	Fraction of liquid waste treated	Staniškis and Arbačiauskas (2009), Shen *et al.* (2011), Harik *et al.* (2015)
51.	Amount of liquid waste	Krajnc and Glavic (2003), Ziout *et al.* (2013), Azapagic (2004)
52.	Landfill area	Clarke-Sather *et al.* (2011), Heller and Keoleian (2000), Shen *et al.* (2011)
53.	Quantity of toxic released	Veleva and Ellenbecker (2001), Ziout *et al.* (2013), Clarke-Sather *et al.* (2011), Castellini *et al.* (2012)
54.	Total raw material used	Krajnc and Glavic (2003), IChemE (2002), Ziout *et al.* (2013), Singh *et al.* (2007), Husgafvel *et al.* (2014), Winroth *et al.* (2016), Jasinski *et al.* (2016)
55.	Fraction of recycled material used	Krajnc and Glavic (2003), GRI Guidelines (2011 - 2015), Clarke-Sather *et al.* (2011), Staniškis and Arbačiauskas (2009), Li *et al.* (2012)
56.	Hazardous material used	Krajnc and Glavic (2003), GRI Guidelines (2011 - 2015), IChemE (2002), Singh *et al.* (2014)
57.	Fraction of reused material	Singh *et al.* (2014), Geng *et al.* (2012), Remery *et al.* (2012)
58.	Fraction of raw material recycled within	IChemE (2002), Dassisti *et al.* (2016), Tsiliyannis (2015)
59.	Amount of hazardous material used by contracted service provider	Veleva and Ellenbecker (2001), Tseng (2013), Vinodh *et al.* (2013)
60.	Fraction of recyclable material used	Krajnc and Glavic (2003), GRI Guidelines (2011 - 2015), Singh *et al.* (2014), Li *et al.* (2012), Jasinski *et al.* (2016)
61.	Fraction of production to raw material by weight	Krajnc and Glavic (2003), Singh *et al.* (2014), Ziout *et al.* (2013)
62.	Quantity of chemical used	Veleva and Ellenbecker (2001), Azapagic (2004), Clarke-Sather *et al.* (2011), Heller and Keoleian (2000)

S. No.	Indicator	Important references
63.	Consumption of ozone depleting substance	Krajnc and Glavic (2003), IChemE (2002), Delai and Takahashi (2011), Winroth *et al.* (2016), Jasinski *et al.* (2016)
64.	Weight of packaging	Sangwan (2013), Krajnc and Glavic (2003), Azapagic (2004), Winroth *et al.* (2016)
65.	Fraction of reclaimed packaging	Sangwan (2013), Krajnc and Glavic (2003), Azapagic (2004), GRI Guidelines (2011 - 2015)
66.	Total energy used in distribution	Wang and Yang (2014), Shen *et al.* (2011), Heller and Keoleian (2000)
67.	Resources consumed in maintenance/service/repair	Lu *et al.* (2011), Sangwan (2013), Garbie (2014)
68.	Fossil fuel used	OECD (2001), Krajnc and Glavič (2005), Castellini *et al.* (2012), Bragança *et al.* (2010), Azapagic (2003)
69.	Average employee cost to company(CTC)	Azapagic (2004), Shen *et al.* (2011), Winroth *et al.* (2016), Chalmeta *et al.* (2012), Krajnc and Glavic (2003)
70.	Average social benefits to average (CTC)	GRI Guidelines (2011 - 2015), UNCSD (2001- 2007), IChemE (2002), Veleva and Ellenbecker (2001), Azapagic (2004), Winroth *et al.* (2016), Adams and Ghaly (2006)
71.	Investment in employee health and safety	Labuschagne *et al.* (2005), Lu *et al.* (2011), Heller and Keoleian (2000), Azapagic (2003), Jasinski *et al.* (2016), Sureeyatanapas *et al.* (2014)
72.	Employee retention rate	GRI Guidelines (2011 - 2015), Veleva and Ellenbecker (2001), Delai and Takahashi (2011), Azapagic (2004), Chalmeta *et al.* (2012), Sureeyatanapas *et al.* (2014)
73.	Employee complaints and suggestions	IChemE (2002), Krajnc and Glavič (2005), Husgafvel *et al.* (2014), Chalmeta *et al.* (2012)
74.	Employee satisfaction	Heller and Keoleian (2000), Li *et al.* (2012), Singh *et al.* (2007), Winroth *et al.* (2016)
75.	Total hours of employee training	Winroth *et al.* (2016), Chalmeta *et al.* (2012), Husgafvel *et al.* (2014), Singh *et al.* (2014), Azapagic (2004), GRI Guidelines (2011 - 2015), Krajnc and Glavic (2003), Sutherland *et al.* (2016)
76.	Number of promotions per employee	Winroth *et al.* (2016), Krajnc and Glavic (2003), IChemE (2002)
77.	Fraction of employees covered through performance appraisal	Harik *et al.* (2015), Winroth *et al.* (2016), GRI Guidelines (2011 - 2015)
78.	Gender ratio	Azapagic (2003), Jasinski *et al.* (2016), Winroth *et al.* (2016), GRI Guidelines (2011 - 2015), Li *et al.* (2012), Azapagic (2004), Sutherland *et al.* (2016),

S. No.	Indicator	Important references
79.	Level of growth and opportunity	Delai and Takahashi (2011), Azapagic (2004), Singh *et al.* (2007)
80.	Female to male salary ratio	Chalmeta *et al.* (2012), Harik *et al.* (2015), Winroth *et al.* (2016), GRI Guidelines (2011 - 2015), Jasinski *et al.* (2016)
81.	Level of social security	Labuschagne *et al.* (2005), Winroth *et al.* (2016), GRI Guidelines (2011 - 2015), Jasinski *et al.* (2016), Baumann and Genoulaz (2014), Sutherland *et al.* (2016)
82.	Fraction of local employee	Ziout *et al.* (2013), Azapagic (2004), Heller and Keoleian (2000)
83.	Number of jobs created	Chalmeta *et al.* (2012), Baumann and Genoulaz (2014), Garbie (2014), Delai and Takahashi (2011)
84.	Fraction of employees provided with continue education facility	Azapagic (2003), Boggia and Cortina (2010), Delai and Takahashi (2011)
85.	Fraction of income difference relative to industry	Veleva and Ellenbecker (2001), UNCSD (2001- 2007), Boggia and Cortina (2010), Shen *et al.* (2011), Jasinski *et al.* (2016), Sureeyatanapas *et al.* (2014)
86.	Fraction of skilled labor	Sutherland *et al.* (2016), IChemE (2002), Clarke-Sather *et al.* (2011), Jain S. and Kibira (2010)
87.	Fraction of worker with work-related disease	GRI Guidelines (2011 - 2015), Winroth *et al.* (2016), Azapagic (2004), Veleva and Ellenbecker (2001), Shen *et al.* (2011), Li *et al.* (2012)
88.	Number of work-related accidents/incidents	Labuschagne *et al.* (2005), IChemE (2002), Krajnc and Glavič (2005), Boggia and Cortina (2010), Bragança *et al.* (2010), Azapagic (2004), Azapagic (2003)
89.	Total number of complaints from local community	Husgafvel *et al.* (2014), Krajnc and Glavič (2005), Azapagic (2004), Azapagic (2003)
90.	Fraction of supplier from local area	Azapagic (2003), Veleva and Ellenbecker (2001), Sureeyatanapas *et al.* (2014), GRI Guidelines (2011 - 2015)
91.	Community involvement	Azapagic (2003), Jasinski *et al.* (2016), Garbie (2014), Baumann and Genoulaz (2014) Sureeyatanapas *et al.* (2014), Singh *et al.* (2014), Azapagic (2004), Govindan *et al.* (2016)
92.	Stakeholders empowerment	Labuschagne *et al.* (2005), IChemE (2002), Azapagic (2004), Azapagic (2003), Winroth *et al.* (2016), Adams and Ghaly (2006),
93.	Expenditure in social development	Labuschagne *et al.* (2005), Azapagic (2004), Veleva and Ellenbecker (2001), Krajnc and Glavic (2003), Krajnc and Glavič (2005), Harik *et al.* (2015), Li *et al.* (2012)
94.	Reported customer health and safety issues	Veleva and Ellenbecker (2001), Sureeyatanapas *et al.* (2014), Delai and Takahashi (2011), Azapagic (2004), Singh *et al.* (2007), Winroth *et al.* (2016)

S. No.	Indicator	Important references
95.	Cost of man-hours lost in accidents/incidents	IChemE (2002), Azapagic (2004), Azapagic (2003), Staniškis and Arbačiauskas (2009),
96.	New customer added in the year	Sangwan (2013), Vinodh (2010), Jindal and Sangwan (2015), Garbie (2014)
97.	Fraction of compressed air utilized	Herrmann *et al.* (2014), Hesselbach *et al.* (2008), Gupta *et al.* (2016), Li *et al.* (2016)
98.	Fraction of product upgraded	Ratnayake and Markeset (2012), Rose (2000), Rose *et al.* (1998), Jawahir *et al.* (2006)
99.	Non-monetary sanctions and warnings	GRI Guidelines (2011 - 2015), Gomes *et al.* (2013), Delai and Takahashi (2011)
100.	Fraction of production collected from customer at EOL	Jindal and Sangwan (2015), Sangwan (2013), Brockhaus *et al.* (2016)
101.	Water treatment and recycling cost	OECD (2001), Moran *et al.* (2014), Sangwan (2006), Scholz *et al.* (2012)
102.	Fraction of wastewater reused†	Mascarenhas *et al.* (2015), United Nations (2012), Gabaldón-estevan *et al.* (2014)
103.	Fraction of energy generated through cogeneration	Saravia-Cortez *et al.* (2013), Tanzil and Beloff (2003), Madlool *et al.* (2011)
104.	Energy consumed in use phase	Sangwan (2013), Brockhaus *et al.* (2016), Sweeting and Winfield (2012)
105.	Energy consumed to get one unit of raw material at plant	Verrier *et al.* (2014), Lee *et al.* (2014)
106.	Solid waste used (i.e. by-products)	Hasanbeigi *et al.* (2012), Veleva and Ellenbecker (2001), Jia *et al.* (2016)
107.	Fraction of production landfilled	Romli *et al.* (2014), Mangun and Thurston (2002), Myhre *et al.* (2013)
108.	Fraction of production incinerated	Romli *et al.* (2014), Mangun and Thurston (2002), Myhre *et al.* (2013)
109.	Fraction of supplementary material used	Sangwan (2013), Herrmann *et al.* (2014), Supino *et al.* (2016)
110.	Total fossil fuel used in distribution	Dale *et al.* (2013), Pressley *et al.* (2014)
111.	Fraction of renewable resources used in distribution	Dale *et al.* (2013), Pressley *et al.* (2014)
112.	Fraction of remanufactured parts used	Sari *et al.* (2015), Subramoniam *et al.* (2013), Abdallah *et al.* (2012)
113.	Resources consumed in use phase (operation)	Sangwan (2013), Aschehoug and Boks (2013)

S. No.	Indicator	Important references
114.	Fraction of production recycled	Nordheim and Barrasso (2007), Govindan *et al.* (2016)
115.	Fraction of production remanufactured	Sangwan (2013), O'Brien, (2002)
116.	Total fossil fuel used in reverse logistics	Sarkis *et al.* (2010), Jindal and Sangwan (2015)
117.	Fraction of renewable resources used in reverse logistics	Jindal and Sangwan (2015), Dubey *et al.* (2016), Govindan *et al.* (2016)
118.	Average sick leave per employee	Veleva and Ellenbecker (2001), Singh *et al.* (2007), Husgafvel *et al.* (2014)
119.	Fraction of contractual labor	GRI Guidelines (2011 - 2015), Amirmostofian *et al.* (2014), Husgafvel *et al.* (2014)
120.	Company image in market	Sureeyatanapas *et al.* (2014), Vimal and Vinodh (2013), Aɫan *et al.* (2016), Epstein and Marie-Josée (2001)
121.	Percentage of outsourced components/sub-assembly	Moosavirad *et al.* (2014), Gunasekaran and Irani (2010), Mendoza and Clemen (2013)

Table 5.3 Sustainability assessment indicators with units, sustainability dimension, critical factor and resources represented by them

S. No.	**Indicators (critical factor)**	**Unit**	**Sustainability Dimension**	**Resources**						
				P	**Mo**	**M**	**E**	**I**	**W**	**A**
1.	Investment in employee training (P1)	USD per annum	Economic	√	√					
2.	Labor productivity (P3)	Hrs per unit production (UP)	Economic	√	√					
3.	Cost of man-hours lost in accidents/incidents (P3)	USD per annum	Economic	√	√	√				
4.	Penalties due to violation of rules (P3)	USD per annum	Economic		√		√	√	√	√
5.	Technology and innovation cost (P1)	USD per annum	Economic		√	√	√	√		
6.	Operational cost (P3)	USD per UP	Economic	√	√	√	√			
7.	Transportation cost (P2)	USD per annum	Economic		√	√				
8.	Total cost (P2)	USD per UP	Economic	√	√	√	√	√	√	
9.	Capital employed (P2)	USD	Economic		√			√		
10.	Investment in new services and products (P1)	USD per annum	Economic		√	√				
11.	Fraction of production cost used for supplier development (P1)	Supplier development cost/ total production costs	Economic	√	√					
12.	Average disassembly cost (P3)	USD per UP	Economic		√					
13.	Maintenance and improvement cost (P3)	USD per UP	Economic		√			√		
14.	Warranty cost (P2)	USD per UP	Economic		√	√				
15.	Market share in percentage (P2)	%	Economic		√					
16.	Return on investment (P1)	Profit/ Cost	Economic		√					
17.	Profit gained (P2)	USD per annum	Economic	√	√					
18.	Value addition in production (P3)	USD per UP	Economic		√	√				
19.	Income (P2)	USD per annum	Economic		√					

S. No.	Indicators (critical factor)	Unit	Sustainability Dimension	Resources						
				P	Mo	M	E	I	W	A
20.	Annual sales volume (P2)	Number	Economic		√					
21.	New customer added in the year (P2)	Number	Economic		√			√		
22.	Customer satisfaction (P2)	Likert Scale	Economic	√	√	√				
23.	Fraction of compressed air utilized (P3)	Compressed air used/ total compressed air produced	Economic		√		√	√		
24.	Energy taxes paid (P3)	USD	Economic		√		√			
25.	Waste treatment cost (P1)	USD per annum	Economic		√			√		
26.	Fraction of product upgraded (P2)	Product upgraded/ total sales volume	Economic		√	√				
27.	Land used (P2)	m^2 per UP	Environmental					√		
28.	Number of trees planted in the year (P1)	Number per unit area	Environmental					√		√
29.	Land rehabilitation (P1)	m^2 per annum	Environmental					√		
30.	Non-monetary sanctions and warnings (P3)	Number per annum	Environmental			√			√	√
31.	Environmental liability cost (P1)	USD per annum	Environmental		√					
32.	Packaging cost (P3)	USD per UP	Environmental		√	√				
33.	Economical risk (P1)	Likert scale	Environmental		√			√		
34.	Fraction of production collected from customer at EOL (P2)	Production collected/ total sales volume	Environmental	√		√				
35.	Noise emissions (P3)	Decibel or number of complaints	Environmental	√				√		√
36.	Wicked smell in air (P3)	Likert scale	Environmental	√						√
37.	Carbon dioxide (CO_2) emission (P3)	gm per UP	Environmental	√		√	√			√

S. No.	Indicators (critical factor)	Unit	Sustainability Dimension	Resources						
				P	Mo	M	E	I	W	A
38.	Total hydrocarbon (THC) (P3)	gm per UP	Environmental	√		√	√			√
39.	NO_x emissions (P3)	gm per UP	Environmental	√		√	√			√
40.	Particulate matter (PM) (P3)	gm per UP	Environmental	√		√	√			√
41.	Water cost fraction (P3)	water cost to total cost per UP	Environmental		√				√	
42.	Water treatment and recycling cost (P1)	USD	Environmental		√				√	
43.	Potable water used (P3)	m^3	Environmental	√					√	
44.	Water used (P2)	m^3 per UP	Environmental						√	
45.	Fraction of wastewater reused† (P3)	Wastewater reused/ total wastewater	Environmental						√	
46.	Fraction of water recycled (P3)	Water recycled/total water consumed	Environmental						√	
47.	Fraction of water reused† (P3)	Water reused/total water consumed	Environmental						√	
48.	Liters of BOD(bio-chemical oxygen demand) (P3)	mg/L	Environmental						√	
49.	Liters of COD(chemical oxygen demand) (P3)	mg/L	Environmental						√	
50.	Total amount of energy used (P3)	KWh per UP	Environmental				√			
51.	Fraction of renewable energy used (P3)	Renewable energy used to total energy used per UP	Environmental				√			
52.	Energy required for material recycling (P3)	KWh per kg of material recovered	Environmental				√			
53.	Fraction of energy generated through cogeneration (P1)	Energy cogenerated/ total energy consumed	Environmental				√	√	√	
54.	Energy utilized for maintenance and repair (P3)	KWh per UP	Environmental				√	√		

S. No.	Indicators (critical factor)	Unit	Sustainability Dimension	Resources						
				P	Mo	M	E	I	W	A
55.	Energy consumed in use phase (P2)	MJ per UP	Environmental				√			
56.	Energy consumed to get one unit of raw material at plant (P2)	MWh	Environmental				√			
57.	Amount of hazardous solid waste (P3)	Tonnes per annum	Environmental			√				
58.	Liquid waste generated (P3)	m^3 per UP	Environmental			√			√	
59.	Amount of total solid waste (P3)	Tonnes per annum	Environmental			√				
60.	Fraction of solid waste recycled (P1)	Solid waste recycled to total waste	Environmental			√	√			
61.	Solid waste used (i.e. by-products) (P3)	Tonnes per annum	Environmental		√	√				
62.	Fraction of liquid waste treated (P3)	Liquid waste treated to total liquid waste	Environmental				√		√	
63.	Amount of liquid waste (P3)	m^3 per annum	Environmental			√			√	
64.	Landfill area (P1)	m^3 per annum	Environmental					√		
65.	Quantity of toxic released (P3)	Kg per UP	Environmental			√			√	√
66.	Fraction of production landfilled (P2)	Production landfilled/ total sales volume	Environmental			√				
67.	Fraction of production incinerated (P2)	Production incinerated/ total sales volume	Environmental			√		√		
68.	Total raw material used (P2)	Kg per UP	Environmental			√	√			
69.	Fraction of recycled material used (P2)	Recycled material to total material per UP	Environmental		√	√	√			
70.	Hazardous material used (P2)	Kg per tonne of total material used	Environmental	√		√				

S. No.	Indicators (critical factor)	Unit	Sustainability Dimension	Resources						
				P	Mo	M	E	I	W	A
71.	Fraction of reused material (P2)	Reused material to total raw material	Environmental		√	√	√			
72.	Fraction of raw material recycled within (P1)	Material recycled within process to total material recycled	Environmental	√	√					
73.	Amount of hazardous material used by contracted service provider (P3)	Kg per UP	Environmental			√				
74.	Fraction of supplementary material used (P3)	Supplementary material used to total material used	Environmental			√				
75.	Fraction of recyclable material used (P2)	Recyclable material used to total material used	Environmental			√				
76.	Fraction of production to raw material by weight (P2)	Total production to total raw material used	Environmental			√				
77.	Quantity of chemical used (P3)	Kg per UP	Environmental			√				
78.	Consumption of ozone depleting substance (P3)	Kg per UP	Environmental			√				
79.	Weight of packaging (P3)	Kg per UP	Environmental			√				
80.	Fraction of reclaimed packaging (P3)	Reclaimed packaging used to total packaging used	Environmental		√	√				
81.	Total fossil fuel used in distribution (P3)	Kg. Oil eq. per UP	Environmental				√			
82.	Total energy used in distribution (P3)	KWh per UP	Environmental				√			
83.	Fraction of renewable resources used in distribution (P3)	Renewable resources used to total resources used	Environmental				√			
84.	Fraction of remanufactured parts used (P2)	Re-manufactured parts/ total parts	Environmental			√	√			

S. No.	Indicators (critical factor)	Unit	Sustainability Dimension	Resources						
				P	Mo	M	E	I	W	A
85.	Resources consumed in use phase (operation) (P2)	Kg. of material by type and weight	Environmental			√	√			
86.	Resources consumed in maintenance/service/repair (P2)	Kg. of material by type and weight	Environmental			√	√			
87.	Fraction of production recycled (P2)	Production recycled/ total sales volume	Environmental			√	√			
88.	Fraction of production remanufactured (P2)	Production re-manufactured/ total sales volume	Environmental	√		√	√			
89.	Total fossil fuel used in reverse logistics (P2)	Kg. oil eq. per UP	Environmental			√	√			
90.	Fraction of renewable resources used in reverse logistics (P2)	Renewable resources used to total resources used	Environmental			√	√			
91.	Fossil fuel used (P3)	Kg. oil Eq. per UP	Environmental				√			
92.	Average employee cost to company (CTC) (P1)	USD	Social	√	√					
93.	Average social benefits to average (CTC) (P1)	USD per employee	Social	√	√					
94.	Investment in employee health and safety (P1)	USD per annum	Social	√	√					
95.	Employee retention rate (P1)	%	Social	√	√					
96.	Average sick leave per employee (P3)	Number	Social	√	√				√	√
97.	Employee complaints and suggestions (P1)	Number	Social	√					√	√
98.	Employee satisfaction (P1)	Likert scale	Social	√	√				√	√
99.	Total hours of employee training (P1)	Hours/annum/employee	Social	√	√					
100.	Number of promotions per employee (P1)	Number per annum	Social	√	√					

