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A FRAMEWORK AND METRICS FOR SUSTAINABLE MANUFACTURING PERFORMANCE EVALUATION AT THE PRODUCTION LINE, PLANT AND ENTERPRISE LEVELS

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A FRAMEWORK AND METRICS FOR SUSTAINABLE MANUFACTURING PERFORMANCE EVALUATION AT THE PRODUCTION LINE, PLANT AND ENTERPRISE LEVELS

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By

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Lexington, Kentucky
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Lexington, Kentucky 2017

ABSTRACT OF DISSERTATION

A FRAMEWORK AND METRICS FOR SUSTAINABLE MANUFACTURING PERFORMANCE EVALUATION AT THE PRODUCTION LINE, PLANT AND ENTERPRISE LEVELS

Sustainable manufacturing is becoming increasingly important due to scarcity of natural resources, stricter regulations and increasing customer demand for sustainable products. Sustainable manufacturing involves the use of sustainable processes and systems to produce more sustainable products. In order to meet these demands for sustainable products, manufacturing companies have to adopt numerous strategies to achieve sustainable manufacturing. The approach for evaluating sustainable products and processes have been investigated in previous work where product/process sustainability indices were proposed. However, no comprehensive methods are available for sustainable manufacturing performance evaluation at the system level. This work aims to develop two alternate methods for evaluating sustainable manufacturing performance at enterprise, plant and production line levels. First, requirements for a sustainability metrics framework are identified through studying and reviewing existing literature where the three pillars of sustainability, total life-cycle stages, and 6R concepts are concurrently addressed. Then index-and value-based methods are proposed to evaluate sustainable manufacturing performance by conducting assessment on economic, environmental and societal aspects. Finally, the application of these two methods is illustrated for a representative enterprise producing consumer electronics at the enterprise level; a case study for a satellite television dish production is used to demonstrate the application of these methods at the production line level. Results obtained from these two methods are compared and analyzed at the enterprise level. The proposed methods can provide information to a company to identify improvement strategies and for decision making for sustainable development.

KEYWORDS: sustainable manufacturing, sustainability performance evaluation, system level, index-based, value-based

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Student's Signature

July 11, 2017

Date

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To my family

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Chapter 1 Introduction

1.1 Background

Sustainable development has been defined in many ways, but the most frequently cited definition is from the report Our Common Future, also known as the Brundtland Report (Brundtland Commission, 1987) which states that:

'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. The definition contains within it two key concepts:

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

Another definition introduces sustainable development as a process of achieving human development (widening or enlarging the range of people's choices; United Nations Development Programme, 1994) in an inclusive, connected, equitable, prudent, and secure manner (Gladwin et al., 1995). In all these definitions, the spirit of sustainable development basically suggests development should consider both protection of natural resources and maintenance of environmental quality while meeting human needs. According to these definitions, sustainability is a state that will be achieved through sustainable development. To bring about sustainable development from industrial operations, the Triple Bottom Line (TBL) of economic prosperity, environmental protection and societal development must be emphasized (Elkington, 1998). Today, as commonly presented in literature, these three dimensions are considered as overlapping circles as shown in Figure 1.1. The overall sustainability can be achieved when performance falls in the center, covering all three circles. Achieving this state is challenging because improving one TBL aspect can negatively affect the other (improving environmental performance or reducing environmental impacts can be easily achieved if there are no limitations on the cost). The challenge to achieving TBL sustainability is the need to improve all three areas together which is difficult due to the trade-offs.