S. No.	Indicators (critical factor)	Unit	Sustainability Dimension	Resources						
				P	Mo	M	E	I	W	A
101.	Fraction of employees covered through performance appraisal (P1)	Employee covered through performance appraisal/ total employee	Social	√	√					
102.	Gender ratio (P1)	No. of female employee/ No. of male employee	Social	√						
103.	Level of growth and opportunity (P1)	Likert scale	Social	√						
104.	Female to male salary ratio (P1)	Avg. female employee salary/avg. male employee salary	Social	√	√					
105.	Level of social security (P1)	Likert scale	Social	√	√					
106.	Fraction of local employee (P1)	Employee from local community/ total employee	Social	√						
107.	Number of jobs created (P1)	Number per annum	Social	√	√			√		
108.	Fraction of employees provided with continue education facility (P1)	Employee with continue education/total employee	Social	√	√					
109.	Fraction of income difference relative to industry (P1)	Avg. income of employee/avg. income of the industry	Social	√	√					
110.	Fraction of skilled labor (P3)	Skilled labor/total labor	Social	√	√			√		
111.	Expenditure in social development (P1)	USD per annum	Social	√	√			√		
112.	Fraction of worker with work related disease (P3)	Worker with work related disease/total worker	Social	√	√	√				√
113.	Fraction of contractual labor (P1)	Contractual labor/total labor	Social	√	√					
114.	Number of work related accidents/incidents (P3)	Number per annum	Social	√				√		

S. No.	Indicators (critical factor)	Unit	Sustainability Dimension	Resources						
				P	Mo	M	E	I	W	A
115.	Total number of complaints from local community (P3)	Number per annum	Social	√				√	√	√
116.	Fraction of supplier from local area (P1)	Supplier from local area/total number of supplier	Social	√	√					
117.	Community involvement (P1)	Likert scale	Social	√						
118.	Stakeholders empowerment (P1)	Likert scale	Social	√						
119.	Company image in market (P2)	Likert scale	Social	√	√	√				
120.	Percentage of outsourced components/sub-assembly (P3)	%	Social		√	√				
121.	Reported customer health and safety issues (P2)	Number per annum	Social	√	√	√				√

USD- US Dollar; UP- Unit production; †Fraction of wastewater reused is addressed to incorporate total wastewater, whereas fraction of water reused represents the fresh water used in production process in close or open loop system and in the production process some water quantity is lost due to consumption, evaporation or leakage (i.e. water circulated through cooling tower)

People – P, Money- Mo, Material –M, Energy – E, Infrastructure – I, Water – W, Air –A; P1- Policy, P2 – Product, P3-Process

5.4 TESTING OF THE PROPOSED SUSTAINABILITY ASSESSMENT INDICATORS

The proposed 121 indicators are tested for the Indian cement manufacturing sector. This particular sector has been chosen for its environmental and social unfriendly nature of the manufacturing processes involved. It is expected that all 121 KPIs (30 social, 26 economic, 65 environmental) may not be applicable for the sustainability assessment of cement sector. The identified indicators are generalized and when applied to some specific manufacturing sector (like cement, automotive, etc.) needs selection. This is due to different product portfolios of the company and applicability of assessment indicators including the different manufacturing processes adopted. To identify the sustainability assessment indicators for Indian cement industry a survey is conducted. The data collection was done by conducting online survey among experts from cement industry. To remove the biased results from the survey responses, indicators were mixed together for all the three dimensions of sustainability. In order to identify indicators for the cement industry, the experts were asked to rate indicators on a 5-point Likert scale, the level of importance of each item as shown in appendix B. Here, 1 means 'no significance', 2 means 'low significance', 3 means 'medium significance', 4 means 'high significance', and 5 means 'very high significance'. Respondents were also asked to select indicators, which are found 'not applicable' for cement industry. The respondents are holding positions of engineer, senior engineer, senior manager, deputy manager, assistant manager, deputy chief manager, human resource personnel, engineering, and social scientists. A total of 250 survey questionnaire were distributed and 153 responses were received. In these responses, due to missing data or insufficient information, 26 responses are eliminated and remaining 127 responses are used for final analysis. 30 indicators (4 social, 3 economic, 23 environmental) were found "not applicable" and hence, removed from the list.

The reliability was estimated using Cronbach alpha method. The reliability of total 91 indicators is 0.933. The reliability of social indicators is 0.832, economic indicators is 0.828, and environmental indicators is 0.906. Next, corrected item-to-total correlation (CITC) was carried out to remove the "trash indicators" before performing EFA (Churchill, 1979). Indicators exhibiting CITC less than 0.5 are usually candidates for elimination. 24 indicators (7 social, 6 economic, 11 environmental) got eliminated by this process. Remaining 67 indicators (19 social, 17 economic, 31 environmental) were retained for further analysis. An EFA is carried out to determine the number of latent factors or variables or constructs.

The main objective of this empirical study was to test indicators for sustainability assessment of cement industry. Factor analysis was chosen to assess the proposed indicators across three dimensions of sustainability. Correlation matrix, Barlett's test of sphericity and Kaiser-Meyer-Oklin (KMO) measure of sampling adequacy are the three measures recommended in the literature for the purpose of determining the strength of relationship before carrying out the factor analysis. The results of KMO and Bartlett's test of sphericity are shown in Table 5.4 (a-c), which indicate that the data is adequate for further analysis. Eigen value and scree plot have been used for the segregation of number of factors from the data set. According to Tabachnick and Fidell (2007), a good thumb rule for minimum loading is 0.4 for an item, which is approximately 10% overlapping of variance with other indicators in the particular factor. Indicators with a value of more than 0.4 were considered as an acceptable factor loading.

Table 5.4 (a) KMO and Bartlett's test of social dimension

KMO and Bartlett's test for social indicators		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.787
Bartlett's Test of Sphericity	Approx. Chi-Square	425.775
	Df	136
	Sig.	.000

Table 5.4 (b) KMO and Bartlett's test for economic dimension

KMO and Bartlett's Test for economic indicators		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.738
Bartlett's Test of Sphericity	Approx. Chi-Square	382.902
	Df	105
	Sig.	.000

Table 5.4 (c) KMO and Bartlett's test for environmental dimension

KMO and Bartlett's Test for environmental indicators		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.746
Bartlett's Test of Sphericity	Approx. Chi-Square	1527.421
	Df	190
	Sig.	.000

5.4.1 Factors Analysis of Social Sustainability Indicators

The analysis of factor loadings for social sustainability indicators results into four social factors covering 17 indicators as shown in Table 5.5. The two indicators were deleted because of poor factor loading. Factor related to employee covers indicators like employee retention, health & safety, training, growth & opportunity, social benefits, etc. These findings are also observed by Saratun (2016), who observed that employee engagement as a potential factor for an organizations' ability for being innovative, competitive, effective, and sustainable. The second factor for social sustainability is related to complaints from community due to manufacturing operations, complaints from customer regarding health and safety, work related accidents/incidents, and supplier from local area. In short these indicators are about quality of products and processes, and supplier plays a vital role for the same. The third social factor covers local employee, social security, and gender ratio; and fourth factor comprises employee satisfaction, jobs created, and stakeholder empowerment. There are eight, four, three, and three indicators in the first, second, third, and fourth factor respectively.

Table 5.5 Factor analysis results of social sustainability indicators

S. No.	Social Indicators	Mean	Standard deviation	Social Factor 1	Social Factor 2	Social Factor 3	Social Factor 4
1.	Employee retention rates	3.69	0.842	0.803			
2.	Investment in employee health and safety	3.91	0.605	0.750			
3.	Total hours of employee training	3.65	0.878	0.736			
4.	Number of promotions per employee	3.06	1.15	0.692			
5.	Level of growth and opportunity	3.72	0.899	0.669			
6.	Average social benefits to average CTC	3.39	0.798	0.598			
7.	Average sick leave per employee	3.36	0.763	0.549			
8.	Total number of complaints from local community	3.52	1.09		0.859		
9.	Number of work related accidents/incidents	3.62	1.17		0.710		
10.	Reported customer health and safety issues	3.72	0.897		0.572		
11.	Fraction of supplier from local area	3.37	0.924		0.442		
12.	Fraction of local employee	3.24	0.879			0.782	
13.	Level of social security	3.61	0.918			0.715	
14.	Gender ratio	3.05	1.15			0.661	
15.	Employee satisfaction	3.95	0.872				0.474
16.	Number of jobs created	3.43	0.851				0.874
17.	Stakeholders empowerment	3.28	1.00				0.723

Note: Extraction Method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization; a. Rotation converged in 6 iterations

There is no absolute threshold value of variance acceptance but 60% cumulative variance is commonly accepted (Hair *et al.*, 2006). The examination of variance explained indicates that Eigen-value of four social factors or constructs are 6.260, 1.639, 1.337, and 1.279 and the cumulative variance explained by four social factors is 61.9%, as shown in Table 5.6.

Table 5.6 Factor variance explanation percentage of four sub scales of social sustainability indicators

Total Variance Explained									
Component	**Initial Eigenvalues**			**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loadings**		
	Total	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	6.260	36.823	36.823	6.260	36.823	36.823	3.973	23.371	23.371
2	1.639	9.640	46.463	1.639	9.640	46.463	2.539	14.933	38.304
3	1.337	7.867	54.330	1.337	7.867	54.330	2.086	12.270	50.574
4	1.279	7.524	61.854	1.279	7.524	61.854	1.918	11.280	61.854

5.4.2 Factors Analysis of Economic Sustainability Indicators

The factor analysis formed four factors of economic sustainability indicators as shown in Table 5.7. These four factors load 15 indicators and two factors were deleted. Factor 1 consists indicators related to monetary terms between the company and its stakeholders. The indicators in this factor are profit gained, annual sales, income, customer satisfaction, return on investment, and capital employed. These indicators are established financial indicators for any industry’s economic assessment as they are used frequently for sustainability assessment (Azapagic, 2003; Adams and Ghaly, 2006; Garbie, 2014). The second economic factor consists of indicators related to energy taxes paid, utilization of compressed air and maintenance and improvement cost. These indicators are related to each other as compressed air requires energy for its generation and losses occurring in the compressed air system cause extra cost to company and more energy consumption. Energy cost and taxes vary from industry to industry and from country to country (OECD, 2001). The third economic factor includes indicators related to cost incurring to the company during operations, warranty, transportation, and technology and innovation. The last factor is more about investment of the organization for employee training and new products and processes. It includes cost of the company for man-hours lost due to incidents/accidents. Indicators like technology and innovation cost and investment in new processes and products can become a source of competitive advantage for the organizations (Boons and Lüdeke-Freund, 2013; Scrivener and Kirkpatrick, 2008). There is no absolute threshold value of variance acceptance but 60% cumulative variance is commonly accepted (Hair *et al.*, 2006).

Table 5.7 Factor analysis results of economic sustainability indicators

S. No.	Economic Indicators	Mean	Standard deviation	Economic Factor 1	Economic Factor 2	Economic Factor 3	Economic Factor 4
1.	Profit gained (USD per annum)	3.98	0.840	0.853			
2.	Annual sales volume	3.83	1.07	0.791			
3.	Income (USD per annum)	3.63	0.958	0.746			
4.	Customer satisfaction	4.06	1.09	0.728			
5.	Return on investment	3.95	0.991	0.632			
6.	Capital employed	3.66	0.961	0.602			
7.	Energy taxes paid	3.54	0.880		0.874		
8.	Fraction of compressed air utilized	3.28	0.833		0.839		
9.	Maintenance and improvement cost	3.63	0.862		0.602		
10.	Warranty cost	3.43	0.772			0.765	
11.	Transportation cost	3.86	0.843			0.703	
12.	Technology and innovation cost	3.91	0.713			0.651	
13.	Cost of man-hours lost in accidents/incidents	3.73	1.05				0.801
14.	Investment in employee training	3.71	1.03				0.689
15.	Investment in new processes and products	3.72	0.786				0.670

Note: Extraction Method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization; a. Rotation converged in 6 iterations

Table 5.8 Factor variance explanation percentage of four sub scales of economic sustainability indicators

Total Variance Explained									
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.272	35.147	35.147	5.272	35.147	35.147	3.535	23.566	23.566
2	1.935	12.900	48.047	1.935	12.900	48.047	2.145	14.301	37.867
3	1.597	10.648	58.695	1.597	10.648	58.695	2.120	14.137	52.004
4	1.020	6.801	65.496	1.020	6.801	65.496	2.024	13.492	65.496

The examination of variance explained (Table 5.8) indicates that Eigen value of four economic factors are 5.272, 1.935, 1.597, and 1.020 and the cumulative variance explained by four economic factors is 65.5%.

5.4.3 Factors Analysis of Environmental Sustainability Indicators

Five factors emerged for environmental sustainability indicators covering 20 indicators as shown in Table 5.9. 11 indicators were deleted because of poor factor loading. Factor 1 is related to emissions and waste. The list of indicators includes carbon dioxide emissions, NO_x emissions, wicked smell in air, particulate matter, total hydrocarbon, and amount of hazardous solid waste. CO_2 emission is observed as a big environmental threat from cement industry (Isaksson and Steimle, 2009). It is observed that Indian cement industry is responsible for 9% of the emissions and its CO_2 emissions has increased 2.5 times from 87 million of tonnes per year in 1990 to 218 million of tonnes per year in 2013 (Garg *et al.*, 2017). Second factor is related to material consumed in various operations, especially reused and recycles material, hazardous material, and ozone depleting substances. Third factor is about the packaging used and reclaimed packaging. Fourth and fifth factors are about process related inputs and energy requirements respectively.

Table 5.9 Factor analysis results of environmental sustainability indicators

S. No.	Environmental Indicators	Mean	Standard deviation	Envir. Factor 1	Envir. Factor 2	Envir. Factor 3	Envir. Factor 4	Envir. Factor 5
1.	NO_x emissions per UP	3.81	1.33	0.840				
2.	Carbon di-oxide (CO_2) emission per UP	3.76	1.34	0.801				
3.	Wicked smell in air	3.26	1.40	0.760				
4.	Particulate matter (PM) per UP	3.83	1.30	0.720				
5.	Total hydrocarbon (THC) per UP	3.66	1.77	0.720				
6.	Amount of hazardous solid waste	3.70	1.12	0.678				
7.	Fraction of reused material	3.62	1.04		0.839			
8.	Amount of hazardous material used by contracted service provider	3.55	1.08		0.828			
9.	Hazardous material used	3.91	1.10		0.777			
10.	Fraction of recycled material used	3.71	0.993		0.691			
11.	Consumption of ozone depleting substance	3.56	1.05		0.466			
12.	Weight of packaging (per UP)	3.22	1.10			0.910		
13.	Packaging cost per UP	3.03	1.14			0.779		
14.	Fraction of reclaimed packaging	3.27	1.21			0.756		
15.	Landfill area (per annum)	3.48	1.04				0.757	
16.	Water used (Total water)	3.83	0.985				0.691	
17.	Solid waste used (i.e. by-products)	3.35	1.3				0.603	
18.	Fraction of renewable energy used	3.81	1.05					0.750
19.	Total amount of energy used	4.15	0.883					0.686
20.	Fraction of energy generated through cogeneration	3.26	1.114					0.565

Note: Extraction Method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization; a. Rotation converged in 6 iterations

The examination of variance (Table 5.10) indicates that Eigen value of five environmental factors are 6.591, 2.440, 2.212, 1.459, and 1.107 and the cumulative variance explained by five environmental factors is 69.1%. Thus, the total variance explained by the scale for social, economic and environmental indicators are under the acceptable range (Moon *et al.*, 2013).

Table 5.10 Factor variance explanation percentage of five sub scales of environmental sustainability indicators

Total Variance Explained									
Component	**Initial Eigenvalues**			**Extraction Sums of Squared Loadings**			**Rotation Sums of Squared Loadings**		
	Total	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	6.591	32.953	32.953	6.591	32.953	32.953	4.000	20.000	20.000
2	2.440	12.200	45.153	2.440	12.200	45.153	3.597	17.987	37.987
3	2.212	11.061	56.214	2.212	11.061	56.214	2.304	11.519	49.506
4	1.459	7.295	63.509	1.459	7.295	63.509	2.149	10.743	60.249
5	1.107	5.537	69.046	1.107	5.537	69.046	1.759	8.797	69.046

After careful analysis of the groups of sustainability indicators under the three dimensions, the four factors of economic sustainability are named as: capital and gains, utility cost, service cost, and training and support cost for economic sustainability indicators (Figure 5.2). The four factors for social sustainability are named as: employee, local community, social justice, growth and empowerment. The five factors for environmental sustainability are named as: emissions, material, end-of-life, packaging, and energy (Figure 5.2).

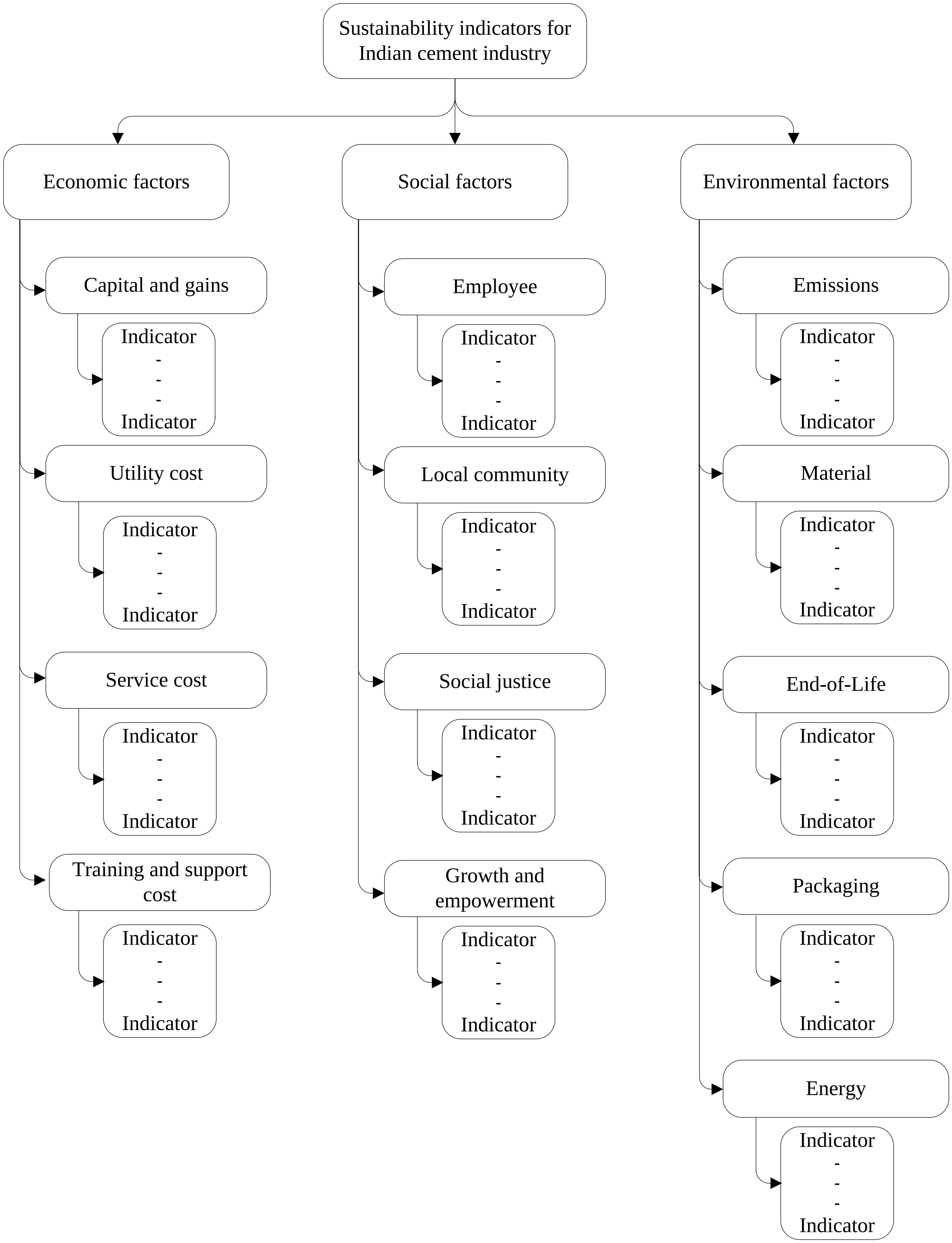


Figure 5.2 Classification of sustainability indicators for cement industry

5.5 SUMMARY

This chapter presents a sustainability assessment model for manufacturing organizations. The four-level sustainability assessment model includes product life cycles, resources, critical factors, and sustainability dimensions. 121 indicators have been identified, from literature, to assess the progress of an organization towards sustainability and to measure the sustainable performance of a manufacturing organization from different perspectives: critical factor perspective, resource perspective, sustainability dimension perspective, and life cycle perspective throughout the supply chain. It ensures that no aspect of the organization is left without assessment. The identified indicators are capable to measure the product sustainability (33 indicators), process sustainability (51) and sustainability policies (37). The identified indicators are able to measure the effect of manufacturing on the seven resources: people (48 indicators), money (58 indicators), material (49 indicators), energy (33 indicators), infrastructure (22 indicators), water (21 indicators), and air (16 indicators). The proposed model is also strong to assess social sustainability (30 indicators), economic sustainability (26 indicators) and environmental sustainability (65 indicators). The implementation and assessment of sustainability improvement initiatives is made easier by the model because of the mapping of indicators across critical factors, resources, sustainability dimensions, and life cycle. This mapping makes the decision making process visual, hence easy to explain the different stakeholders including employees. The ease of use and effectiveness of the model are high to assess the sustainability of a manufacturing organization. However, the ease of use is low for the pre-manufacturing stage, where the data acquisition is difficult for the internal people.

The proposed sustainability assessment model and the identified indicators are tested using data from the Indian cement manufacturing industry. The data collected from 127 respondents is analyzed statistically using SPSS 20.0 statistical tool. 30 indicators were marked by the respondents as 'not applicable' to cement industry and 24 indicators were deleted because their CITC (corrected item to total correlation) was less than 0.5. An exploratory factor analysis (EFA) was carried out on the remaining 67 indicators. 15 indicators were deleted during EFA because of their poor factor loadings. The remaining 52 indicators were classified into different categories using exploratory factor analysis. The economic indicators are grouped into four factors – capital and gains, utility cost, service cost, and training and support cost. The social indicators are also grouped into four factors – employees, local community, social justice, and growth and empowerment. The environmental indicators are grouped into five factors – emissions, material, end of life, packaging, and energy.

CHAPTER 6

DEVELOPMENT OF A COMPOSITE SUSTAINABILITY INDEX

This chapter presents a composite sustainability index to demonstrate the usefulness of the sustainability assessment model and indicators developed in the last chapter. A case study of Indian cement industry is presented to show the application of the composite sustainability index.

6.1 INTRODUCTION

The sustainability assessment model developed in the last chapter provides information on sustainability in terms of an organizations' performance on 121 indicators in general and 52 indicators for the cement industry. These indicators measure the environmental, economic and social sustainability performance in an integrated way encompassing the whole organization along the product life, critical factors, and resources. The data so gathered for the various indicators is in different units and the effect of these indicators have different weightage on the sustainability performance. For example, the effect of same amount of CO_2 as compared to NO_x is less harmful and Nitrogen-trifluoride (NF_3) has 17000 times more global warming potential than CO_2 . The sustainability report can be used to see the progress of sustainability initiatives on individual indicator but the interdependencies among indicators can not be assessed. For example, the use of alternative derived fuels from waste like waste oil, waste solvents, wood chips and plastics, shredded tyres, etc. may decrease the CO_2 and CO emissions but it may increase NO_x and SO_x emissions which are more harmful. Therefore, the measurement of the performance has limited usefulness unless this measured data is presented in a composite dimensionless index, which can be used for decision making. the composite index embeds the individual indicators to reflect the interdependencies in the individual sustainability dimensions and the overall sustainability performance. The decision makers or experts should be able to provide the importance or weightage of each indicator or dimension. The cement industry is a significant source of emission for carbon monoxide (CO), heavy metals, NO_x, and particulate matters (Zhang *et al.*, 2017). In late 1990s, top cement producers around the world founded the Cement Sustainability Initiative (CSI) as part of the World Business Council for Sustainable Development (WBCSD) program (Supino *et al.*, 2016). CSI published its first reporting protocol in 2005; and this was revised in 2012; with an idea to promote eco-efficiency, corporate social responsibility, and innovation in cement industry (Timberlake, 2005; WBCSD, 2012). However, this report too provides only measured data for the indicators. The indicator data can have utility as benchmark values for year on year improvement but has limited usefulness in decision making at strategic level.

China and India are the two major cement producing countries in the world, with annual production of 2400 and 280 million metric tonnes respectively in 2017 (Statista, 2018). India is the second largest cement producer after China. It's cement production capacity in 2015 was 366 million tonnes and is expected to increase upto 550 million tonnes by 2025 (IBEF, 2017). The Indian cement industry is expected to grow faster due to the government of India's focus on "make in India" with direct investments in infrastructure and residential projects to sustain the urban growth (Seth *et al.*, 2016). The government of India is also committed to Paris climate change agreement to reduce its emissions intensity by 33-35% during 2005-2030. The share of Indian cement industry alone amounts to approximately 9% of the national CO_2 emissions (Garg *et al.*, 2017). The expected growth of cement industry in India is posing a challenge to meet emissions targets due to energy-intensive and environmental unfriendly processes in cement production. It is estimated that the share of cement production is approximately 5% in the total CO_2 emission globally (Singh *et al.*, 2017). The specific electricity consumption per tonne cement production in India is 88 KWh and specific thermal energy consumption per tonne is approximately 3 GJ (Madlool *et al.*, 2011). Therefore, it is pertinent to study the sustainability assessment of cement manufacturing organizations.

A composite index is required for policy making decisions. The composite index can be used by decision makers in government, industry, NGOs, and other stakeholders to judge the performance of organizations in different sustainability dimensions or overall (all the three dimensions together). This removes the bias from individual indices performance. Moreover, the different dimensions of sustainability as well as indicators may have different importance for the country, organization or plant. For example, the importance for economic performance in developing countries may outweighs the environmental performance importance. Similarly, the importance of individual indicators may be different in different countries, regions, organizations, plants, etc. Therefore, a composite sustainability index is required to assess and compare the environmental, social, economic and overall performance of the organizations.

6.2 CASE STUDY: SUSTAINABILITY ASSESSMENT OF FOUR INDIAN CEMENT MANUFACTURING ORGANIZATIONS

The main purpose of this case study is to develop a composite sustainability index and use it to assess and compare the four major Indian cement manufacturing organizations based on their environmental, economic, social, and overall sustainability performance using the sustainability assessment model and sustainability indicators developed in the last chapter. Annual sustainability reports of these organizations are available in the public domain. These reports contain data for indicators of social, economic, and environmental dimensions as per GRI Guidelines (2015). However, these reports are not sufficient to provide a clear picture of their sustainability performance in different dimensions because the performance varies from indicator to indicator. For example, an organization may have decreased its CO_2 emissions but it may have consumed more water or electricity. Therefore, it is difficult or impossible to judge the environmental performance of the organization from the sustainability reporting data. A composite sustainability index is developed for the case study to assess and compare the four cement manufacturing organizations. These organizations, chosen from the top 10 Indian cement manufacturing organizations on the basis of production capacity, are named A, B, C, and D to avoid their identification.

6.2.1 Methodology for the Computation of the Composite Sustainability Index

A four-step methodology is used to compute the composite sustainability index. The four steps are: data collection, non-dimensionalization of the data, weight determination of the three dimensions and indicators, and computation of the index.

6.2.2 Data Collection

Many cement manufacturing organizations were approached to provide the data for the 52 indicators (20 environmental, 15 economic, 17 social) identified for the cement industry in the last chapter. However, no organization came forward to share the data on these indicators. Therefore, publicly available sustainability reports of the four case organizations were used for the data collection. The sustainability reports for these four case organizations is downloaded from the global reporting initiative database. This a well-known database of sustainability reports for thousands of organizations around the world (GRI, 2016). The data related to one financial indicator is collected from the financial reports available in the public domain. Finally, the data for 15 indicators, five each under the three sustainability dimensions, is available. The data for the 14 indicators is available in sustainability reports and the data for the indicator ‘capital employed’ is from the financial reports. The data for these 15 indicators is recorded for the financial years 2013-14 and 2014-15 (the latest available reports for all the case organizations on 22 February 2017). The collected data is given in Tables 6.1 and 6.2 for the years 2013-14 and 2014-15 respectively.

Table 6.1 Collected data for the case organizations for the year 2013-14

Indicator	**A**	**B**	**C**	**D**
Operational cost (USD per UP)	47.16	50.47	43.76	33.94
Profit gained (Million USD)	173.32	221.99	318.15	116.82
Annual sales volume (Million tonnes)	24.21	22.15	54	17.5
Capital employed (USD)	7.2E+08	1.12E+09	2.25E+09	6.48E+08
Return on investment (Profit/Cost)	0.74	0.69	0.4	0.35
CO_2 emissions (gm per UP)	526000	560000	633540	588000
NO_x emissions (gm per UP)	1044	1346	1583	933.2
Particulate matter (PM) (gm per UP)	26.14	44	107.85	96.74
Water used (m^3 per UP)	0.65	0.31	0.27	0.1
Energy used (KWh per UP)	81.45	78.9	85.3	71.97
Average social benefits to average CTC	12219.97	14242.6	12206.43	12485.86
Total hours of employee training (hours/annum/employee)	55.5	24	17.6	15.48
Fraction of supplier from local area	0.99	0.99	0.74	0.99
Expenditure in social development (Million USD)	4.07	5.05	7.21	1.72
Gender ratio	0.04	0.03	0.02	0.01

6.2.3 Non-dimensionalization of Collected Data

The non-dimensionalization of the data is carried out to remove the effect of dissimilar units of different magnitudes. For example, the indicator gender ratio is dimensionless indicator whereas the indicator CO_2 emission and annual sales are the indicators having units of gm CO_2 equivalent and million tonnes respectively.

Table 6.2 Collected data for the case organizations for the year 2014-15

Indicator	A	B	C	D
Operational cost (USD per UP)	48.69	51.48	41.89	28.47
Profit gained (Million USD)	87.85	119.9	299.01	63.26
Annual sales volume (Million tonnes)	23.62	21.54	63	23.6
Capital Employed (USD)	7.23E+08	1.13E+09	2.5E+09	5.75E+08
Return on investment (Profit/Cost)	0.4	0.36	0.39	0.26
Carbon dioxide (CO_2) emission (gm per UP)	533000	553000	643520	576000
NO_x emissions (gm per UP)	1011.16	1267	1159.09	884.95
Particulate matter (PM) (gm per UP)	23.94	21.73	112.49	79.23
Water used (m^3 per UP)	0.62	0.31	0.24	0.09
Energy used (KWh per UP)	81.56	78	82.3	72.12
Average social benefits to average CTC	13654.43	15410.97	13182.16	13138.24
Total hours of employee training (hours/annum/employee)	73.65	17	22.01	16.43
Fraction of supplier from local area	0.99	0.98	0.7	0.98
Expenditure in social development (Million USD)	4.62	6.08	6.68	2.75
Gender ratio	0.04	0.02	0.02	0.01

The indicators are of two types: direct and indirect. For direct indicators, higher the value better the sustainability and for indirect indicators, lower the value better the sustainability. The direct and indirect indicators are non-dimensionalized as:

For direct indicators

$$X_i^m = \frac{x_i^m - n_i}{N_i - n_i} = \begin{cases} 1, & x_i^m = n_i \\ \frac{x_i^m - n_i}{N_i - n_i}, & n_i < x_i^m < N_i \\ o, & x_i^m = N_i \end{cases} \tag{6.1}$$

For indirect indicators

$$X_i^m = \frac{N_i - x_i^m}{N_i - n_i} = \begin{cases} 1, & x_i^m = n_i \\ \frac{N_i - x_i^m}{N_i - n_i}, & n_i < x_i^m < N_i \\ o, & x_i^m = N_i \end{cases} \tag{6.2}$$

where:

X_i^m is dimensionless value of indicator *i* for the case organization *m* (*m* = A, B, C, or D)

N_i is highest value of indicator *i* among the four case organization

n_i is lowest value of indicator *i* among the four case organization

x_i^m is value of indicator *i* for the case organization *m*

Non-dimensionalization of two indicators (one direct and another indirect) is shown below:

a) 'Profit gained' for the case organization in 2014-15:

The profit gained by the case organizations in 2014-15 (Table 6.2):

x_i = (87.85; 119.89; 299.01; 63.26); N_i = 299.01; n_i = 63.26;

Hence, $X_{63.26}^D = \frac{63.26-63.26}{299.01-63.26} = 0$; $X_{299.01}^C = \frac{299.01-63.26}{299.01-63.26} = 1$;

$X_{87.85}^A = \frac{87.85-63.26}{299.01-63.26} = 0.104$; $X_{119.89}^B = \frac{119.89-63.26}{299.01-63.26} = 0.240$;

b) 'CO$_2$ emission' for the case organizations in 2014-15:

The value of CO_2 emission by the four cement manufacturing organizations are (Table 6.2)

x_i = (533000; 553000; 643520; 576000); N_i = 643520; n_i = 533000;

Hence, $X_{53300}^A = \frac{643520-533000}{643520-533000} = 1$; $X_{643520}^C = \frac{643520-643520}{643520-533000} = 0$;

$X_{553000}^B = \frac{643520-553000}{643520-533000} = 0.819$; $X_{576000}^D = \frac{643520-576000}{643520-553000} = 0.611$;

Similarly, the other indicators are also non-dimensionlized and the value for the year 2013-14 and 2014-15 are given in the Table 6.3 and Table 6.4 respectively.

Table 6.3 Non-dimensionalized data for the four cement organizations for the year 2013-14

Indicator	**A**	**B**	**C**	**D**
Operational cost	0.2	0	0.406	1
Profit gained	0.281	0.522	1	0
Annual sales volume	0.184	0.127	1	0
Capital employed	0.045	0.295	1	0
Return on investment	1	0.862	0.12	0
CO_2 emissions	1	0.684	0	0.423
NO_x emissions	0.829	0.365	0	1
Particulate matter (PM)	1	0.781	0	0.136
Water used	0	0.63	0.696	1
Energy used	0.289	0.48	0	1
Average social benefits to average CTC	0.007	1	0	0.137
Total hours of employee training	1	0.213	0.053	0
Fraction of supplier from local area	1	0.984	0	0.986
Expenditure in social development	0.428	0.606	1	0
Gender Ratio	1	0.558	0.323	0

Table 6.4 Non-dimensionalized data for the four cement organizations for the year 2014-15

Indicator	**A**	**B**	**C**	**D**
Operational cost	0.121	0	0.417	1
Profit gained	0.104	0.24	1	0
Annual sales volume	0.05	0	1	0.05
Capital employed	0.077	0.289	1	0
Return on investment	1	0.736	0.901	0
CO_2 emissions	1	0.819	0	0.611
NO_x emissions	0.67	0	0.282	1
Particulate matter (PM)	0.976	1	0	0.366
Water used	0	0.585	0.714	1
Energy used	0.072	0.422	0	1
Average social benefits to average CTC	0.227	1	0.019	0
Total hours of employee training	1	0.01	0.097	0
Fraction of supplier from local area	1	0.966	0	0.98
Expenditure in social development	0.478	0.848	1	0
Gender Ratio	1	0.496	0.295	0

6.2.4 Determination of Dimension/Indicator Weights by Using AHP

AHP is multi criteria decision making method developed by Saaty (1980). AHP enables the decision maker to represent the simultaneous interaction of many factors in complex, unstructured situation. AHP is a philosophy of estimation, which offers the capability to include both quantitative and qualitative features in the decision process. It also supports the decision method by individual or organizational perspective, personal emotions, memories, and judgments within a hierarchical structure consisting various levels. The process of analytical hierarchy starts with the development of a structured problem in a hierarchical form. After development of hierarchical structure the elements are evaluated by decision makers in pairwise comparisons. The judgments based on observations are fed into AHP for each attribute and sub-attribute of all levels of hierarchy. Pairwise comparisons of attribute at each level are done on a scale of relative importance as shown in Table 6.5.

Table 6.5 Relative importance scale for pair wise comparison

Saaty Scale	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over the other	Experience and judgment slightly favour one over another
5	Fair importance	Experience and judgment slightly favour one over another
7	Strong importance	An activity is strongly favoured and its dominance is demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest degree
2, 4, 6, 8	The intermediate values between two adjacent scales	When compromise is needed

The steps to follow for using the AHP (Roger, 1987; Sangwan, 2011) are:

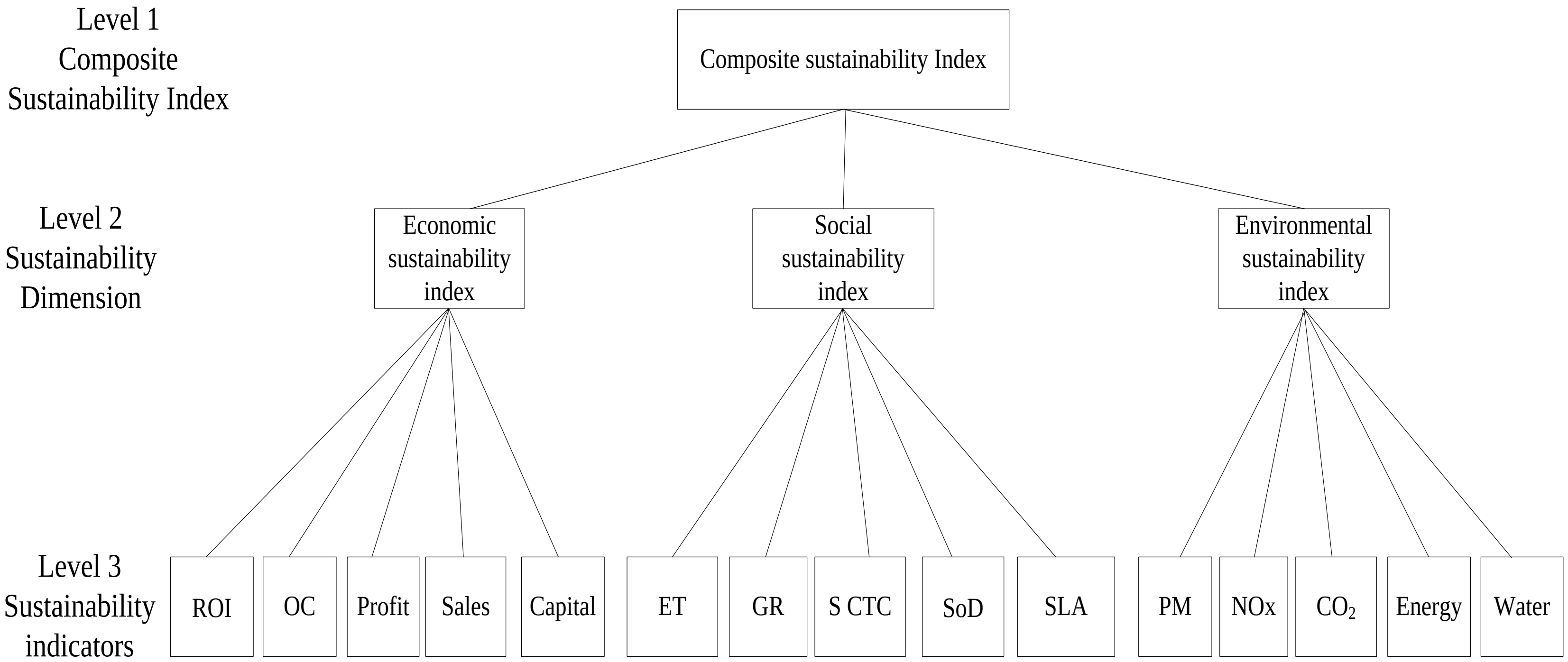
Step 1. Define the problem and determine the objective.

Step 2. Structure the hierarchy from the top through the intermediate levels to the lowest level as shown in Figure 6.1.

Step 3. Construct a set of pairwise comparison matrices for each of the lower levels. An element at the higher level is said to be a governing element for those at the lower level. The elements at the lower level are then compared to each other based on their effect on the governing element at higher level. This yields a square matrix of judgments. The pairwise comparisons are done and the expert judgments are then expressed as integers. If element *p* dominates over element *q*, then the whole number integer is entered in row *p*, column *q* and reciprocal is entered in row *q*, column *p*. If the elements being compared are equal, a one is assigned to both positions. Table 6.6 shows the pairwise comparison matrix for level 2 dimensions.

Step 4. n (n-1)/2 judgments are required to develop the set of matrices in step 3 (reciprocals are automatically assigned in each pairwise comparisons).

Step 5. Having done all the pairwise comparisons, the consistency is determined using the eigenvalue. To do so, normalize the columns by dividing each entry by the sum of all entries. Then sum each row of the normalized values and take the average. This provides Principal Vector (PV). The check of the consistency of judgments is as:



Return on investment – ROI; Operational cost – OC; Profit gained – Profit; Annual sales volume – Sales; Capital employed – capital; Gender ratio – GR; Expenditure in social development – SoD; Average social benefits to CTC – S CTC; Total hours of employee training – ET; Fraction of suppliers from local area – SLA; Particulate matter – PM; NOx emissions -Nox; Carbon dioxide emissions – CO_2; Energy used – Energy; Water used - Water

Figure 6.1 Hierarchical structure for computation of composite sustainability index

Table 6.6 Pairwise comparison matrix for level 2 attributes (sustainability dimension)

Dimension	**Social**	**Environmental**	**Economic**
Social	1.00	0.33	0.20
Environmental	3	1.00	1.00
Economic	5	1.00	1.00

Let the pairwise comparison matrix be denoted M1 and principal vector be denoted M2.

Then define M3 = M1*M2; and M4 = M3/M2.

λ_{max} = average of the elements of M4.

Consistency Index (CI) = (λ_{max} - N) / N – 1

Consistency Ratio (CR) = CI/RI corresponding to N

where RI : Random Consistency Index, and

N: Number of elements

Random index table

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

If CR is less than 10%, judgments are considered consistent and if CR is greater than 10%, the quality of judgments should be improved to have CR less than or equal to 10%.

Step 6. Steps 3-5 are performed to have relative importance of each dimension/indicator for all levels in the hierarchy. Table 6.7 (a-c) illustrates the indicator analysis of economic indicators, social indicators, and environmental indicators.

Table 6.7 (a) Pairwise comparison matrix for level 3 (economic indicators)

Economic indicator	OC	Profit	Sales	Capital	ROI
OC	1.00	0.20	3.00	1.00	0.20
Profit	5	1.00	7	5.00	0.33
Sales	0.33	0.142	1.00	0.33	0.14
Capital	1	0.20	3.00	1.00	0.14
ROI	5	3.00	7.00	7.00	1.00

Table 6.7 (b) Pairwise comparison matrix for level 3 (social indicators)

Social indicator	CTC	ET	SLA	SoD	GR
CTC	1.00	1.00	3.00	5.00	0.33
ET	1	1.00	7	3.00	0.33
SLA	0.33	0.14	1.00	0.33	0.11
SoD	0.2	0.33	3.00	1.00	0.14
GR	3	3.00	9.00	7.00	1.00

Table 6.7 (c) Pairwise comparison matrix for level 3 (environmental indicators)

Environmental indicator	CO_2	NO_x	PM	Water	Energy
CO_2	1.00	3.00	5.00	7.00	5.00
NO_x	0.33	1.00	3.00	5.00	7.00
PM	0.20	0.33	1.00	1.00	3.00
Water	0.14	0.20	1.00	1.00	1.00
Energy	0.20	0.14	0.33	1.00	1.00

Step 7. The desirability index for each alternative is calculated by multiplying each value in ‘weight’ of indicator column by the respective value of ‘dimension weight’ column.