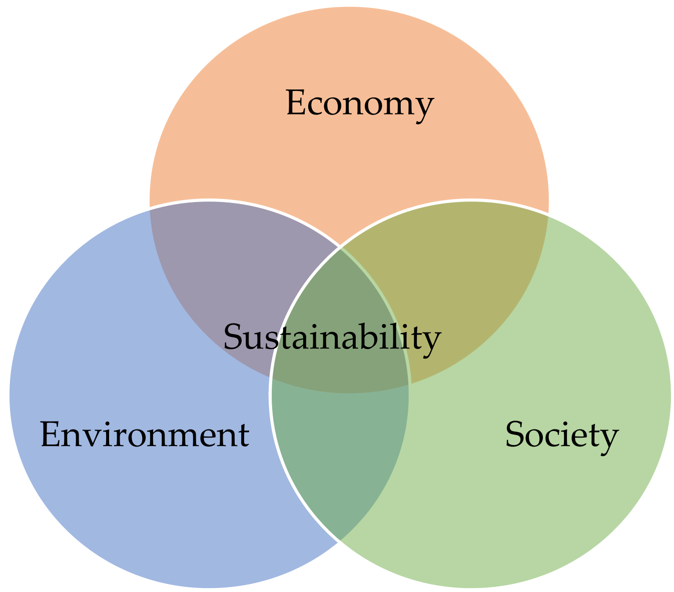

Figure 1.1 Sustainability: overlapping of economy, environment and society

1.2 Concepts and Scope of Sustainable Manufacturing

Recently, a large and growing number of companies realize the potential financial, environmental and societal benefits by implementing sustainable business practices. According to World Bank data, manufacturing contributes to 14.95% of total GDP worldwide, and 12% within US (The World Bank, 2014) which indicates that manufacturing has the highest effect on the economic growth in industry (Bureau of Economic Analysis, 2011). To achieve sustainable development in manufacturing industry, manufacturing companies must treat "sustainability" as an important objective for improvement. Due to stricter environmental regulations, customer demands for more sustainable products and globally fierce market competition, the manufacturing companies need to develop new strategies to transform raw materials into finished products while promoting sustainable development. Therefore, the concept of sustainable manufacturing should be incorporated into their strategy and operations. In addition, the development and application of sustainable manufacturing practices is essential to promote industrial operations to meet TBL goals.

The U.S. Department of Commerce has defined sustainable manufacturing as "the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers" (USDC, 2009). By studying and understanding this definition, the National Council for Advanced Manufacturing (NCFAM) recognized two dimensions in the way sustainable manufacturing should be referred to and addressed both of them. These two dimensions are to include the manufacturing of "sustainable" products and the sustainable manufacturing of all products (NCFAM, 2009). According to these two definitions, the definition of sustainable manufacturing has evolved by integrating product, process and systems levels, which read as "demonstrate reduced negative environmental impacts, offer improved energy and resource efficiency, generate minimum quantity of waste, provide operational personnel health while maintaining and/or improving the product and process quality with the overall life-cycle cost benefits." (Jawahir et al., 2013). The objective of sustainable manufacturing is to provide sustainable benefits to all the stakeholders. Therefore, the economic, environmental, societal benefits must be enhanced and negative impacts in these areas to all stakeholders must be minimized to achieve sustainable manufacturing. The goal of sustainable manufacturing cannot be achieved by focusing independently on the products made, or processes and systems used to make those products. As shown in Figure 1.2, there are complex interrelationships between the products, manufacturing processes and systems used; each one of them affects the other two. For example, the enterprise's (one aspect of the systems) performance primarily depends on whether the products can meet the customer's demands; it is also influenced by whether the manufacturing processes and operational methods used can improve organizational performances. Therefore, to promote sustainable manufacturing, the sustainability performance of products, processes and systems must be considered simultaneously, with adequate consideration of the impact of one aspect on the other.