The values of consistency index (CI), consistency ratio (CR), and principal eigenvalue (λ) for both level 2 and level 3 are shown in Table 6.8.

It is clear that the economic sustainability indicators are on priority of Indian cement organizations under the circumstances of the developed case situation as shown in Table 6.9 (a-d).

Table 6.8 Value of CI, CR, and λ for both level attributes

Level (attributes)	**CI**	**CR**	**λ**
Level 2 Sustainability dimensions	0.017	0.030	3.03
Level 3 Economic indicators	0.100	0.090	5.41
Level 3 Social indicators	0.069	0.061	5.27
Level 3 Environmental indicators	0.054	0.048	5.21

Table 6.9 (a) Weightage for social, economic, and environmental dimensions

Main attributes	**Weight**
Economic	0.479
Environmental	0.405
Social	0.115

Table 6.9 (b) Weightage for economic sustainability indicators

Indicator	**Weight**
Operational cost	0.089
Profit gained	0.2982
Annual sales volume	0.0416
Capital employed	0.0833
Return on investment	0.4874

Table 6.9 (c) Weightage for social sustainability indicators

Indicator	**Weight**
Average social benefits to average CTC	0.1947
Total hours of employee training	0.205
Fraction of supplier from local area	0.0416
Expenditure in social development	0.0726
Gender Ratio	0.4861

Table 6.9 (d) Weightage for environmental sustainability indicators

Indicator	Weight
CO_2 emissions	0.4470
NO_x emissions	0.2713
Particulate matter (PM)	0.1175
Water used	0.0748
Energy used	0.0510

The calculated AHP rankings and weights of the indicators are shown in the Table 6.10.

Table 6.10 Dimension and indicator weights obtained by using AHP

Dimension	Weight	Indicator	Unit	Weight	Global weight	Rank
Economic	0.4796	Operational cost	USD per UP	0.090	0.043	7
		Profit gained	USD per annum	0.298	0.143	3
		Annual sales volume	Million tonnes	0.042	0.020	13
		Capital employed	USD (Total Assets - current liabilities)	0.083	0.040	8
		Return on investment	profit/cost	0.487	0.234	1
Environmental	0.4055	CO_2 emissions	gm per UP	0.447	0.181	2
		NO_x emissions	gm per UP	0.271	0.110	4
		Particulate matter (PM)	gm per UP	0.118	0.048	6
		Water used	m^3 per UP	0.075	0.030	9
		Energy used	KWH per UP	0.051	0.021	12
Social	0.115	Average social benefits to average CTC	USD per employee	0.195	0.022	11
		Total hours of employee training	hours/annum/employee	0.205	0.024	10
		Fraction of supplier from local area	Supplier from local area/total number of supplier	0.042	0.005	15
		Expenditure in social development	Million USD	0.073	0.008	14
		Gender Ratio	No. of female employee/ No. of male employee	0.486	0.056	5

6.2.5 Computation of the Composite Sustainability Index

The sustainability performance of Indian cement industry can be assessed using the values given in Table 6.3 and 6.4 for the years 2013-14 and 2014-15 respectively. The performance can be computed using the following equation:

$$S_{eco} = \sum_{i=1}^{s} X_i^m k_i \qquad (6.3)$$

Where, S_{eco} is the economic sustainability index, *s* is the maximum number of indicators in economic dimension. X_i is the value of non-dimensionlized indicator to measure the performance, and k_i is the weight obtained for the indicator using expert opinion.

$$S_{soc} = \sum_{i=1}^{r} X_i^m k_i \qquad (6.4)$$

Where, S_{soc} is the social sustainability index, *r* is the maximum number of indicators in social dimension.

$$S_{env} = \sum_{i=1}^{l} X_i^m k_i \qquad (6.5)$$

Where, S_{env} is the environmental sustainability index, *l* is the maximum number of indicators in environmental dimension. The sustainability performance of the organization *m* in terms of composite sustainability index $\mathrm{S_{CI}^{m}}$ is:

$$S_{CI}^{m} = \sum S_{eco} + S_{soc} + S_{env} \qquad (6.6)$$

The assessment of individual dimensions of sustainability has been carried out as discussed. Economic, social, environmental, and overall indices for the case organization A for the year 2014-15 are computed as:

- Economic sustainability index = ∑ (the dimensionless indicators of case organization 2014-2015*the global weights of economic indicators) = (0.121*0.042+ 0.104*0.143 + 0.050*0.019 + 0.077*0.083 + 1*0.233) = 0.258
- Social sustainability index = ∑ (the dimensionless indicators of case organization 2014-15*the global weights of social indicators) = (0.227*0.022 + 1*0.023 + 1*0.004 + 0.478*0.008 + 1*0.056) = 0.093
- Environmental sustainability index = ∑ (the dimensionless indicators of case organization 2014-15*the global weights of environmental indicators) = (1*0.181 + 0.669*0.11 + 0.975*0.047 + 0*0.03 + 0.072*0.020) = 0.303
- Overall sustainability performance = (Social sustainability index + economic sustainability index + environmental sustainability index) = 0.258 + 0.093 + 0.329 = 0.654

The estimated sustainability indices of the four case Indian cement manufacturing organizations is presented in the Table 6.11.

Table 6.11 Sustainability performance index for triple bottom line and overall sustainability index

Sustainability Index	**A**		**B**		**C**		**D**	
	2013-14	**2014-15**	**2013-14**	**2014-15**	**2013-14**	**2014-15**	**2013-14**	**2014-15**
Economic sustainability index	0.288	0.258	0.291	0.218	0.248	0.432	0.043	0.044
Environmental sustainability index	0.326	0.303	0.230	0.223	0.021	0.053	0.244	0.289
Social sustainability index	0.088	0.093	0.068	0.062	0.028	0.028	0.008	0.005
Overall sustainability index	**0.702**	**0.654**	**0.589**	**0.503**	**0.297**	**0.512**	**0.295**	**0.338**

6.2.6 Results and Discussion

The economic sustainability indices for year 2013-14 shown in Figure 6.2 that organization A, B, and C are comparable whereas the economic performance of organization D is very poor. The same results for the year 2014-15 shows that the performance of the organization C is better than the performance of organization A, B, and D. This is because of the return of investment for organizations A and B decreased sharply and the organization C was able to maintain its return of investment. The weight for the return on investment is highest among all economic sustainability indicators (Table 6.10). Moreover, there was a decrease in the profit gained for all organizations for the year 2014-15. However, the decrease in profit for organization C is less as compare to other organizations.

The social sustainability indices for the all the case organizations shown in Figure 6.3 for the years 2013-14 and 2014-15 shows that the performance of organization A is better than B, which is better than C, which is better than D. The organization A is best in employee training, gender ratio, and local supplier hiring. The social sustainability performance of organization B has decreased into 2014-15 even though it has improved its performance in employee training and expenditure on social development. This is because its performance in gender ratio has decreased and the weightage of gender ratio is much higher than the weightage for the employee training hours and local area supplier sourcing.

The environmental sustainability indices for the year 2013-14 and 2014-15 (in Figure 6.4) show that the environmental sustainability performance of the organization C is extremely poor as compare to the other three organizations. The results shows a manifold environmental sustainability performance improvement in 2014-15 for the organization

C, yet its performance is very poor as compare to others. The environmental performance of organization D has improved in year 2014-15 because of the decrease in CO_2 and particulate matter over last year.

The composite sustainability index shows that the overall sustainability performance of the case organization C and D has improved over in 2014-15 over 2013-14 (in Figure 6.5). The performance of the organizations A and B has decreased in 2014-15 over 2013-14. Although overall sustainability performance of the organization D is the lowest but its environmental performance is better than organizations B and C. The overall ranking of organization C is third into 2014-15 even though its economic performance is much better than all other organizations. One of the reasons for this is its high CO_2 emissions and particulate matter emissions. If the organization can improve decrease its CO_2 and particulate matter emissions than it can be improve its overall sustainability performance.

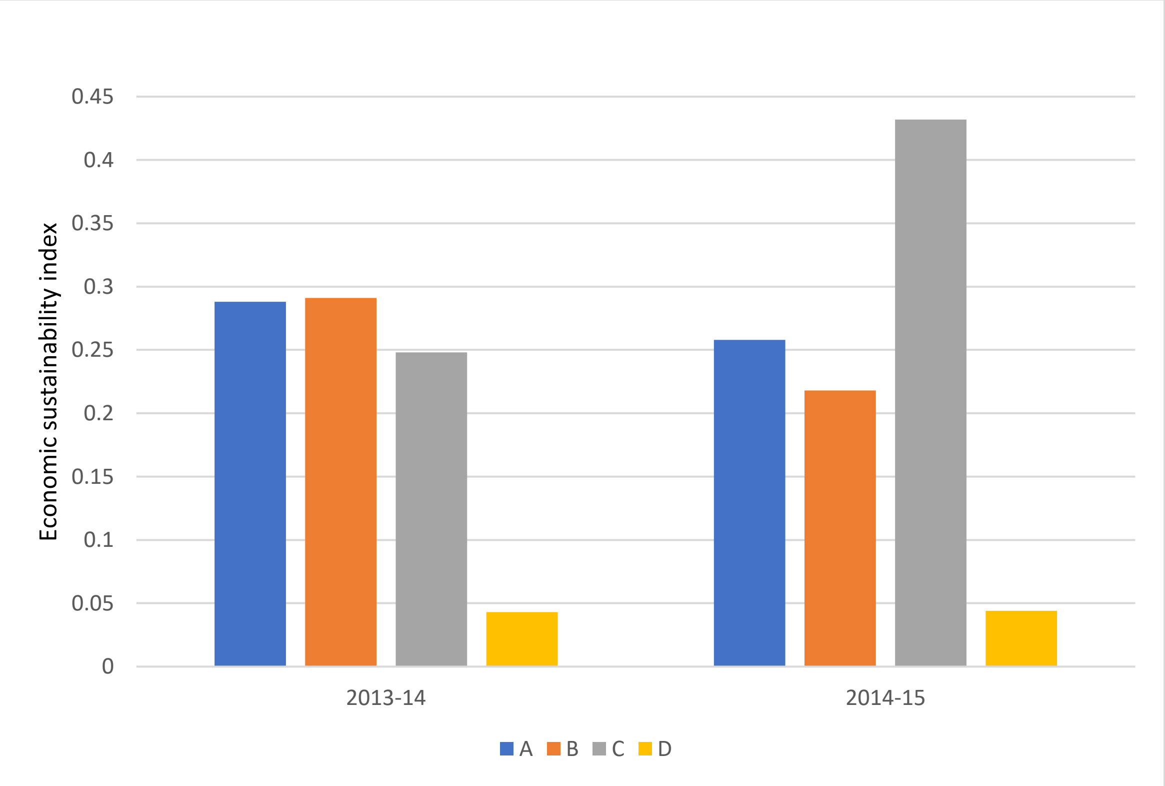


Figure 6.2 Economic performance of the case cement manufacturing organizations

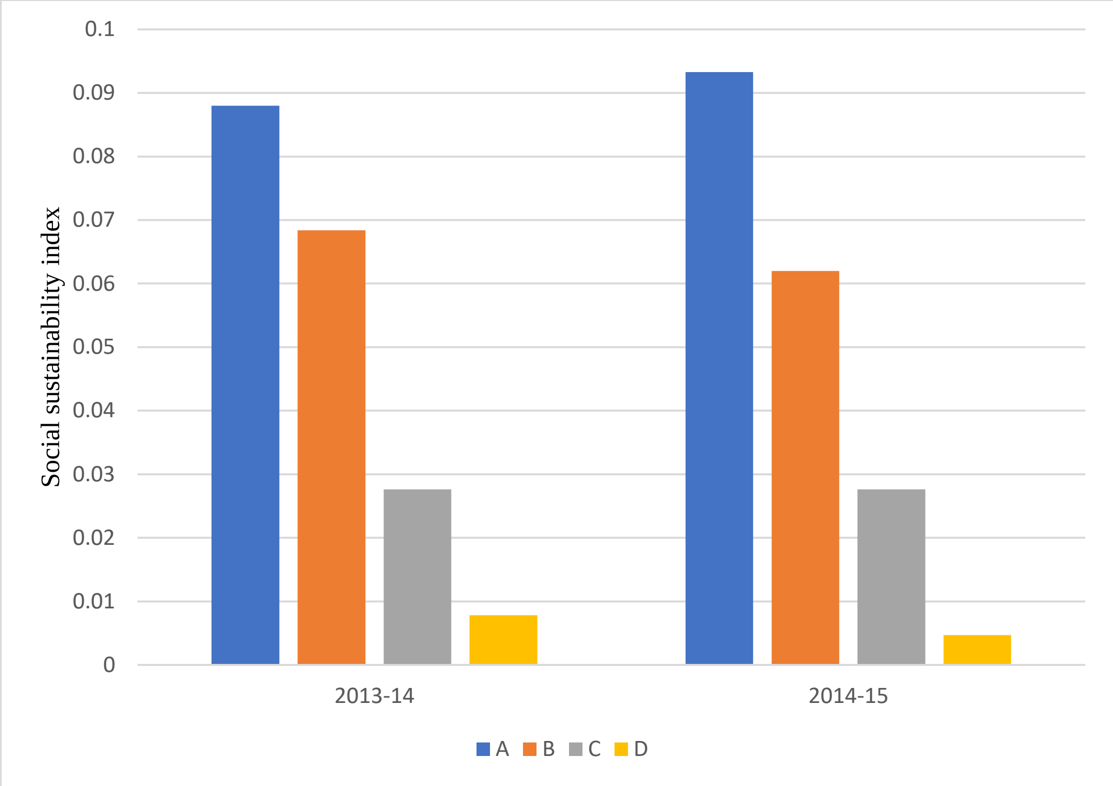


Figure 6.3 Social performance of the case cement manufacturing organizations

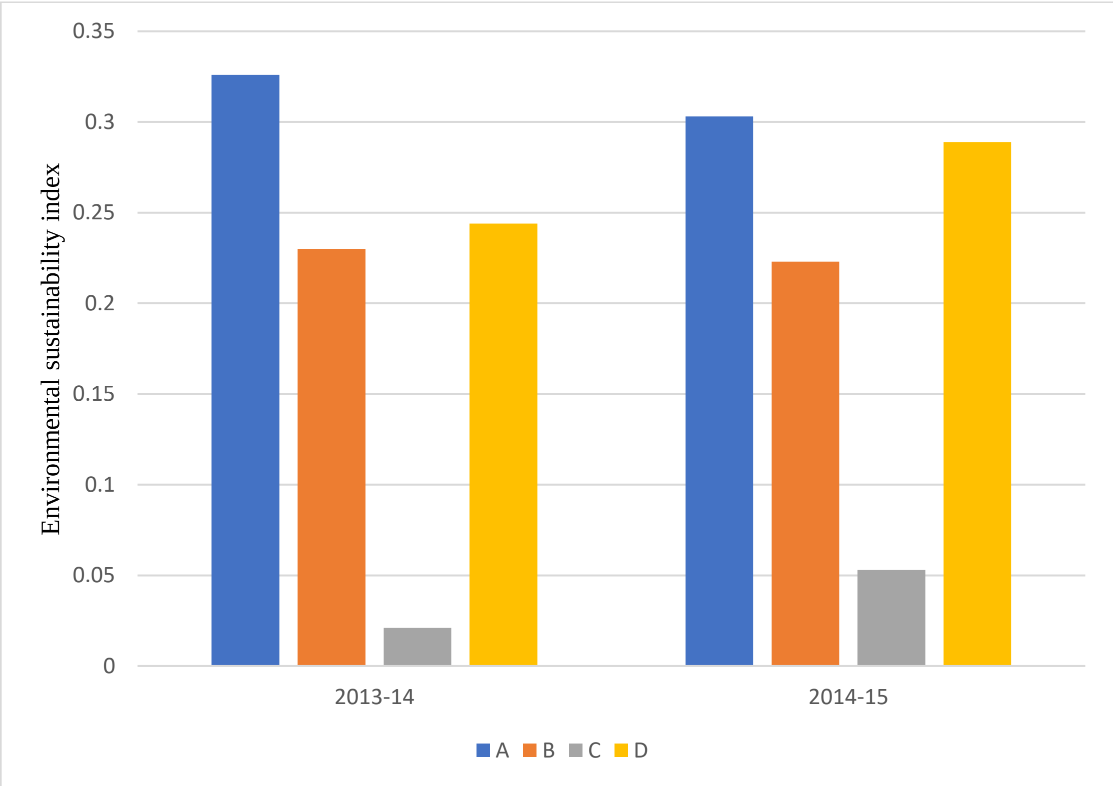


Figure 6.4 Environmental performance of the case cement manufacturing organizations

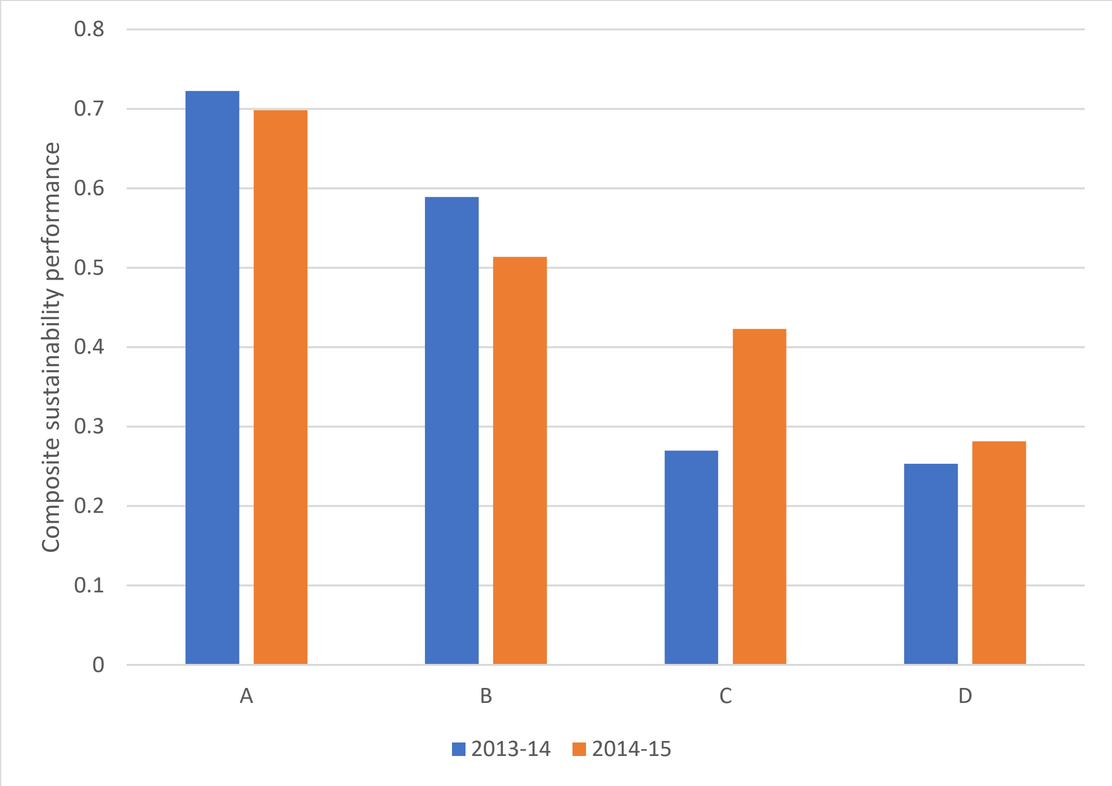


Figure 6.5 Overall sustainability performance of the case cement manufacturing organizations

In conclusion, the sustainability performance of company C and D has been observed low as compared to the other two companies. From the estimated sustainability performance across the triple bottom line, it is observed that all the four leading Indian cement manufacturing companies are not performing better in social aspects of sustainability. The above-discussed results of the current study should be viewed in details to make quality decision making.

6.3 SUMMARY

This chapter proposes a composite sustainability index and demonstrates its usefulness using the indicators identified in chapter 5. The usefulness of the model is demonstrated by assessing and comparing the sustainability performance of four Indian cement organizations. The weightage of the three sustainability dimensions and sustainability indicators is computed using analytical hierarchy process (AHP). The Indian experts have given high weightage to the economic sustainability performance (48%) and environmental sustainability performance (40%) and very low weightage to social sustainability performance (12%). The highest weightage is given to return on investment followed by CO_2, profit gained, NO_x emissions and gender ratio. Local area suppliers, expenditure in social development, annual sales volume, and energy used are given low weightage by the Indian cement manufacturers.

CHAPTER 7

ENVIRONMENTAL SUSTAINABILITY ASSESSMENT OF CEMENT MANUFACTURING PROCESS USING LIFE CYCLE ANALYSIS

This chapter presents environmental sustainability assessment of a cement manufacturing process using a life cycle analysis (LCA).

7.1 INTRODUCTION

The case study in the last chapter evaluates the cement manufacturing organizations and compares their sustainability performance using a composite sustainability indices. The composite sustainability indices help the various stakeholders (government agencies, industry, NGOs, Banks, etc) to take informal policy decisions at strategic level. However, one drawback of the composite sustainability index is that it cannot guide the organization to find weak spots to improve the sustainability performance. LCA is well suited to find the weak spots or hot spots contributing to poor sustainability. Moreover, the composite sustainability index provides the assessment in term of observed variables but does not provide information on the ill-effects of the poor performance. For example, composite sustainability index provides performance in term of energy usage but it does not tell the effects of energy usage on resource depletion or human health or global warming potential. Composite sustainability indices usually reflect the effect of manufacturing activities at regional or local level and does not include the effects of pre-manufacturing and post-manufacturing activities.