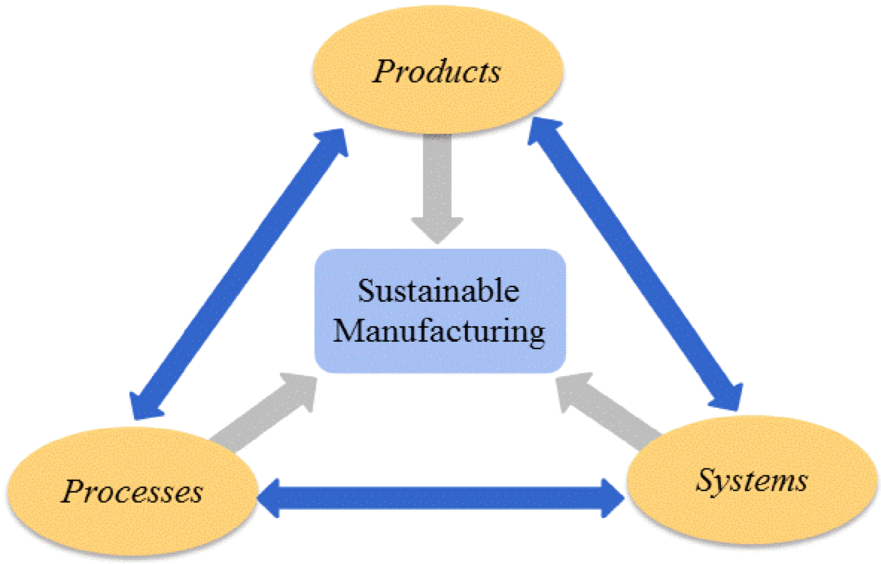

Figure 1.2 Product, process, system integration for sustainable manufacturing (Badurdeen et al., 2013)

In addition to the consideration of TBL for achieving sustainable manufacturing, a consideration of the total life-cycle stages from pre-manufacturing, manufacturing, use and post-use should also be incorporated; the concept of 6Rs (reduce, reuse, recycle, recover, redesign and remanufacture) also needs to be considered concurrently for a closed-loop material flow as shown in Figure 1.3. All these important factors need to be covered to make sure all requirements for sustainable manufacturing is covered simultaneously and comprehensively.

Figure 1.3 Total life-cycle emphasis and 6Rs implementation (Bradley et al., 2016)

1.3 Need for a Metrics-based Method for Sustainable Manufacturing Performance Assessment

Although the concepts and scope of sustainable manufacturing have been introduced and studied, comprehensive quantitative measurement methods to measure and improve sustainable manufacturing performance at the manufacturing systems level are still lacking. Sustainable manufacturing performance cannot be evaluated if there are no methods to measure it accurately and comprehensively. Moreover, the measurement must be covering all three aspects - products, processes and systems. Currently there is some work done in the product and process areas to comprehensively assess the performance (Shuaib et al., 2014; Lu, 2014). The systems level spans the production line, plant, enterprise and the supply chain. While there are many tools available for systems level performance evaluation (Faulkner and Badurdeen, 2014; Zhang and Haapala, 2015; Winroth et al. 2012), none are able to conduct a comprehensive evaluation to cover all the required aspects described in the earlier section pointing to a gap in the systems level sustainable manufacturing performance measurement methods available. Therefore, there is a need to develop more comprehensive methods to measure the performance at the systems level. In order to fill this gap, three research questions are formulated below for developing measurement methods at the systems level.

Research question 1*: What key factors should be considered for developing a framework for sustainable manufacturing performance evaluation at the system level?*

Research question 2*: What metrics should be used and how should they be integrated to measure sustainable manufacturing performance at the system level?*

Research question 3*: How can enterprise sustainable value added be measured from a value perspective?*

1.4 Research Objectives

Based on the research questions raised in the previous section, the major objectives of this work are to:

(1). *Propose a sustainable performance measurement evaluation framework*

The purpose of a performance measurement evaluation framework is to ensure the systematic collection of information about the activities, characteristics, and outcomes of performances to make judgment about measurement system, improve performance effectiveness, and inform decisions about measurement system development. This research will present a sustainable performance measurement evaluation framework by adapting and modifying an existing performance measurement evaluation framework by considering sustainability requirements.

(2). *Develop a framework and metrics for sustainable manufacturing performance assessment at the systems level*

The goal of this part is to create frameworks and metrics for the production line, plant and enterprise levels that can help managers and engineers to measure and evaluate the sustainability performance at those respective levels. By considering the strengths and shortcomings of current approaches and the requirements for sustainable manufacturing performance evaluation, a comprehensive and holistic systems level hierarchy and metrics will be proposed. The specific deliverables will be:

- Metrics and Index-based method for production line sustainable manufacturing performance evaluation
- Metrics and Index-based method for plant sustainable manufacturing performance evaluation
- Metrics and Index-based method for enterprise sustainable manufacturing performance evaluation

Finally, the application of the proposed methods will be illustrated using case studies.

(3). *Propose an alternate value-based method for enterprise sustainable value added evaluation*

Organizations aim to generate value by delivering products/services to consumers. In manufacturing, companies create economic value through the use of environmental and social resources. During this process, however, positive and/or negative economic, environmental and societal impacts can result affecting other stakeholders (e.g.: customers, communities, governments, etc.). Therefore, for sustainable development through sustainable manufacturing, the concept of sustainable value generation, or generating value for all stakeholders, must be pursued. Another objective of this research is to define the concept of sustainable value (and sustainable value-added) more comprehensively and use this to develop an alternate method to quantify sustainable manufacturing performance at the enterprise level. The sustainable value based method will be applied to an industry case study to compare results with the index-based method developed in (2) above.

1.5 Dissertation Outline

The remainder of this dissertation is organized as follows. Chapter 2 presents a literature review for the performance measurement evaluation framework and existing established sustainability assessment methods at the product, process, facility, and corporation levels. The requirement for sustainability assessment methods are also summarized and presented. One of the most comprehensive sustainability performance evaluation methods at product/process level has also been studied and reviewed.

Chapter 3 presents the research methodology of this work. The research questions are revisited. Also, the flow diagram of this research is presented to outline the steps followed in this research.

Chapter 4 presents the sustainable performance measurement evalaution framework and discuss the development of Sustainable Manufacturing

Performance Measurement House by integrating product, process and systems levels.

Chapter 5 presents the metrics identification and development for the sustainable manufacturing performance evaluation at the production line and plant levels. An index-based method is described to evaluate production line and plant sustainability performance. The application of the method is demonstrated at the production line level using a case study for satellite dish production.

In Chapter 6, the enterprise sustainability framework and metrics development are discussed based on the currently existing literature. Two alternate sustainable manufacturing performance evaluation methods at the enterprise level are described in detail. These two methods are demonstrated using a case study for a consumer electronics company to validate the proposed methods.

In Chapter 7, conclusions from the research is summarized, and future work is presented.

Chapter 2 Literature Review

This chapter reviews the existing literature on performance measurement evaluation frameworks and explores the existing sustainability assessment tools across product, process, facility and corporation levels. These reviews will provide the foundation for research methodology development.

2.1 Performance Measurement Evaluation Frameworks

Performance measurement is a topic which is often discussed but not well defined. Neely et al. (2002) proposed a definition for performance measurement as "the process of quantifying the efficiency and effectiveness of past actions". This definition emphasizes the effectiveness as well as efficiency, but does not demonstrate what/why to quantify. Another definition was proposed by Moullin (2003) as "performance measurement is evaluating how well organizations are managed and the value they deliver for customers and other stakeholders". This definition gives better guidance to those involved in performance measurement of the importance of measuring the value that must be delivered to customers. Based on these basic definitions, researchers have proposed many performance measurement evaluation frameworks. The purpose of a performance measurement evaluation framework is to ensure the systematic collection of information about the activities, characteristics, and outcomes of performances that is being measured to make judgments about the measurement system, improve performance effectiveness, and/or inform decisions about measurement system development.