Life cycle assessment is a scientific quantitative evaluation technique for assessing environmental impacts and resource consumption for producing a product or for a process from the raw materials extraction, to final disposal (from cradle to grave) (Klöpffer, 1997). The life cycle of a product is connected to a large number of resource extraction and substance emissions (Huijbregts et al., 2016). LCA can be used as a technical tool to evaluate environmental consequences of a product, process, packaging or any activity across the entire life cycle of a product or service (Sangwan, 2006). The life cycle assessment is a valuable tool for better understanding the environmental impacts generated by different life cycle stages. It can visualize the impacts in such a way that manufacturers can identify hotspots, and reduce or optimize them by alternative solutions.

7.2 CASE STUDY: LCA OF CEMENT MANUFACTURING

In this case study, LCA has been performed on one of the cement manufacturing organizations producing portland cement.

Some researchers (Heede, 2012; Huntzinger and Eatmon, 2009; Li *et al.*, 2015; WBCSD, 2016) have evaluated environmental performance of cement industry using life cycle approaches (life cycle inventory or LCA). Availability and quality of data are two important aspects to carry out the LCA analysis. It is possible to calculate the CO_2, NO_x and SO_x emissions directly from the decomposition of limestone and coal burning by using standard values (Li *et al.*, 2015; Hanle *et al.*, 2006; WBCSD, 2011). However, in this calculation, the emissions and environmental impacts generated in the pre-manufacturing activities will remain unaccounted. Some efforts to incorporate the energy and CO_2 emissions in cement manufacturing organizations are reported for countries like China, Japan, Thailand, and Europe (Hasanbeigi *et al.*, 2010; Li *et al.*, 2015; Supino *et al.*, 2016). Huntzinger and Eatmon (2009) assessed the environmental impacts from different cement manufacturing technologies. Energy consumption (electric and thermal) is found to be a major contributor to the environmental impacts from cement industry.

Madlool *et al.* (2011) reviewed different technologies for energy use and savings in cement industry. Hasanbeigi *et al.* (2010), discussed the energy-efficiency opportunities in Chinese cement industry. Zhang *et al.* (2017) investigated the emergy-based sustainability assessment of Chinese cement industry. Luo *et al.* (2017) presented a sustainable production framework for cement manufacturing firms from a behavioral perspective.

This chapter presents a case study to identify the environmental impacts associated with the Portland cement manufacturing in Indian cement organizations. The case study also attempts to find suitable ways to reduce the emissions and to save resources and energy required for cement production. The study utilizes the ISO 14040 methodology to estimate the environmental impacts from cement manufacturing process.

7.3 MATERIALS AND METHOD

The Portland cement manufacturing consists of raw materials quarried from mines, transported to the plant, crushed and milled into fine powdered material, preheated before entering to the rotary kiln where the material is heated to a temperature of more than 1400°C to produce the clinker. The heat is generated using fossil fuels, coal, biomass, and alternative fuels (waste oil, tyres, wood chips, etc.) and the excess heat after the clinker production is reused in preheaters. The clinker produced in the kiln is then cooled and mixed with gypsum in order to provide a required setting time of cement. This fine-grained (~ 10 microns) mixture is called as Portland cement and packed in bags. The LCA analysis of the Portland cement manufacturing has been carried according to ISO 14040 standard (ISO, 1997). LCA as a process is systematic approach and consists of four components, as guided by the ISO 14040 series standards – goal and scope definition, inventory analysis, impact assessment, and interpretation – as shown in Figure 7.1. Rebitzer et al. (2004) discussed the ISO 14040 series standards in details for different applications: ISO 14040 (1997) for principles and framework, ISO 14041 (1998) for goal and scope definition and inventory analysis, ISO 14042 (2000) for life cycle impact assessment, and ISO 14043 (2000) for life cycle interpretation. The environmental impact of the cement manufacturing process has been assessed with the help of Umberto NXT universal (IFU Hamburg, 2015) software tool and Eco-invent dataset version 3 (Swiss Centre for Life Cycle Inventories, 2017). The well-known ReCiPe method is employed for both midpoint and endpoint assessments of inventories. ReCiPe method is known for its harmonization at both midpoint and endpoint levels (Huijbregts *et al.*, 2016). It extensively covers a wide range of midpoint and endpoint categories, which are useful to envisage the several environmental impacts. The ReCiPe method of impact assessment is an upgrade of eco-indicator and CML method (Goedkoop *et al.*, 2009).

7.3.1 Goal and Scope Definition

The main aim of the study is to analyze the environmental impacts generated by Portland cement manufacturing process at an Indian cement industry.

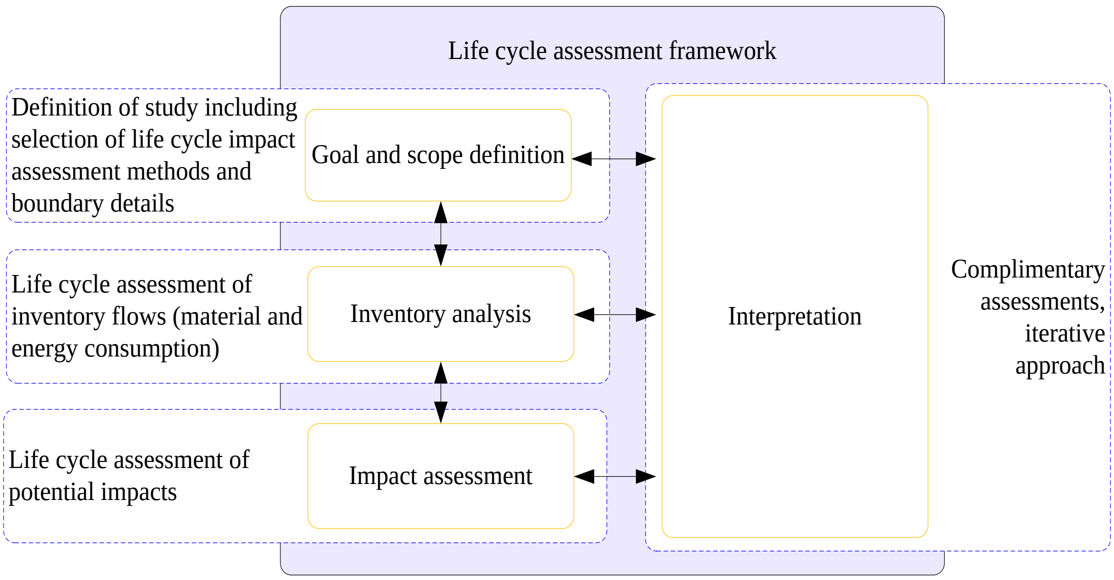


Figure 7.1 Life cycle assessment framework (source: ISO 14040)

7.3.2 Functional Unit

The functional unit taken for the study is the production of one tonne of Portland cement in India.

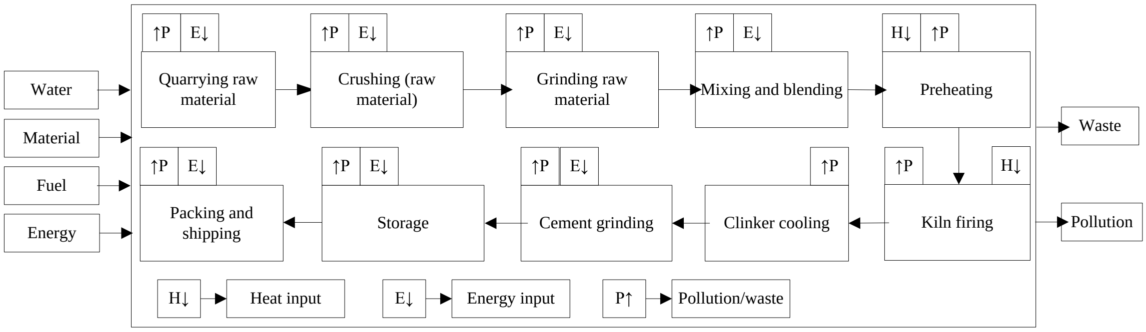


Figure 7.2 System boundary of the Portland cement manufacturing process

7.3.3 System Boundary

The system boundary for the study is defined as cradle to gate as shown in Figure 7.2. It consists of pre-manufacturing activities (raw material extraction and transportation), manufacturing, and post-manufacturing (packing). The end of life phase of the cement is not considered in the study as the disposal of the cement is as inert waste, which does not produce environmental impacts. The scope does not incorporate the effect of infrastructure (technical building services, equipment, and compressed air). The operational system boundary of the current study is taken as one year. The organizational system boundary of the study includes raw material (limestone, gypsum, clay, sand, iron ore, slag, etc.), electricity consumed (in the manufacturing processes), thermal energy (in the form of coal, fossil fuel, and alternative fuels), water consumed (surface water, rainwater, municipal water, and groundwater), and waste and effluents (hazardous waste, scrap, and hazardous material consumed).

7.3.4 Inventory Analysis

The inventory analysis for one-tonne cement production is given in Table 7.1. Primary data for inventory analysis has been collected from actual measurements. Secondary and process specific data has been collected from literature and by making personal visits to cement plants. The CaO and MgO contents in the lime used at Indian cement plant is approximately 65% and 5% respectively. The $CaCO_3$ and $MgCO_3$ contents in limestone can be identified using X-ray diffraction method (XRD). It is possible to calculate the CO_2, NO_x and SO_x emissions directly from the decomposition of limestone and coal burning by using standard values (Li *et al.*, 2015; Hanle *et al.*, 2006; WBCSD, 2011). However, in this calculation, the emissions and environmental impacts generated due to pre-manufacturing activities will remain unaccounted. The pre-manufacturing activities include the purchased electricity, raw material transportation, raw material mining and excavation, etc. Generally, Indian cement manufacturing industry measures the environmental emissions of the manufacturing processes and on-site captive electricity production. The environmental impacts of pre-manufacturing activities and use of infrastructure are not measured. Similarly, the Indian cement industry measures the dust emitted from various cement production systems, which is approximately 0.2 to 0.3 kg/t cementitious product. The dust emission during the pre-manufacturing activities is again not accounted in the sustainability reports. The LCA process accounts the environmental impacts of pre-manufacturing activities also.

The case organization uses rotary dry kiln process for the production of cement. Most of the plants in India have migrated to the rotary dry kiln process from wet kiln or semi-dry kiln process. In a recent study, Garg *et al.*, (2017) informs that 98% of the cement in India is produced using rotary dry kiln process. The inventory analysis, as shown in the Table 7.1, has been divided into basic resources (material, energy sources, and water) and related waste. The main aim of the study is to assess environmental impacts of one-tonne cement manufacturing. Therefore, man, money, and infrastructure resources are not included in the scope of the study.

Table 7.1 Inventory table for cement production LCA

Inventory	Unit	Quantity
Raw material		
Limestone	Kg/t	966.13
Gypsum	Kg/t	48.26
Clay	Kg/t	7.44
Sand	Kg/t	1.86
Blast furnace slag	Kg/t	110.49
Fly ash	Kg/t	176.96
Bauxite	Kg/t	16.73
Iron ore	Kg/t	16.73
Lubricating oil	liters/t	0.020
Grease	Kg/t	0.007
Packaging bags	kg/t	1.33
Recycled materials used	%	22.04
Water		
Surface water	m3/t	0.22
Rain water	m3/t	0.33
Municipal water	m3/t	0.002
Ground water	m3/t	0.052
Water reused	%	9.84
Energy		
Electricity	KWH/t	86.41
Coal and pet coke in kiln	MJ/t	1937.63
Diesel oil in kiln	MJ/t	1.73
Alternative fossil fuel (waste oil, waste tyres, plastics, solvents, etc.)	MJ/t	45.21
Bio-mass consumed in Kiln	MJ/t	11.98
Diesel oil for on-site transport	MJ/t	19.47
Diesel for drying of raw material	MJ/t	53.59
Coal for onsite power generation	MJ/t	969.01
Diesel for onsite power generation	MJ/t	0.63
Alternative fossil fuels for onsite power generation	MJ/t	6.26
Biomass for onsite power	MJ/t	0.72
Hazardous material and waste		
Waste oil	Kg/t	0.009
Grease	Kg/t	0.0007
Steel scrap	Kg/t	0.45
Others (unspecified waste)	Kg/t	0.19
Filter bags	Kg/t	0.002
Hazardous material use	Kg/t	31.76

The inventory is assumed to provide necessary chemical balance for clinker production in the Kiln and cement production. The inventory dataset for raw material acquisition (limestone, clay, sand, iron ore, and gypsum) along with Indian electricity production, thermal energy generation by different fossil fuels for various operations/processes is obtained from eco-invent dataset contained in Umberto NXT Universal software.

7.4 RESULTS AND DISCUSSION

The environmental impacts of cement manufacturing are in terms of local, regional, and global impacts. Local impacts can be air emissions, noise emissions, change in the land area, and impacts the local ecosystem by means of mining or other related activities. If the mining activities are carried out at locations other than plant location, the effect will be more regional than local. The effect of SO_x and NO_x emissions can cause acid rains, which is again a regional impact. The different emissions generated due to the production processes also effect the natural ecosystem at the global level. The environmental impacts at the global level are in the terms of global warming potential, acidification potential, eutrophication potential, various toxicity potentials, human health, and resource depletion.

The main environmental impacts categories included in the midpoint assessment are: Agricultural land occupation (ALOP), Climate change (GWP100), Fossil depletion (FDP), Freshwater ecotoxicity (FETP), Freshwater eutrophication (FEP), Human toxicity (HTP), Ionizing radiation (IRP), Marine ecotoxicity (METP), Marine eutrophication (MEP), Metal depletion (MDP), Natural land transformation (NLTP), Ozone depletion (ODP), Particulate matter formation (PMFP), Photochemical oxidant formation (POFP), Terrestrial acidification (TAP100), Terrestrial ecotoxicity (TETP), Urban land occupation (ULOP), and Water depletion (WDP).

The main environmental impacts categories included in the endpoint assessment are: ecosystem quality, human health, and resources.

7.4.1 Endpoint Assessment

It is observed from the results of the case study that the clinker production process is the energy-intensive and environmental impact generating process. Table 7.2 and Table 7.3 presents the endpoint assessment results of cement manufacturing. Figure 7.3 illustrates the major contributors to the environmental impacts. The energy (electricity energy and thermal energy) consumes maximum resources. Fly-ash, slag, hazardous waste treatment, gypsum and iron ore also have significant contribution as shown in Figure 7.3. The human health is largely impacted by energy, fly-ash, slag, hazardous waste treatment, limestone and iron ore used in the cement pre-manufacturing and manufacturing activities. It is observed that energy followed by fly-ash, slag, hazardous waste, and gypsum are also dominating the ecosystem quality. Figure 7.4 shows the effects of other contributors to the endpoint results after removing the effect of energy, fly-ash, slag, hazardous waste, and gypsum to visualize the effect of other material and activities. It is observed that limestone, iron ore and polypropylene cement bags are affecting the environment in all the categories and especially is human health and resources categories. The calcination process and combustion of fossil fuel (natural gas, biomass, coal, and fossil fuel) contribute significantly to CO_2 emissions and particulate emissions.

Table 7.2 Endpoint assessment results for the case study

Major contributors to environmental impacts	Ecosystem quality (climate change)	Ecosystem quality (Total)	Human health (particulate matter)	Human health (total)	Resources (Total)
Fly ash	2.29E+00	2.39E+00	5.71E-01	4.28E+00	1.53E+00
Slag	1.54E+00	1.63E+00	7.27E-01	3.23E+00	2.20E+00
Hazardous waste treatment	1.50E+00	1.62E+00	3.19E-01	2.82E+00	1.03E+00
Gypsum	3.44E-01	5.80E-01	3.19E-01	9.33E-01	6.52E-01
Cement bag	4.69E-02	4.82E-02	1.53E-02	9.34E-02	2.77E-01
Limestone	3.73E-02	4.64E-02	3.14E-01	3.76E-01	8.65E-02
Iron ore	3.65E-02	4.39E-02	2.49E-01	3.10E-01	6.85E-01
Bauxite	2.05E-03	1.72E-03	1.16E-02	1.50E-02	2.39E-02
Sand	9.83E-04	1.42E-03	8.50E-04	2.55E-03	2.50E-03
Scrap steel	6.98E-04	1.38E-03	3.31E-04	1.62E-03	1.47E-03
Lubricating oil	5.60E-04	8.15E-04	3.93E-04	1.37E-03	6.39E-03
waste mineral oil	5.10E-04	5.10E-04	6.83E-06	8.18E-04	1.08E-05
Clay	4.56E-04	5.09E-04	4.59E-04	1.24E-03	1.20E-03
Water used	5.69E-05	6.34E-05	3.86E-05	1.40E-04	1.15E-04
Energy consumption	3.18E+00	3.71E+00	2.97E+00	8.13E+00	1.21E+01

Table 7.3 Endpoint assessment results for energy consumption

Major contributors to environmental impacts	Ecosystem quality (climate change)	Ecosystem quality (Total)	Human health (particulate matter)	Human health (total)	Resources (Total)
Biomass used in Kiln	1.22E-02	2.20E-02	3.68E-03	2.38E-02	1.01E-02
diesel to dry raw material	8.86E-02	9.73E-02	1.05E-01	2.48E-01	2.28E-01
Indian electricity mix	2.13E+00	2.29E+00	1.86E+00	5.30E+00	3.56E+00
Coal and pet coke	5.90E-01	8.16E-01	6.20E-01	1.60E+00	5.43E+00
Alternative fossil fuel	2.49E-02	3.03E-02	9.09E-03	5.05E-02	2.68E-02
Onsite transportation	3.04E-02	3.33E-02	5.23E-02	1.01E-01	7.56E-02
Coal for onsite power	2.95E-01	4.08E-01	3.10E-01	7.99E-01	2.71E+00
Diesel used in Kiln	2.86E-03	3.14E-03	3.38E-03	8.01E-03	7.35E-03
Diesel for onsite transport	9.82E-04	1.08E-03	1.69E-03	3.28E-03	2.44E-03

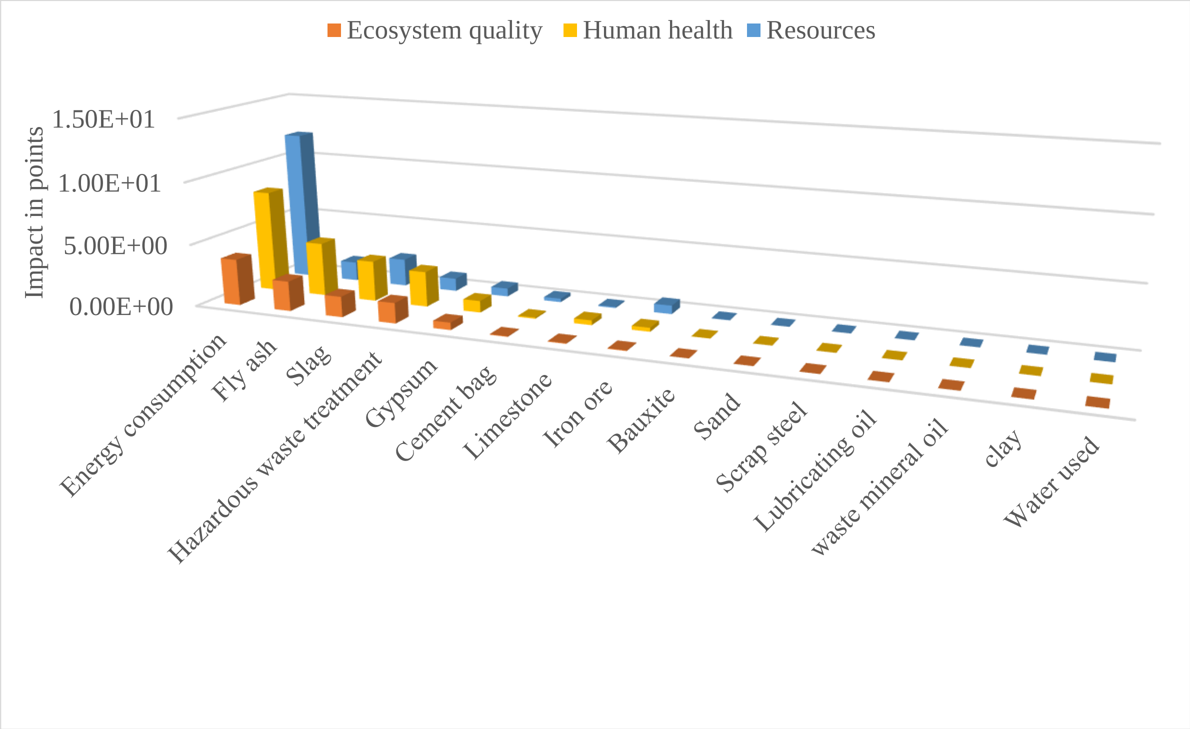


Figure 7.3 Endpoint assessment results

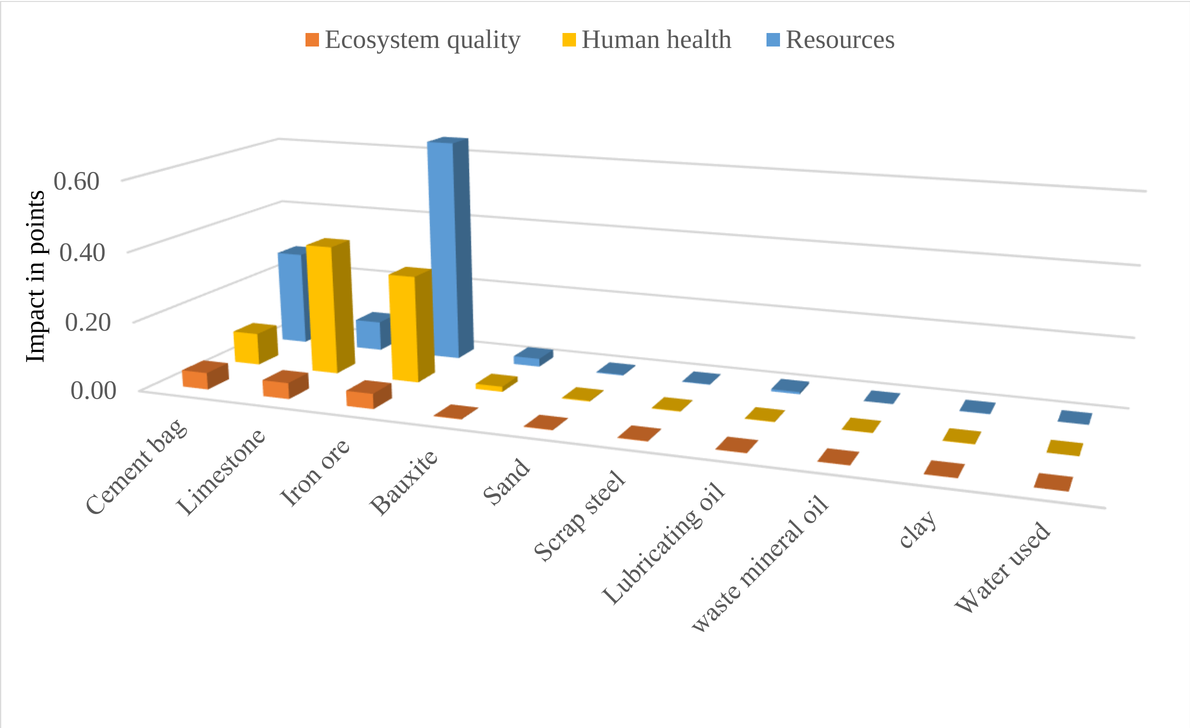


Figure 7.4 Endpoint assessment results without contribution of energy, fly-ash, slag, hazardous waste treatment, and gypsum

The environmental impacts of energy consumption are investigated further to find the major contributors (Table 7.3 and Figure 7.5). It is observed that major environmental impacts are generated by electricity consumption, coal and pet coke used in the kiln; coal for onsite captive power generation; and diesel consumed in the drying of the raw material. The effect of electricity consumption in the human health category is more severe than the effect of coal and pet coke used in the kiln. The effect of electricity is lesser than that of coal and pet coke in case of the resources category. This is because the emissions generated from the electricity generation are more potent to create the global warming whereas resource depletion is affected more severely by the consumption of coal and pet coke.