In the following section, several widely adopted performance measurement evaluation frameworks are reviewed. In order to develop a sustainable performance evaluation framework, the objective of identifying the best method should incorporate all the required criteria.

The Balanced Scorecard

The most widely adopted performance measurement system is the balanced scorecard (Kaplan and Norton, 1992), which provides a structured approach for identifying improvement opportunities and threats, and translating companies' strategies into achievable goals. The balanced scorecard can be used to describe, implement and manage strategies at all levels in organizations. The core of this method is to elaborate and implement a strategy of an organization into fixed targets and intelligible set of financial and non-financial indicators. The general balanced scorecard model focuses on four strategic perspectives: the financial, the customer, the internal processes, and the learning and growth, all of which need to be balanced (See Figure 2.1). These perspectives provide answers to four questions:

- How do we look to our shareholders (financial perspective)?

- What must we excel at (internal business perspective)?
- How do our customers see us (customer perspective)?
- How can we continue to improve and create value (innovation and learning perspective)?

According to Ghalayini et al (1997), the main weakness of this approach is that it is primarily designed to provide senior managers with an overall view of performance. Thus, it is not intended for or applicable at the factory operations level. Further, they also argue that the balanced scorecard is constructed as a monitoring and controlling tool rather than an improvement tools. Furthermore, Neely et al (2000) argue that although the balanced scorecard is a valuable framework suggesting important areas in which performance measures might be useful, it provides little guidance on how the appropriate measures can be identified, introduced and ultimately used to manage the business. They also concluded that the balanced scorecard does not at all consider competitors.

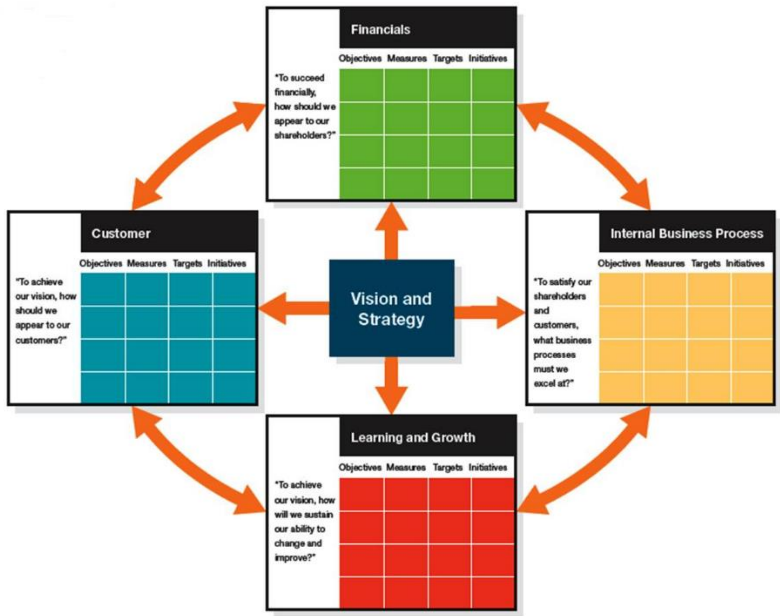

Figure 2.1 Balanced scorecard (Kaplan, 2010)

The Performance Measurement Matrix

Keegan et al. (1989) originally presented the performance measurement matrix in 1989. This method integrated different dimensions of performance, and employs generic terms such as internal, external, cost and non-cost as shown in Figure 2.2. The advantage of this method is that it integrates different classes of business performance for financial and non-financial as well as internal and external perspective. Based on the modification of this method, Fitzgerald et al. (1991) developed desired results and their determinants. This modified performance measurement matrix has two basic types of performance measures included, which relate to results (competitiveness, financial performance), and the determinants of results (quality, flexibility, resource utilization and innovation) as shown in Table 2-1. This method highlights the fact that the obtained results are a function of past business performance with regard to specific determinants.

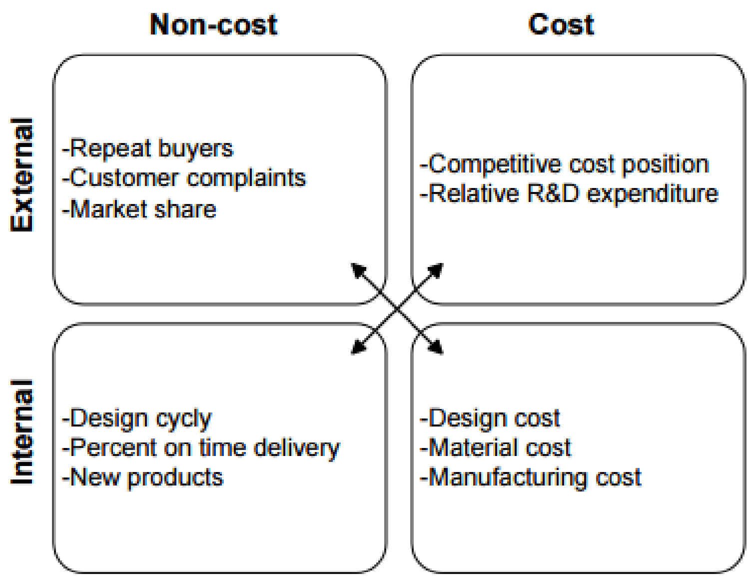

Figure 2.2 Performance matrix (Keegan et al., 1989)

Table 2-1 Results and determinants framework (Fitzgerald et al., 1991)

Dimensions of performance	Types of measures
Results	
Financial performance	Profitability, Liquidity, Capital structure, Market ratios
Competitiveness	Relative market share and position, Sales growth, Measures of the customer base
Determinants	
Quality of service	Reliability, Responsiveness, Aesthetics/appearance, Cleanliness/tidiness, Comfort, friendliness, Communication, Courtesy, Competence, Access, Availability, Security
Flexibility	Volume flexibility, Delivery speed flexibility, Specification flexibility, Productivity, Efficiency
Innovation	Performance of the innovation Process, Performance of individual innovations

The Performance Pyramid

Another performance measurement framework is the SMART (Strategic Measurement Analysis and Reporting Technique) performance pyramid, which was proposed by Lynch and Cross (1992). This framework contains four levels of objectives that affect the organization's external effectiveness and simultaneously its internal efficiency as shown in Figure 2.3. The first level is defined as corporate vision, which is then divided into individual objectives. The second level is short-term targets and long-term goals with the third level being daily operational measures. The fourth level has four key performance indicators: quality, delivery, cycle time and waste. The SMART pyramid attempts to integrate corporate objectives with operational performance indicators. As stated by Ghalayini et al. (1997), the main strength of the performance pyramid is its attempt to integrate corporate objectives with operational performance indicators. However, this approach does not provide any mechanism to identify key performance indicators, nor does it explicitly integrate the concept of continuous improvement.