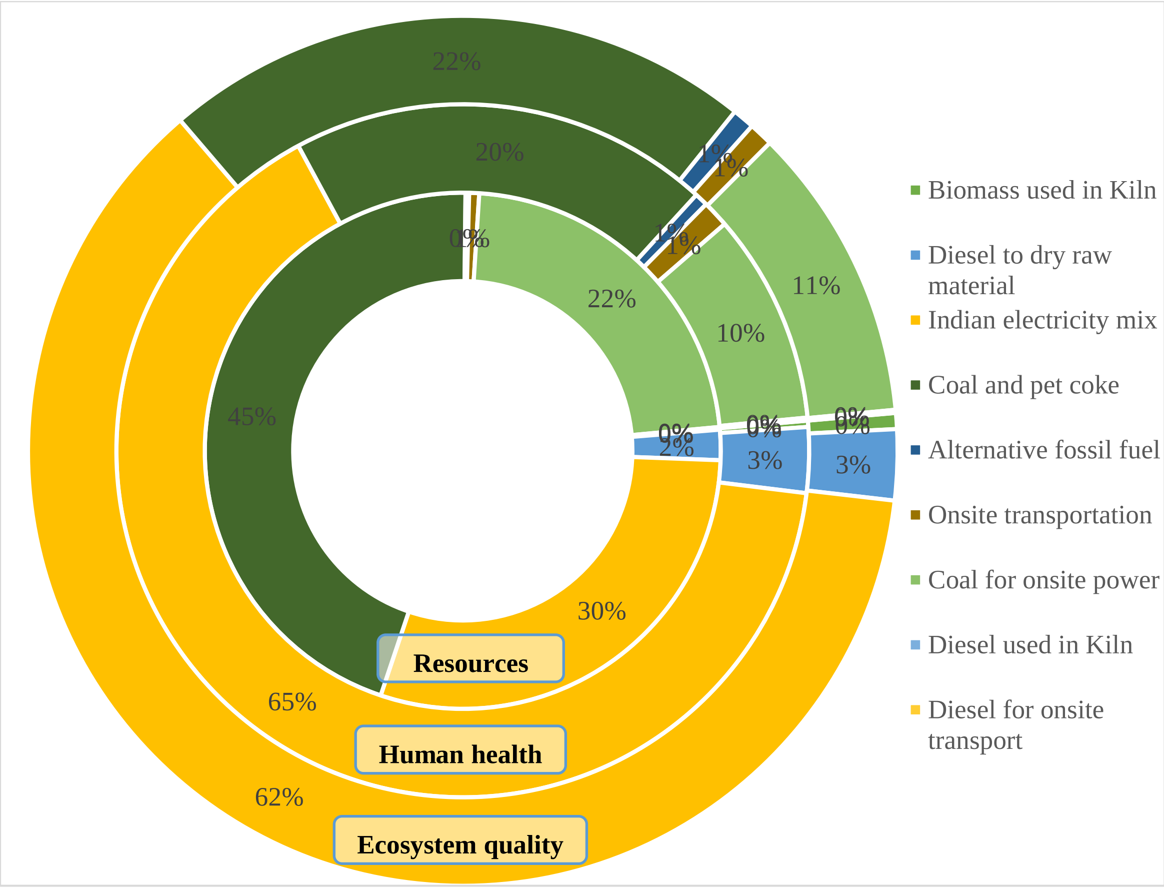


Figure 7.5 Endpoint assessment results for energy consumption

7.4.2 Midpoint Assessment

The results of midpoint assessment are given in Table 7.4 and Table 7.5. The results show (Figure 7.6) trends similar to endpoint assessment: electricity and heat input effects are highest followed by hazardous waste treatment, fly ash, slag, gypsum, and limestone in almost all the categories. The consumption of iron ore has also shown significant impact in on metal depletion potential. The effect of hazardous waste treatment is high potential for toxicity and ozone depletion. The slag used in the cement manufacturing process also has the high metal depletion potential. The environmental impacts of energy inputs are highest in all categories; therefore, these are detailed further in Figure 7.7. Figure 7.7 shows that major impacts are generated by electricity consumption followed by coal and pet coke and coal for onsite captive power generation.

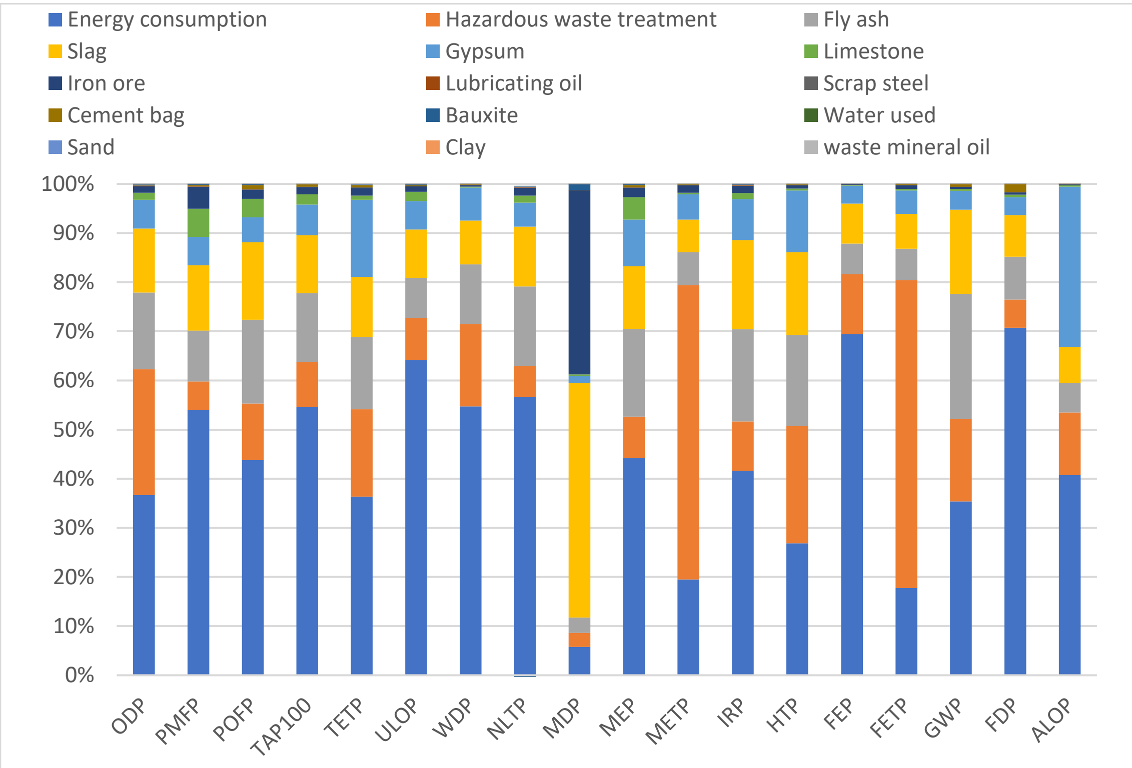


Figure 7.6 Midpoint assessment results

Table 7.4 Midpoint Assessment Results

Major contributors	ODP	PMFP	POFP	TAP100	TETP	ULOP	WDP	NLTP	MDP	MEP	IRP	HTP	FEP	FETP	GWP	FDP	ALOP
Hazardous waste treatment	5.87E-06	6.20E-02	1.62E-01	1.81E-01	2.49E-03	3.85E-01	1.98E-01	3.01E-03	9.79E-01	4.16E-03	9.04E-01	5.71E+00	2.82E-03	2.25E-01	8.54E+01	7.73E+00	2.20E+0
Fly ash	3.59E-06	1.11E-01	2.39E-01	2.74E-01	2.06E-03	3.66E-01	1.43E-01	7.75E-03	1.08E+00	8.82E-03	1.69E+00	4.43E+00	1.45E-03	2.29E-02	1.31E+02	1.17E+01	1.03E+0
Slag	2.98E-06	1.41E-01	2.22E-01	2.32E-01	1.72E-03	4.41E-01	1.05E-01	5.83E-03	1.65E+01	6.27E-03	1.64E+00	4.02E+00	1.90E-03	2.55E-02	8.76E+01	1.13E+01	1.25E+0
Gypsum	1.35E-06	6.20E-02	7.09E-02	1.23E-01	2.21E-03	2.58E-01	7.99E-02	2.37E-03	5.02E-01	4.71E-03	7.52E-01	3.00E+00	8.33E-04	1.72E-02	1.96E+01	4.93E+00	5.60E+0
Limestone	3.23E-07	6.10E-02	5.33E-02	4.03E-02	1.14E-04	8.61E-02	2.20E-03	6.84E-04	9.44E-02	2.23E-03	1.15E-01	9.78E-02	3.27E-05	1.18E-03	2.13E+00	6.50E-01	3.83E-02
Iron ore	3.02E-07	4.84E-02	2.64E-02	3.00E-02	2.19E-04	4.81E-02	3.68E-03	7.72E-04	1.30E+01	9.72E-04	1.34E-01	1.58E-01	4.44E-05	2.53E-03	2.08E+00	6.53E-01	3.66E-02
Lubricating oil	2.58E-08	7.63E-05	4.35E-04	2.45E-04	3.02E-06	3.55E-04	8.65E-05	5.03E-05	2.32E-03	4.40E-06	9.30E-03	3.48E-03	1.41E-06	8.10E-05	3.20E-02	4.97E-02	8.99E-04
Scrap steel	2.33E-08	6.43E-05	1.26E-04	1.59E-04	1.87E-05	1.57E-03	5.47E-04	-6.5E-06	7.82E-03	3.77E-05	1.72E-03	1.10E-02	2.42E-06	1.57E-04	3.98E-02	8.73E-03	1.14E-02
Cement bag	2.02E-08	2.97E-03	1.24E-02	8.61E-03	5.79E-05	6.88E-03	1.60E-03	3.76E-05	8.16E-03	2.10E-04	7.47E-03	3.74E-02	3.77E-06	5.97E-04	2.68E+00	2.15E+00	2.53E-03
Bauxite	1.70E-08	2.25E-03	2.30E-03	1.94E-03	1.25E-05	8.67E-03	1.58E-04	-2.0E-04	4.18E-01	9.88E-05	6.59E-03	6.19E-03	2.16E-06	7.39E-05	1.17E-01	3.52E-02	2.48E-03
Water used	1.32E-08	7.50E-06	1.03E-05	1.83E-05	2.72E-07	1.57E-05	7.16E-06	2.12E-07	6.32E-05	3.64E-07	1.29E-04	4.34E-04	1.08E-07	3.25E-06	3.25E-03	8.70E-04	9.00E-05
Sand	8.39E-09	1.65E-04	4.33E-04	3.78E-04	1.48E-05	4.00E-03	1.50E-04	4.78E-05	4.27E-03	1.46E-05	3.64E-03	8.36E-03	1.82E-06	4.16E-05	5.61E-02	1.82E-02	1.27E-03
Clay	4.74E-09	8.91E-05	2.84E-04	1.75E-04	7.77E-06	1.64E-03	1.84E-05	-7.7E-06	9.96E-04	9.55E-06	1.69E-03	3.70E-03	2.70E-07	1.76E-05	2.60E-02	9.17E-03	2.25E-04
waste mineral oil	3.47E-11	1.33E-06	2.61E-06	2.40E-06	6.18E-08	4.09E-06	4.44E-05	2.57E-08	4.87E-05	1.16E-07	7.33E-06	3.27E-04	1.32E-07	7.18E-06	2.91E-02	6.63E-05	8.89E-06
Energy consumption	8.42E-06	5.76E-01	6.15E-01	1.07E+00	5.10E-03	2.88E+00	6.46E-01	2.71E-02	2.01E+00	2.18E-02	3.76E+00	6.41E+00	1.61E-02	6.37E-02	1.81E+02	9.47E+01	6.98E+0

Table 7.5 Midpoint assessment results for energy consumption

Major contributors	ODP	PMFP	POFP	TAP100	TETP	ULOP	WDP	NLTP	MDP	MEP	IRP	HTP	FEP	FETP	GWP	FDP	ALOP
Biomass used in Kiln	8.04E-02	6.94E-01	6.74E-02	5.49E-04	2.81E-05	3.97E-02	1.38E-02	3.53E-04	2.25E-04	3.23E-02	1.73E-08	7.14E-04	1.21E-03	2.43E-03	3.65E-04	3.40E-03	2.03E-03
Diesel to dry raw material	1.63E-02	5.05E+0	1.74E+0	2.74E-03	3.49E-05	1.24E-01	3.19E-01	2.44E-03	2.29E-03	1.87E-01	9.09E-07	2.03E-02	6.84E-02	4.00E-02	1.75E-04	1.10E-02	2.48E-03
Indian electricity mix	1.95E+0	1.22E+2	2.79E+1	3.41E-02	6.08E-03	3.35E+0	1.32E+0	4.00E-02	1.34E-02	8.09E-01	2.08E-06	3.61E-01	3.76E-01	7.52E-01	2.64E-03	9.63E-01	3.67E-01
Coal and pet coke	3.22E+0	3.37E+1	4.28E+1	1.65E-02	6.60E-03	1.85E+0	1.30E+0	1.98E-02	3.08E-03	5.75E-01	3.34E-06	1.20E-01	8.85E-02	1.68E-01	1.21E-03	1.26E+0	1.81E-01
Alternative fossil fuel	9.89E-02	1.42E+0	1.75E-01	5.75E-04	6.91E-05	9.23E-02	4.54E-02	8.66E-04	1.02E-04	9.47E-02	4.83E-08	1.77E-03	2.51E-03	5.02E-03	7.66E-05	7.24E-03	2.85E-03
Onsite transportation	3.60E-03	1.73E+0	5.94E-01	8.89E-04	6.65E-06	3.27E-02	1.10E-01	8.94E-04	1.09E-03	1.38E-02	3.17E-07	1.02E-02	3.11E-02	1.86E-02	3.45E-05	3.06E-03	6.40E-04
Coal for onsite power	1.61E+0	1.68E+1	2.14E+1	8.24E-03	3.30E-03	9.23E-01	6.49E-01	9.93E-03	1.54E-03	2.87E-01	1.67E-06	6.03E-02	4.43E-02	8.41E-02	6.03E-04	6.30E-01	9.05E-02
Diesel used in Kiln	5.26E-04	1.63E-01	5.60E-02	8.84E-05	1.13E-06	4.00E-03	1.03E-02	7.87E-05	7.41E-05	6.04E-03	2.94E-08	6.57E-04	2.21E-03	1.29E-03	5.66E-06	3.56E-04	8.01E-05
Diesel for onsite transport	1.17E-04	5.60E-02	1.92E-02	2.88E-05	2.15E-07	1.06E-03	3.57E-03	2.89E-05	3.52E-05	4.45E-04	1.02E-08	3.29E-04	1.01E-03	6.03E-04	1.12E-06	9.89E-05	2.07E-05

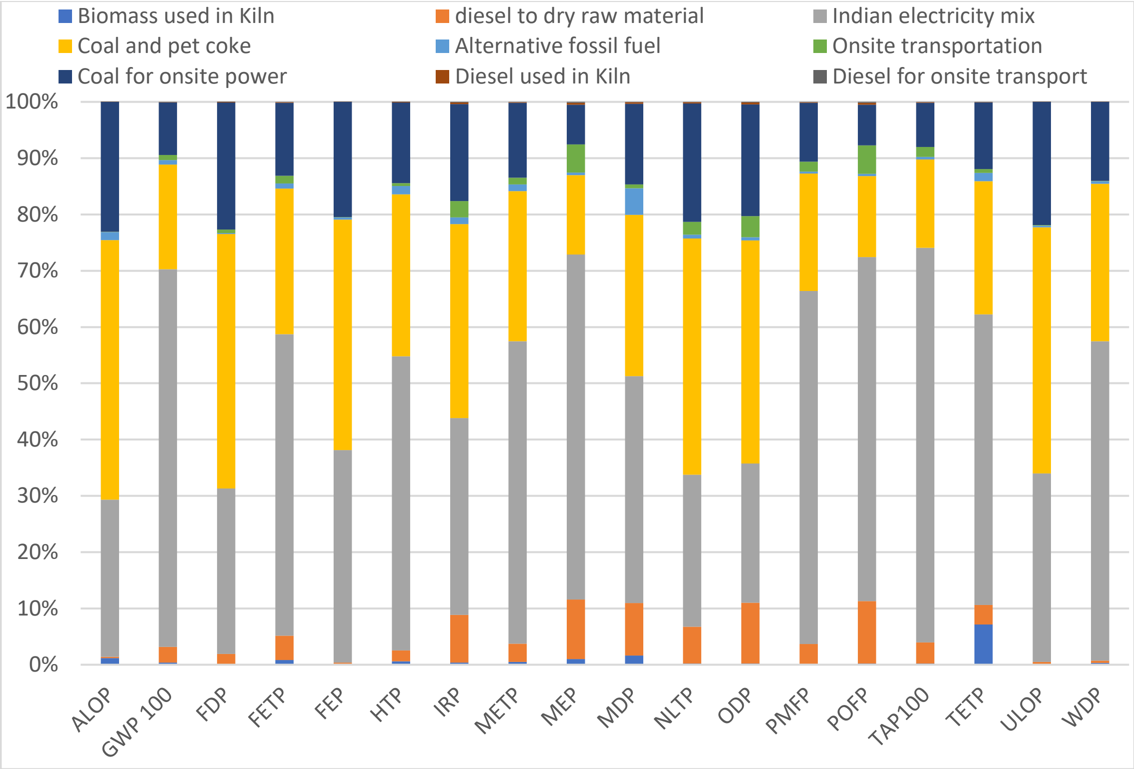


Figure 7.7 Midpoint assessment results for energy

7.4.3 Environmental impacts of electricity consumption

It has been observed that electricity consumption is a major source of environmental impacts in cement manufacturing; therefore, it is studied further to understand the consumption of electricity in various processes. This will help the management to take actions for the reduction of electricity consumption. Figure 7.8 shows the actual electricity consumption and climate change potential of the electricity consumption. The major impacts generated from electricity consumption are from the cement grinding process (~31%); kiln feeders, kiln and clinker coolers (~29%) and raw material grinding (~24%).

Therefore, the organizations need better management of grinding processes and kiln to avoid waste and improve productivity of these processes. Better grinding, kiln and cooling technologies also decrease the electricity consumption in these processes.