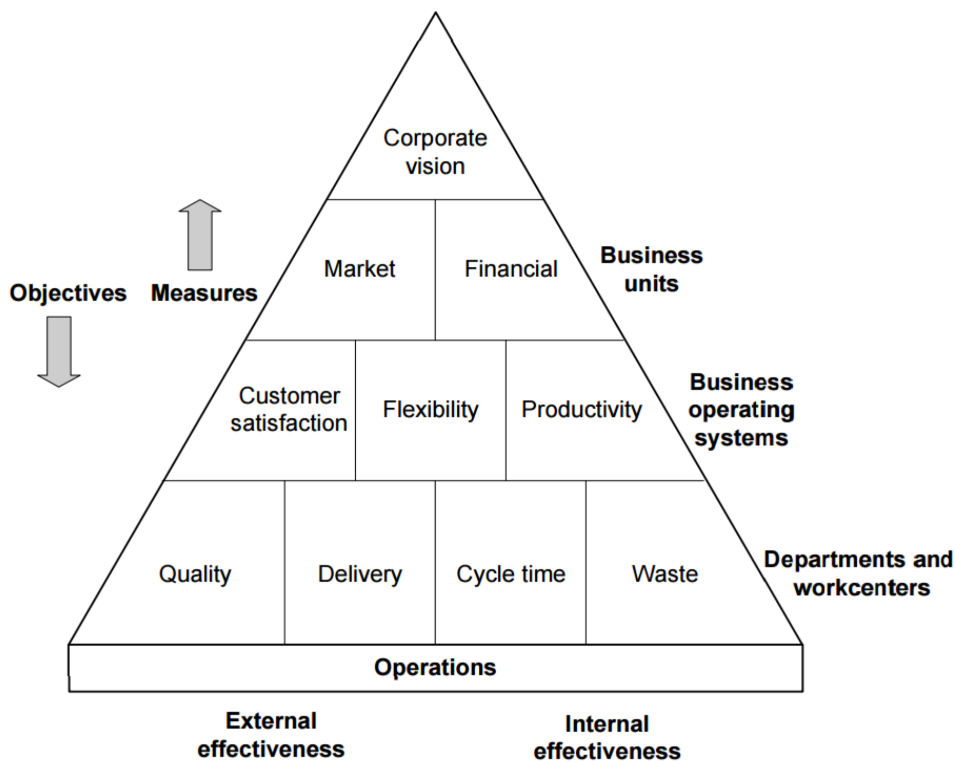

Figure 2.3 Performance pyramid (Ghalayini and Noble, 1996)

The Performance Prism (Prism)

As one of the more recently developed conceptual frameworks, the Performance Prism addressed the key business issues to which a wide variety of organizations can relate to. According to Neely et al., (2002), a performance measurement system should be organized by five distinct but linked perspective of performance:

1. Stakeholder satisfaction – Who are the stakeholders and what do they want and need?
2. Strategies – What are the strategies we require to ensure the wants and needs of our stakeholders?
3. Processes – What are the processes we have to put in place in order to allow our strategies to be delivered?
4. Capabilities – What capabilities do we need to put in place to allow us to operate our processes more effectively and efficiently?

This work also reflected a much more comprehensive list of stakeholders (such as employees, suppliers, alliance partners or intermediaries) than other frameworks, which often neglected the stakeholders and only focused on shareholders when forming performance measures. Another strength of this conceptual framework is that it first questions the company's existence strategy before the process of selecting measures that must be evaluated.

Table 2-2 provides a chronological summary of the literature reviewed above, which provides a brief history of the development of these various performance measurement system evaluation frameworks. Each of them has their relative benefits and limitations. The most common limitation is that little guidance is given for actual selection and implementation of selected measures.

As the Prism framework considers participants for sustainable manufacturing from a new stakeholder's perspective, it is selected as a candidate for developing the sustainability performance measurement evaluation framework in this research. Compared to other frameworks reviewed, Prism emphasizes the processes through which the strategies can be delivered. These processes can be analogous to the processes in sustainable manufacturing. As the goal of this research is to develop a sustainability framework and metrics for the systems level, the Prism approach is better suited.

Table 2-2 Summary of reviewed performance measurement frameworks

Framework and Author(s)	Description
The Performance Measurement Matrix Keegan et al., (1989)	Categorizes measurement as being 'cost' or 'non-cost' and 'internal' or 'external'. Involves decomposing departments into functional equivalents and assessing how the departments support the business
The (SMART) Pyramid Lynch and Cross, (1991)	Include internally and externally focused measures of performance measures at department and work center level reflect the corporate vision as well as internal and external business objectives.
The Results and Determinants Framework Fitzgerald et al. (1991)	Classifies measures into two basic types: results (competitiveness, financial performance) and those that focus on the detriments of those results (quality, flexibility, resource utilization and innovation).
The Balanced Scorecard Kaplan and Norton, (1992)	Translates the vision of a business into objectives and performance measures in four perspectives: financial, customer, internal business process, learning, and growth.
The Performance Prism Neely et al., (2002)	Consists of five integrated facets that identify areas for organizations to address: stakeholder satisfaction, strategies, processes, capabilities and stakeholder contribution. Reorganized reciprocal relationship between the stakeholder and the organization.