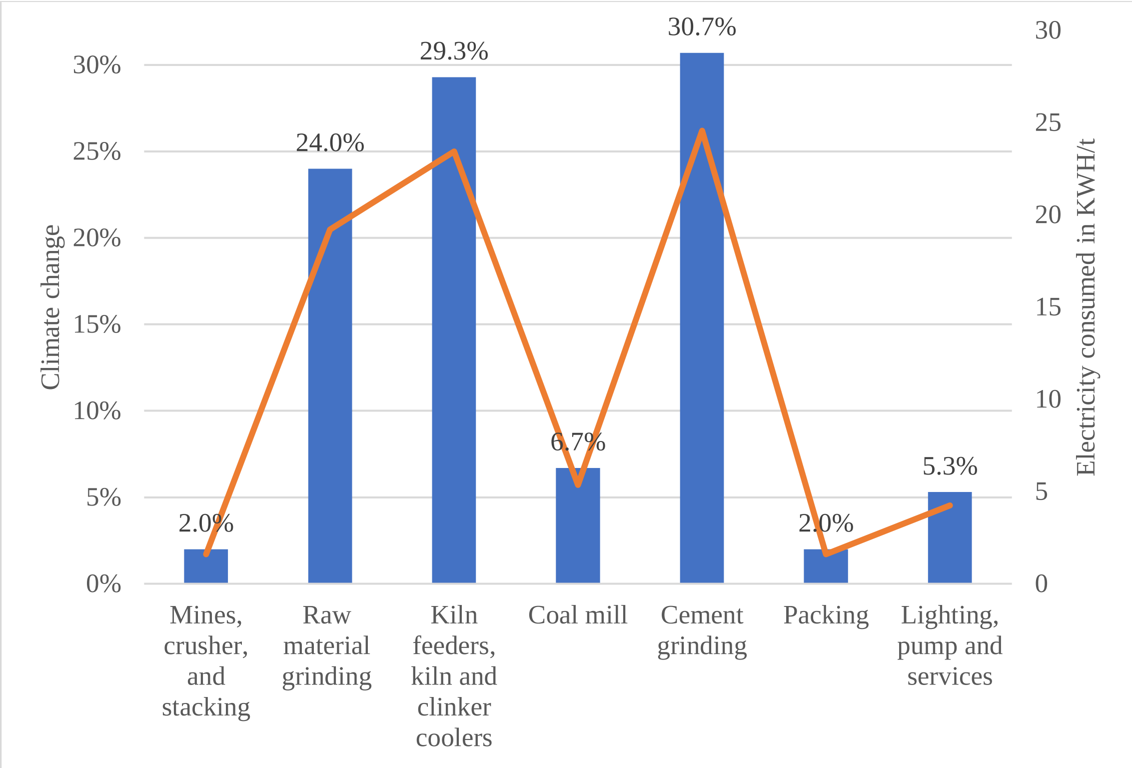


Figure 7.8 Climate change potential of major electricity consuming processes

Madlool *et al.* (2011) also suggested that the energy consumption can be reduced by energy efficient technologies which are also economically viable. Choice of alternative fossil fuels (i.e. waste gas, landfill gas, hydraulic oils, low chorine spent solvents, sawdust, whole tyres, plastic bags, etc.) can be helpful in improving the energy efficiency of cement manufacturing process. It is observed from the study that, Indian cement industry has already started using waste oil, plastics, tyres in the kilns as shown in Table 7.1. It is also observed from the sustainability reports that waste heat recovery system is also becoming a popular practice for improving the energy efficiency of cement manufacturing in Indian industry. Madlool *et al.* (2011) suggested some important energy saving measures for cement industry: optimization of grinding energy use, high efficiency classifier (to separate fine and coarse particles), waste heat recovery (WHR), use of WHR steam generator, utilization of waste heat to preheat raw material, kiln surface heat recovery, utilization of waste heat to dry the raw material. It is observed that practically all cement plants utilize waste heat from clinker in pre-heater, and partially the waste heat from clinker cooler is utilized in cement mills. The remaining thermal energy from clinker cooler has a potential to provide a significant amount of energy. Specific energy consumption of dry cement manufacturing process can be reduced by the use of vertical mills (Madlool *et al.*, 2011).

7.5 COMPARATIVE ANALYSIS WITH OTHER STUDIES

This section provides a comparative analysis of energy consumption and environmental impacts of cement production with similar studies in different countries as given in Table 7.6. The goals and scope of the different studies are different but the comparison provides an overall idea of environmental impacts generated by cement production. The study by Li *et al.* (2015) compared the environmental impacts of cement production in China and Japan for both process and onsite captive power generation. Huntzinger and Eatmon (2009) compared four different cement manufacturing processes for their environmental impacts. Heede (2012) provides data on cement industry statistics related to energy consumption and CO_2 emissions from 1950-2010. The reports of cement sustainability initiative by world business council for sustainable development (WBCSD) provide data for energy and emission performance for cement manufacturing. Table 7.6 shows that Indian cement manufacturers are doing well in terms of energy consumption as compared to other countries. This is due to the use of dry rotary kilns in most of the Indian cement plants. Particulate matter emissions are not good for the Indian plant. This is partially due to the mis-handling of the cement. The CO_2 emissions are comparable to other countries. The thermal substitution rate (TSR) in European cement plants (Belgium, France, Germany, the Netherlands, and Switzerland) has reached up to 35% (International Energy Agency, 2007), which is approximately 1% in Indian cement manufacturing sectors. The increase in TSR can improve the energy efficiency and decrease the environmental impacts of Indian cement industry.

Table 7.6 Comparative analysis of energy consumption and emissions for one tonne of cement production

Particulars	**Unit**	**Current study (India)**	(Li et al., 2015) **(China & Japan)**	**Heede (2012)**	**Huntzinger and Eatmon (2009) (USA)**	**WBCSD (2016)**
CO_2 emissions	Kg/tonne cement	511*	798 China 779Japan	655	511	~620
Electric energy (SEC)	Kwh/tonne cement	86	40 China# 30.92 Japan#	111	215.5	110
Thermal energy (SEC)	GJ/tonne cement	3.046	2.814 China** 2.931 Japan**	3.690	4.61	3.00
Particulate matter	Kg/tonne cement	1.067	0.065 China 0.036 Japan	-	0.043	0.0467

*= without direct co_2 from clinker; #= electricity produced within the organization and from waste heat recovery systems; **= without biomass and recycled waste fossil fuel; SEC= specific energy consumption

One major environmental impact, which is not included in the current case study is process specific emissions (chemical reactions). The process specific emissions are also significant particularly in term of CO_2 emissions. This value can be approximated by using clinker factor as per IPCC guidelines for national greenhouse gas inventories as mentioned in Hanle *et al.* (2006). It is taken as 78.5% (molecular weight ratio of CO_2/CaO). The clinker factor is percentage of clinker required to produce one-tonne cement.

Therefore, total CO_2 emissions per tonne of cement production

= 511 + clinker factor *0.785

= 511 (Kg)+ 0.72 *0.785 (tonne)

= 1076 Kg CO2

(Assuming average clinker factor for Indian cement industry as 72%)

7.6 SUMMARY

This chapter presents a life cycle analysis of a cement manufacturing process to identify the major processes contributing to the environmental impacts and the environmental effects in terms of end point and midpoint categories as per ISO 14040 standard by using UMBERTO NXT Universal software. This assessment provides the hot spots (major contributing factors) of environmental impacts. LCA takes into account the pre-manufacturing activities which hitherto not accounted by the cement manufacturers in their sustainability reports. In fact, the action plans for sustainability improvement can be made after analyzing the LCA results.

It is observed from the case study results that energy, fly-ash, slag, hazardous waste treatment, and gypsum are major contributors to the environmental impacts on ecosystem quality, human health, and resources. Energy, fly-ash, slag, and hazardous waste treatment also have major impacts on global warming, ozone depletion and ionizing radiation. However, the effect of energy dominates other effects in most of the categories. Grinding processes, kiln feeding, kiln, and clinker cooling are main electricity consuming processes in the cement manufacturing industry. Specific energy consumption of dry cement manufacturing process can be reduced by the use of vertical mills. Thermal substitution has high potential to improve the environmental impacts of the Indian cement industry.

CHAPTER 8

CONCLUSIONS

Around the world, manufacturing organizations are orienting towards sustainability and sustainable development but the assessment of sustainability is a challenge to them. The sustainability reports from manufacturing organizations, in terms of triple bottom line indicators, have increased the awareness of sustainability among various stakeholders. To facilitate the easy and effective implementation of sustainability improvement initiatives, the organizations should understand the interrelationship among elements (product, process. policy, life cycle, and resources) related to manufacturing value chain. This study has provided a sustainability readiness self-assessment model and a sustainability assessment model for sustainability assessment with appropriate indicators mapped across the manufacturing value chain elements.

Chapter 2 presents a systematic literature review of 248 articles addressing manufacturing sustainability. The study has traced the growth of manufacturing sustainability literature in term of levels of sustainability, elements of sustainability, types of research methodologies used, and focus areas. The systematic literature review finds that most of the articles do not consider the three dimensions of sustainability simultaneously for sustainability assessment; all the resources used by the manufacturing organizations are not considered throughout the supply chain for sustainability assessment; and there is lack of social sustainability research from manufacturing perspective.

Chapter 3 proposes a conceptual framework, for the manufacturing sustainability assessment, consisting three phases: pre-implementation or sustainability readiness self-assessment phase, post-implementation or sustainability assessment phase, and sustainability reporting phase. The emphasis has also been put on sustainability reporting and readiness self-assessment in addition to sustainability assessment.

Chapter 4 proposes a sustainability readiness self-assessment model for assessing the organizational preparedness for sustainability assessment and improvement using resource based theory. A list of 229 questions has been developed for the readiness self-assessment of three critical factors of product sustainability, process sustainability and sustainability polices. Readiness of each critical factor is assessed under different categories of resources. The proposed model is tested in two organizations – an automotive manufacturing organization and a cement manufacturing organization. The proposed model is simple and easy to use yet very effective to identify the weak areas of sustainability for improvement.

Chapter 5 presents a sustainability assessment model for manufacturing organizations. The four-level sustainability assessment model includes product life cycles, resources, critical factors, and sustainability dimensions. 121 indicators have been identified, from literature, to assess the progress of an organization towards sustainability and to measure the sustainable performance of a manufacturing organization from different perspectives: critical factor perspective, resource perspective, sustainability dimension perspective, and life cycle perspective throughout the supply chain. It ensures that no aspect of the organization is left without assessment. The identified indicators are capable to measure the product sustainability (33 indicators), process sustainability (51) and sustainability policies (37). The identified indicators are able to measure the effect of manufacturing on the seven resources:

people (48 indicators), money (58 indicators), material (49 indicators), energy (33 indicators), infrastructure (22 indicators), water (21 indicators), and air (16 indicators). The proposed model is also strong to assess social sustainability (30 indicators), economic sustainability (26 indicators) and environmental sustainability (65 indicators). The implementation and assessment of sustainability improvement initiatives is made easier by the model because of the mapping of indicators across critical factors, resources, sustainability dimensions, and life cycle. This mapping makes the decision making process visual, hence easy to explain the different stakeholders including employees. The ease of use and effectiveness of the model are high to assess the sustainability of a manufacturing organization. However, the ease of use is low for the pre-manufacturing stage, where the data acquisition is difficult for the internal people.

The proposed sustainability assessment model and the identified indicators are tested using data from the Indian cement manufacturing industry. The data collected from 127 respondents is analyzed statistically using SPSS 20.0 statistical tool. 30 indicators were marked by the respondents as ‘not applicable’ to cement industry and 24 indicators were deleted because their CITC (corrected item to total correlation) was less than 0.5. An exploratory factor analysis (EFA) was carried out on the remaining 67 indicators. 15 indicators were deleted during EFA because of their poor factor loadings. The remaining 52 indicators were classified into different categories using exploratory factor analysis. The economic indicators are grouped into four factors – capital and gains, utility cost, service cost, and training and support cost. The social indicators are also grouped into four factors – employees, local community, social justice, and growth and empowerment. The environmental indicators are grouped into five factors – emissions, material, end of life, packaging, and energy.

Chapter 6 proposes a composite sustainability index and demonstrated its usefulness using the indicators identified in chapter 5. The usefulness of the model is demonstrated by assessing and comparing the sustainability performance of four Indian cement organizations. The weightage of the three sustainability dimensions and sustainability indicators is computed using analytical hierarchy process (AHP). The Indian experts have given high weightage to the economic sustainability performance (48%) and environmental sustainability performance (40%) and very low weightage to social sustainability performance (12%). The highest weightage is given to return on investment followed by CO_2, profit gained, NOx emissions and gender ration. Local area suppliers, expenditure in social development, annual sales volume, and energy used are given low weightage by the Indian cement manufacturers.

Chapter 7 presents a life cycle analysis of a cement manufacturing process to identify the major processes contributing to the environmental impacts and the environmental effects in terms of end point and midpoint categories as per ISO 14040 standard by using UMBERTO NXT Universal software. This assessment provides the hot spots (major contributing factors) of environmental impacts. LCA takes into account the pre-manufacturing activities which hitherto not accounted by the cement manufacturers in their sustainability reports. In fact, the action plans for sustainability improvement can be made after analyzing the LCA results.

It is observed from the case study results that energy, fly-ash, slag, hazardous waste treatment, and gypsum are major contributors to the environmental impacts on ecosystem quality, human health, and resources. Energy, fly-ash, slag, and hazardous waste treatment also have major impacts on global warming, ozone depletion and ionizing radiation. However, the effect of energy dominates other effects in most of the categories. Grinding processes, kiln feeding, kiln, and clinker cooling are main electricity consuming processes in the cement manufacturing industry. Specific energy consumption of dry cement manufacturing process can be reduced by the use of vertical mills. Thermal substitution has high potential to improve the environmental impacts of the Indian cement industry.

MAJOR CONTRIBUTIONS OF THE THESIS

- First systematic literature review on manufacturing sustainability.
- First readiness self-assessment model to assess preparedness for assessing the organizational preparedness for sustainability assessment and improvement using resource based theory.
- Manufacturing sustainability assessment model to measure the sustainable performance of a manufacturing organization from different perspectives: critical factor perspective, resource perspective, sustainability dimension perspective, and life cycle perspective.
- Identification of 121 manufacturing sustainability indicators mapped across environmental, social and economic dimensions; people, material, money, energy, infrastructure, air, and water resources; and assessing product sustainability, process sustainability and sustainability policies.

- Development of 52 reliable and tested sustainability assessment indicators for Indian cement manufacturing industry.
- A composite sustainability index for Indian cement manufacturing organizations.
- Life cycle assessment of cement manufacturing process.

LIMITATIONS AND FUTURE RESEARCH SCOPE

The study explicitly addresses sustainability of manufacturing organizations in terms of triple bottom line dimensions. The literature review in this study has been aimed to identify the current status of sustainability in manufacturing with main focus on keywords used, which can be further extended to include some core manufacturing sustainability efforts like energy efficiency of machines/equipment, energy consumption from technical building services, social life cycle assessment, etc. can be included in the scope of this study. The survey instrument consisting 121 indicators can be used to develop sustainability indicators for the other manufacturing sectors. The cement industry indicators has been tested for reliability and classified but these indicators can be further validated using structure equation modeling. The LCA studies can be further extended to include the concepts of life cycle costing and social life cycle assessment to comprehensively address the life cycle engineering of products and processes. The study has been carried out in India and also the case studies were performed in Indian organizations, which may have induced some bias towards emerging countries. It will be interesting to carry similar studies for developed countries. The future research can also incorporate aspects like sustainability trade-off management, optimum transportation problems for raw material and products, sustainable outsourcing etc. Effective use of sustainability assessment data can be studied with by using big data analytics.

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Birla Institute of Technology & Science, Pilani
Pilani Campus
Vikrant Bhakar, Research Scholar, Mechanical Engineering Department

Dear Sir/Madam,

I am Vikrant Bhakar pursuing my doctoral thesis in the area of "sustainability assessment" at Birla Institute of Technology and Science, Pilani under the supervision of Prof. (Dr.) Kuldip Singh Sangwan and Prof. (Dr.) Abhijeet K. Digalwar. It gives me immense pleasure to interact with working professionals like you.

I have found from the literature that many of the Indian companies have implemented sustainability (read environmental) improvement initiatives because of the international pressure or governmental regulations. Some organizations provide sustainability reports on their websites. What is the usefulness of this reporting? Who reads it? How much time and effort is required to make this report? How much money is paid to external agencies to make this report? Are these reports useful in Indian context? Are these reports integrated with the company ERP? Do these reports represent all sustainability aspects of the organization? With these questions in the background, I have proposed a conceptual model for sustainability assessment. The first step in this direction is to understand the readiness of the company to implement sustainability improvement initiatives.

I have developed a simple self-assessment model to check the readiness of the company. I would like to improve this model so that it is useful for Indian companies. If you take some time out of your busy schedule, it will be a great help for me to find areas of improvement in my model. Your judicious response will assure substantial judgment in this exercise and help me to carry out my research successfully. It will take approximately 15 minutes to complete the survey form.

I fully understand the sacredness of the environmental topic in India and therefore assure you that the views expressed in this survey will be kept strictly confidential and will be used only for academic research.

Thanking you.

Yours truly

Vikrant Bhakar

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APPENDIX - A

PART – 1| General information of responding person

Name and location of the Organization : ____________________

Name of the responding person (optional) : ____________________

Designation (optional) : ____________________

Department (optional) : ____________________

Experience (years) : ____________________

E-mail (optional) : ____________________

Ph. No. / Mobile No. (optional) : ____________________

Would you like to be contacted for any further information? YES/ NO

APPENDIX - A

PART – 2 | Sustainability Readiness Self-Assessment Questions

Kindly put a √ mark against the question in appropriated box. If you think the question is probable then please put a √̶ mark against the question in appropriated box. For example:

People - Policy self-assessment questions	Yes	No	Type of response
Does the organization prohibit child labor?	√		If you are sure that it is prohibited
Does the organization prohibit child labor?		√	If you are sure it is not prohibited
Does the organization prohibit child labor?	√̶		It is probably prohibited (but not
Does the organization prohibit child labor?		√̶	It is not prohibited (but not sure)

NA: Not applicable

A-1)	People - Policy	Yes	No	NA
1.	Are the organizational environmental policies written and displayed to guide the employees?			
2.	Does the organization have a written strategy to guide organization to achieve social vision?			
3.	Does the organization involve employees in environmental and social policy making process?			
4.	Does the organization prohibit child labor?			
5.	Does the organization provide minimum wages?			
6.	Does the organization have a strong policy against sexual harassment?			
7.	Does the organization provide equal opportunity to women employees?			
8.	Does the organization have a provision for paternity and maternity leave?			
9.	Does the organization have a documented corporate social responsibility policy?			
10.	Does the top management monitor the progress of employee through performance appraisal?			
11.	Is the top management commitment for environment visible to all employees?			
12.	Is the top management commitment for society visible to all employees?			
13.	Does the organization hava an explicit social policy?			
14.	Are social issues addressed as business issues?			
15.	Does the top management monitor the progress of social projects?			
16.	Does the top management monitor the progress of environmental projects?			
17.	Is the managerial staff involved in environmental policy development?			
18.	Is the managerial staff involved in social policy development?			
19.	Are the environmental goals clear to managerial staff?			
20.	Are the social goals clear to managerial staff?			
21.	Does the organization conduct sustainability awareness/training/competence programs regularly?			
22.	Does the organization document the social lessons learned?			

23.	Are employees involved in process of determining environmental goals?			
24.	Are employees involved in process of determining social goals?			
25.	Are in-house employee involved in environmental and social project implementation?			
26.	Are social competence programs conducted for managerial staff?			
27.	Does the organization have a separate team to tackle social issues?			
28.	Does the organization have a separate team to tackle environmental issues?			
29.	Are the employees authorized to handle environmental problems?			
30.	Are the employees encouraged to provide suggestion on environmental performance improvement?			
31.	Are the employees encouraged to provide suggestion on social performance?			
32.	Are the employees recognized for their contribution to sustainable performance improvement?			
33.	Does the organization regularly review the environmental and social training programs?			
34.	Does the organization have enough internal sustainability experts?			
35.	Does the organization employ external environmental experts?			
36.	Does the organization involve environmental experts in technology development/procurement?			
37.	Does the organization involve social experts in technology development/procurement?			
38.	Does the organization have a policy to receive complaints from local community?			
39.	Does the organization conduct periodic environmental audits?			
40.	Does the organization conduct periodic social audits?			
	Suggest your questions			
1				
2				
A-2)	**People - Product**	**Yes**	**No**	**NA**
1.	Does the organization provide details of environmental emissions of the product to the customer?			
2.	Does the organization involve cross functional team in product design?			
3.	Is the top management committed for environmentally sustainable products?			
4.	Does the organization have an explicit policy for product return?			
5.	Does the organization recycle the products after customer use?			
6.	Does the top management aim to recycle the product in environment friendly manner?			
7.	Does the organization involve environmental expert in product design?			
8.	Does the organization involve social experts in product design?			
9.	Does top management aim to use recycled material in product?			

APPENDIX - A

	Suggest your questions			
1				
2				
A-3)	**People - Process**	**Yes**	**No**	**NA**
1.	Does the production process incorporate employee suggestions?			
2.	Does the organization provide proper equipment for the employees to work with hazardous materials?			
3.	Are the employees trained to incorporate customization in production process?			
4.	Does the organization provide a written methodology for sustainability implementation?			
5.	Are environmental awareness programs conducted for managerial staff?			
6.	Are social awareness programs conducted for managerial staff?			
7.	Are environmental training programs conducted for managerial staff?			
8.	Are social training programs conducted for managerial staff?			
9.	Are environment competence programs conducted for managerial staff?			
10.	Does the organization have requisite knowledge of sustainability implementation?			
	Suggest your questions			
1				
2				
B-1)	**Energy - Policy**	**Yes**	**No**	**NA**
1.	Does the organization have an explicit energy policy?			
2.	Is the energy policy documented to guide the managerial staff?			
3.	Does the organization include environmental issues in developing energy policy?			
4.	Does the organization use renewable energy source for captive power generation?			
5.	Does the organization purchase energy efficient technologies?			
6.	Does the organization follow the energy management standards (i.e. ISO 50004:2014)?			
7.	Does the organization produce energy through cogeneration?			
8.	Are the energy audits conducted regularly?			
9.	Is energy efficiency a criterion for supplier selection?			
	Suggest your questions			
1				
2				
B-2)	**Energy - Product**	**Yes**	**No**	**NA**
1.	Does the organization measure the embodied energy consumption for product?			
2.	Does the organization design the product for less energy consumption during operation?			
3.	Does the organization design the product for less energy consumption during maintenance and repair?			

APPENDIX - A

4.	Does the organization provide product upgradation for low energy consumption?			
5.	Does the organization measure fossil fuel consumption during operation?			
6.	Does the product design give possibilities to use renewable resources during use phase?			
7.	Does the organization monitor energy consumption during distribution phase?			
8.	Does the organization monitor the energy consumption during reverse logistics?			
9.	Does the organization know the energy requirement for EoL treatment (i.e. recycle, landfill, etc.)?			
10.	Does the organization know the energy produced during incineration of product after EoL?			
	Suggest your questions			
1				
2				
B-3)	**Energy – Process**	**Yes**	**No**	**NA**
1.	Does the organization monitor energy consumption during production process?			
2.	Does the organization aim to use renewable energy during production process?			
3.	Does the organization conduct training program for energy efficiency in production?			
4.	Is the operational staff capable to reduce energy consumption during ideal time of equipment and machinery?			
5.	Is the operational staff capable to reduce energy consumption during actual production process?			
6.	Does the organization measure energy consumption for compressed air?			
7.	Does the organization compute the energy requirement for waste treatment?			
8.	Does the organization compute the energy requirement for water treatment?			
9.	Does the organization compute the energy requirement for water used?			
10.	Does the organization use energy efficient vehicles for distribution?			
11.	Is the excess heat generated in production process utilized?			
	Suggest your questions			
1				
2				
C-1)	**Money – Policy**	**Yes**	**No**	**NA**
1.	Does the organization have an explicit economic policy related to social and environmental issues?			
2.	Does the organization monitor the environmental penalties?			
3.	Does the organization allocate financial resources regularly for sustainable development?			
4.	Are environmental issues addressed as business issues?			
5.	Does the organization invest for supplier development?			

6.	Is the organization involved in philanthropy activities?			
7.	Does the organization have an explicit policy for environmental investments?			
8.	Does the organization consider the environmental risks in its financial policies?			
9.	Does the organization invest in employee development?			
10.	Does the organization invest for environmental responsibility?			
11.	Does the organization provide pension benefits to the employees?			
12.	Does the organization provide health benefits to the employees?			
13.	Does the organization provide wages compared to market conditions?			
14.	Does the organization invest in social development in nearby areas?			
15.	Does the organization avoid income discrepancy for male and female employees?			
16.	Does the organization conduct program for skill development of local community?			
17.	Does the organization invest for education of local community?			
18.	Does the organization invest for health of local community?			
19.	Does the organization check the environmental standards of the product?			
20.	Does the organization allocate budget for environment improvement?			
	Suggest your questions			
1				
2				
C-2)	**Money – Product**	**Yes**	**No**	**NA**
1.	Does the organization measure the product operation cost separately?			
2.	Does the organization measure the product maintenance and repair cost separately?			
3.	Does the organization invest for marketing of sustainable products?			
4.	Does the organization allocate budget for the expenditure on warranty of product?			
5.	Does the organization allow replacement of faulty product/components?			
6.	Does the organization provide facility of product upgradation?			
7.	Does the product lead in market?			
8.	Does the top management aim to innovate in product development?			
9.	Does the organization have eco-labels for its products?			
10.	Does the organization aim to dispose off the products in environment friendly manner?			
11.	Does the organization measure distribution cost?			
12.	Does the organization measure reverse logistic cost for the product?			
	Suggest your questions			
1				
2				
C-3)	**Money – Process**	**Yes**	**No**	**NA**
1.	Does the organization invest in green technology?			
2.	Does the organization invest in employee health and safety?			
3.	Does the organization measure man hour lost due to accident/incidents?			

4.	Does the organization measure the cost of annual maintenance for equipment and machinery?			
5.	Does the organization invest in new process development?			
6.	Does the organization provide overtime to employees?			
7.	Does the organization compute waste handling cost?			
8.	Does the organization compute waste categorization cost?			
9.	Does the organization compute solid waste treatment cost?			
10.	Does the organization compute liquid waste treatment cost?			
11.	Does the organization measure the average disassembly cost?			
12.	Does the managerial staff target for cost effective production?			
13.	Does the organization invest for water recycling?			
14.	Does the organization invest in environment friendly packaging?			
15.	Does the organization measure packaging cost separately?			
16.	Does the organization purchase energy efficient technology?			
17.	Does the organization invest for land restoration?			
18.	Does the organization make revenue out of waste?			
	Suggest your questions			
1				
2				
D-1)	**Material – Policy**	**Yes**	**No**	**NA**
1.	Does the organization have an explicit material policy?			
2.	Does the organization monitor its regulated material consumption?			
3.	Does the organization monitor its prohibited material consumption?			
4.	Does the organization promote use of non-toxic/ non-polluting material?			
5.	Does the top management promote recycling of materials?			
6.	Does the organization have a natural resource conservation policy?			
7.	Does the organization have collection center(s) for product recycling?			
8.	Does the organization promote use of environment friendly material?			
9.	Does the organization have a plan to reclaim packaging?			
10.	Does the organization plan for packaging material disposal?			
11.	Does the organization use recycle material for packaging?			
12.	Does the organization use lean tool and techniques?			
13.	Does the organization aim to reduce waste in end-of-life of product?			
14.	Does the organization reduce the use of packaging?			
	Suggest your questions			
1				
2				
D-2)	**Material – Product**	**Yes**	**No**	**NA**
1.	Does the organization measure the total material consumption for a product?			

2.	Does the organization consider use of recycled material in product design?			
3.	Does the organization aim to reduce regulated material consumption?			
4.	Does the organization aim to reduce waste in product maintenance and repair?			
5.	Does the organization assess product durability during design?			
6.	Does the design team estimate quantity of packaging material required?			
7.	Does the organization measure hazardous material consumption in product?			
8.	Are the quality standards available for raw material selection?			
9.	Does the organization document the environmental lessons learned from the products?			
10.	Does the product design allow ease of disassembly?			
11.	Does the product design eliminate secondary processes (i.e. painting/polishing/buffing etc.)?			
12.	Are the products designed for volumetric efficiency?			
13.	Are the products designed for weight efficiency?			
14.	Does the organization monitor the solid/liquid waste generated per product?			
15.	Does the organization measure the regulate/hazardous material consumption in outsourced components?			
16.	Is the design team aware of newer materials?			
	Suggest your questions			
1				
2				
D-3)	**Material – Process**	**Yes**	**No**	**NA**
1.	Does the organization aim to reduce toxic supplementary material consumption?			
2.	Does the organization aim to reduce regulated supplementary material consumption?			
3.	Does the organization plan for hazardous waste reduction?			
4.	Does the organization aim to reduce waste in manufacturing process?			
5.	Does the organization allow reuse of used parts?			
6.	Does the organization allow use of remanufactured parts?			
7.	Are environmental issues considered in process design?			
8.	Is the possibility to use renewable resource in production considered?			
9.	Are environmental issues considered in production planning and control?			
10.	Does the organization monitor the solid waste generated during manufacturing process?			
11.	Does the organization monitor the liquid waste generated during manufacturing process?			
12.	Does the organization treat the waste?			
13.	Does the organization aim to use clean technology in product manufacturing?			
	Suggest your questions			

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1				
2				
E-1)	**Infrastructure – Policy**	**Yes**	**No**	**NA**
1.	Does the organization have an explicit infrastructure policy?			
2.	Does the organization have an explicit policy for land usage?			
3.	Does the organization have separate corporate social responsibility department?			
4.	Does the organization have energy efficient buildings?			
5.	Does the organization use sunlight for illumination?			
6.	Is the organization building used for rain water harvesting?			
7.	Does the organization monitor asset utilization?			
	Suggest your questions			
1				
2				
E-2)	**Infrastructure – Product**	**Yes**	**No**	**NA**
1.	Does the organization measure land requirement for the product?			
2.	Does the organization measure land requirement for the raw material consumption?			
3.	Does the organization measure land requirement for the auxiliary material consumption?			
4.	Are the products designed for storage efficiency?			
	Suggest your questions			
1				
2				
E-3)	**Infrastructure – Process**	**Yes**	**No**	**NA**
1.	Does the organization monitor the landfill area requirement for process waste?			
2.	Does the organization treat the waste before landfill?			
3.	Does the organization perform land restoration?			
4.	Does the organization conduct plantation drives regularly?			
5.	Does the organization aim for conservation of bio-diversity?			
6.	Does the organization have monitor plant/machinery utilization targets?			
	Suggest your questions			
1				
2				
F-1)	**Water – Policy**	**Yes**	**No**	**NA**
1.	Does the organization have an explicit policy for water conversation?			
2.	Does the organization treat the wastewater?			
3.	Does the organization have knowledge about depletion of different water resources in local area?			

4.	Does the organization harvest rainwater?			
	Suggest your questions			
1				
2				
F-2)	**Water – Product**	**Yes**	**No**	**NA**
1.	Does the organization monitor water consumed (by type) for one product?			
2.	Does the organization monitor water consumed (by volume) for one product?			
3.	Does the organization consider the water consumed during use phase of the product?			
4.	Is the organization aware of water requirement for service/maintenance/repair of product?			
	Suggest your questions			
1				
2				
F-2)	**Water – Process**	**Yes**	**No**	**NA**
1.	Does the organization monitor utilization of water during production process?			
2.	Does the organization reuse the water?			
3.	Does the organization measure water pollution?			
4.	Does the organization measure PH level of water discarded?			
5.	Does the organization measure heavy metal content in water discarded?			
6.	Does the organization measure dissolved oxygen in water discarded?			
7.	Does the organization measure suspended and dissolved impurities in water discarded?			
	Suggest your questions			
1				
2				
G-1)	**Air – Policy**	**Yes**	**No**	**NA**
1.	Does the organization have an explicit policy for air quality?			
2.	Does the organization follow local air quality standards?			
3.	Does the organization launch environment conservation program regularly to improve ambient air quality?			
4.	Does the organization measure annual ozone level?			
	Suggest your questions			
1				
2				
G-2)	**Air – Product**	**Yes**	**No**	**NA**
1.	Does the organization monitor the air emissions due to raw material used in the product?			
2.	Does the organization estimate air emissions of the product use phase?			

3.	Does the organization measure air emission during service/maintenance/repair of product?			
4.	Does the organization measure air emission during distribution of product?			
5.	Does the organization measure air emission during disposal of product?			
	Suggest your questions			
1				
2				
G-3)	**Air – Process**	**Yes**	**No**	**NA**
1.	Does the organization measure the process related air emissions?			
2.	Does the organization monitor the in-house air quality?			
3.	Does the organization take measures for reducing air emissions?			
4.	Does the organization measure annual level of particulate matters?			
5.	Does the organization measure annual level of volatile organic compounds (VOC)?			
6.	Does the organization measure annual level of NO_x emission?			
7.	Does the organization measure annual greenhouse gas emission?			
8.	Does the organization use enclosure for noise control?			
	Suggest your questions			
1				
2				

Birla Institute of Technology & Science, Pilani
Pilani Campus
Vikrant Bhakar, M.Tech. research Scholar, Mechanical Engineering Department

Dear Sir/Madam,

I am Vikrant Bhakar pursuing my doctoral thesis in the area of "sustainability assessment" at Birla Institute of Technology and Science, Pilani under the supervision of Prof. (Dr.) Kuldip Singh Sangwan and Prof. (Dr.) Abhijeet K. Digalwar. It gives me immense pleasure to interact with working professionals like you.

Many of the Indian companies are improving their sustainability by implementing various tools/techniques/practices. Have the companies improved their sustainability? Are the companies improving all the three dimensions of sustainability – environmental, social and economic – or just focussing on environmental performance? To answer this question we need to measure the sustainability. Sustainability measurement is difficult as sustainability indicators are limited and have limited applicability for different companies and different countries (even regions). Therefore, I have developed 121 sustainability indicators from literature and company sustainability reports. I want to find the reliability of these indicators for Indian companies. Also, I want to validate these indicators for Indian companies.

This can be done only with your help. Kindly take some time out of your busy schedule to fill the attached questionnaire. It will take approximately 10 minutes to complete this questionnaire.

I fully understand the sacredness of the environmental topic in India and therefore assure you that the views expressed in this survey will be kept strictly confidential and will be used only for academic research.

Thanking you.
Yours truly

Vikrant Bhakar

Birla Institute of Technology & Science, Pilani
Pilani Campus, Vidya Vihar
Pilani 333031, Rajasthan, India

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Tel: +919460173178
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APPENDIX - B

PART – 1| General information of participating organization and responding person

Name and location of the Organization : ____________________

Name of the responding person (optional) : ____________________

Designation (optional) : ____________________

Department (optional) : ____________________

Experience (years) : ____________________

E-mail (optional) : ____________________

Ph. No. / Mobile No. (optional) : ____________________

Would you like to be contacted for any further information? YES/ NO

APPENDIX - B

PART – 2 | Manufacturing Sustainability Assessment Indicators

Please indicate the extent to which you perceive that how important are these indicators for the ***sustainability performance*** of your organization on a scale from 1 to 5, by √ mark in the appropriate box: (where, 1 = no significanc; 2 = low significance; 3 = medium significance; 4 = high significance; and 5 = very high significance).

		No significance	Low significance	Medium significance	High significance	Very high significance	Not applicable
S. No.	**Indicator**	**1**	**2**	**3**	**4**	**5**	**NA**
1.	Land used						
2.	Number of trees planted in the year						
3.	Average employee cost to company (CTC)						
4.	Investment in employee training						
5.	Land rehabilitation						
6.	Non-monetary sanctions and warnings						
7.	Average social benefits to average CTC						
8.	Labor productivity						
9.	Environmental liability cost						
10.	Packaging cost						
11.	Investment in employee health and safety						
12.	Cost of man hour lost in accidents/incidents						
13.	Economical risk						
14.	Fraction of production collected from customer at EOL						
15.	Employee retention rate						
16.	Penalties due to violation of rules						
17.	Noise emissions						
18.	Wicked smell in air						
19.	Average sick leave per employee						
20.	Technology and innovation cost						
21.	Carbon di-oxide (CO_2) emission						
22.	Total hydrocarbon (THC)						
23.	Employee complaints and suggestions						
24.	Operational cost						
25.	NOx emissions						
26.	Employee satisfaction						
27.	Transportation cost						
28.	Particulate matter (PM)						
29.	Water cost fraction						
30.	Total hours of employee training						

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S. No.	Indicator	1	2	3	4	5	NA
31.	Total cost						
32.	Water treatment and recycling cost						
33.	Potable water used						
34.	Number of promotions per employee						
35.	Capital employed						
36.	Water used						
37.	Fraction of wastewater reused						
38.	Fraction of employees covered through performance appraisal process						
39.	Investment in new processes and products						
40.	Fraction of water recycled						
41.	Fraction of water reused						
42.	Gender ratio						
43.	Fraction of production cost used for supplier development						
44.	Liters of BOD(biochemical oxygen demand)						
45.	Liters of COD(chemical oxygen demand)						
46.	Level of growth and opportunity						
47.	Average disassembly cost						
48.	Total amount of energy used						
49.	Fraction of renewable energy used						
50.	Female to male salary ratio						
51.	Maintenance and improvement cost						
52.	Energy required for material recycling						
53.	Fraction of energy generated through cogeneration						
54.	Level of social security						
55.	Warranty cost						
56.	Energy utilized for maintenance and repair						
57.	Energy consumed in use phase						
58.	Fraction of local employee						
59.	Market share in percentage						
60.	Energy consumed to get one unit of raw material at plant						
61.	Amount of hazardous solid waste						
62.	Number of jobs created						
63.	Return on investment						
64.	Liquid waste generated						
65.	Amount of total solid waste						
66.	Fraction of employees provided with continue education facility						
67.	Profit gained						
68.	Fraction of solid waste recycled						
69.	Solid waste used (i.e. by-products)						
70.	Fraction of income difference relative to industry						
71.	Value addition in production						
72.	Fraction of liquid waste treated						

APPENDIX - B

S. No.	Indicator	1	2	3	4	5	NA
73.	Amount of liquid waste						
74.	Fraction of skilled labor						
75.	Income						
76.	Landfill area						
77.	Quantity of toxic released						
78.	Fraction of worker with work related disease						
79.	Annual sales volume						
80.	Fraction of production landfilled						
81.	Fraction of production incinerated						
82.	Fraction of contractual labor						
83.	New customer added in the year						
84.	Total raw material used						
85.	Fraction of recycled material used						
86.	Number of work related accidents/incidents						
87.	Customer satisfaction						
88.	Hazardous material used						
89.	Fraction of reused material						
90.	Total number of complaints from local community						
91.	Fraction of raw material recycled within process						
92.	Amount of hazardous material used by contracted service provider						
93.	Community involvement						
94.	Fraction of compressed air utilized						
95.	Stakeholders empowerment						
96.	Energy taxes paid						
97.	Fraction of supplementary material used						
98.	Fraction of recyclable material used						
99.	Company image in market						
100.	Fraction of production to raw material by weight						
101.	Quantity of chemical used						
102.	Expenditure in social development						
103.	Waste treatment cost						
104.	Consumption of ozone depleting substance						
105.	Weight of packaging						
106.	Fraction of reclaimed packaging						
107.	Reported customer health and safety issues						
108.	Total fossil fuel used in distribution						
109.	Fraction of product upgraded						
110.	Total energy used in distribution						
111.	Fraction of renewable resources used in						
112.	Percentage of outsourced components/sub-						
113.	Fraction of remanufactured parts used						
114.	Resources consumed in use phase (operation)						
115.	Resources consumed in maintenance/service/repair						
116.	Fraction of supplier from local area						
117.	Fraction of production recycled						

APPENDIX - B

118.	Fraction of production remanufactured						
119.	Total fossil fuel used in reverse logistics						
120.	Fraction of renewable resources used in reverse logistics						
121.	Fossil fuel used						

APPENDIX – C

JOURNAL PUBLICATIONS

1. Kuldip Singh Sangwan, Vikrant Bhakar, A. K. Digalwar. (2018). “Sustainability assessment in manufacturing organizations – development of assessment models", Benchmarking: An International Journal, https://doi.org/10.1108/BIJ-08-2017-0227.
2. Vikrant Bhakar, A K Digalwar, Kuldip Singh Sangwan. (2018) “Sustainability assessment framework for manufacturing sector - a conceptual model”. Procedia CIRP. Vol. 69, 248-253. https://doi.org/10.1016/j.procir.2017.11.101.

WORKING PAPERS

1. Vikrant Bhakar, A.K. Digalwar, Kuldip Singh Sangwan, “A sustainability assessment framework for cement industry – A case study”, Benchmarking an International Journal, (under revision)
2. Vikrant Bhakar, A.K. Digalwar, Kuldip Singh Sangwan, “Development of a Composite Sustainability Index – A case study”. (working paper)
3. Vikrant Bhakar, A. K. Digalwar, Kuldip Singh Sangwan, “Environmental Sustainability Assessment of Cement Manufacturing Process Using Life Cycle Analysis”. (working paper)
4. Vikrant Bhakar, A. K. Digalwar, Kuldip Singh Sangwan, “Manufacturing Sustainability: A Systematic Literature Review”. (working paper)

CONFERENCE PUBLICATIONS

1. Vikrant Bhakar, Kiran Kumar, A. K. Digalwar and K. S. Sangwan, Prioritizing 6r strategies for manufacturing sustainability: An AHP approach, In proceedings of 6th International and 27th All India Manufacturing Technology, Design, and Research Conference (AIMTDR 2016), College of Engineering, Pune, Maharastra, India, December 16-18, 2016
2. Vikrant Bhakar, A. K. Digalwar and K. S. Sangwan, Imperative of sustainability measurement framework for Indian manufacturing industry, 6th international conference on decision sciences for performance excellence, held at Hyderabad, India December 27-29, 2012.
3. Vikrant Bhakar, A. K. Digalwar and K. S. Sangwan, "Development of Organizational and Technological Performance Measures for Sustainable Manufacturing", In Proceedings of International Conference on Management and Business Innovation May 18-19, 2013, at MNIT Jaipur.
4. Vikrant Bhakar, Nitesh Sihag, Venkata N.J Mamidi, Shantanab Dinda, A. K. Digalwar, and K S Sangwan Development of A Self-Assessment Model For Enterprise Sustainability, National Conference on Sustainable Manufacturing (NCSM-2015), held on 2nd - 3rd January 2015, MNIT Jaipur, pp. 44-52.

APPENDIX - D

About the author (Vikrant Bhakar)

Vikrant Bhakar is a Ph D candidate in the Department of Mechanical Engineering at Birla Institute of Technology and Science, Pilani, Rajasthan, INDIA. He is pursuing his PhD in Sustainability in manufacturing from BITS Pilani, INDIA. He has published more than 20 research papers in National and International journals and conferences. His teaching and research interests are primarily in the field of industrial and production management and life cycle engineering. In addition to his Ph D he is associated and coordinating various research projects between BITS Pilani, India and Technische Universität Braunschweig, Germany.

About the Co-supervisor (Prof. Abhijeet K. Digalwar)

Dr. Abhijeet K. Digalwar is an Associate Professor of Mechanical Engineering at the Birla Institute of Technology & Science (BITS), Pilani. He has received a PhD from BITS Pilani in 2006. He has over 22 years of teaching experience at graduate and post graduate levels. His current research and teaching interests are in the areas of Manufacturing Systems Engineering and Management, World Class Manufacturing, Lean and Green Manufacturing, Machine Tool Engineering, Cutting tools. He has published more than 90 research papers in National and International journals and conferences. He has been a Member of the PMA (Performance Measurement Association) of a Cranfield University UK, Society of Operations Management, IIIE, IE and ISTE. At present he is a President of Indian Subcontinent region Decision Sciences Institute of USA.

About the supervisor (Prof. Kuldip Singh Sangwan)

Prof. Kuldip Singh Sangwan is a Professor in the Department of Mechanical Engineering and Faculty In-charge Central workshop at Birla Institute of Technology and Science, Pilani, Rajasthan. He is an active researcher in the field of green manufacturing, reverse logistics, lean manufacturing, sustainable manufacturing, life cycle engineering, cellular manufacturing systems, and simulation and analysis of machining processes on Titanium alloy. He has guided 7 PhD's and 7 PhD's are in progress in addition to large number of research practices, dissertations, and thesis supervised. He is also an active person in research activities in collaboration with foreign universities like TU Braunschweig, Germany, Mondragon University, Mondragon, Spain, University of Rhode Island, USA, *etc.* In addition to the teaching and research, he has been on administrative posts like Head of Department, and Chief, Workshop Unit of BITS Pilani.