2.2 Sustainability Assessment Tools and Indicators

The review of established sustainability evaluation methods will be presented by following the sequence shown in Figure 2.4 (Feng et al., 2010) from low to high level in technical detail and application domains. While Feng et al. (2010) present an application domain varying from the product to the global levels, the review here will be limited to methods/tools relevant to the scope of research in this study.

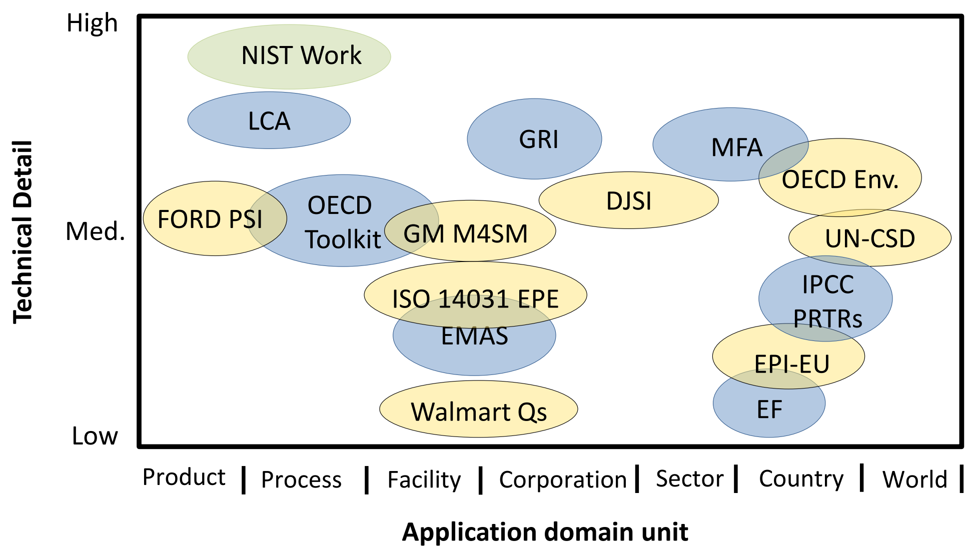

Figure 2.4 Categories of prominent sustainability evaluation methodologies, adapted from Feng et al. (2010).

Ford of European's Product Sustainability Index (PSI)

A Product Sustainability Index (PSI) method was published by Ford Europe in 2006. The PSI incorporates sustainability requirements into product design instead of Eco-design (Schmidt et al., 2006). The PSI consists of eight indicators covering environmental (life cycle global warming potential, life cycle air quality potential, sustainable materials, restricted substances, drive-by- noise), Societal (mobility capability, safety) and economic (life cycle ownership costs) aspects. In this method, the life-cycle considers from raw material extraction through production to use (15000km) and recovery. The PSI considers legal compliance issues as the baseline instead a topic of PSI. In addition, aspects decided before product design (e.g. service aspects) cannot be covered by PSI (Schmidt et al., 2006).

Life Cycle Assessment

As a product-related assessment tool, Life Cycle Assessment (LCA) is the most established and well developed tool. It has been used in various forms over the past 45 years for evaluating environmental impacts of a product or a service throughout its life cycle (Christiansen et al., 1995). LCA is an approach to analyze the real and potential pressure that a product has on environmental during raw material extraction, production processes, use, and disposal of the product. The results from LCA provide information for decision making for product development, eco-design, production system improvements and customers' requirements. Although LCA has been applied in many industries, it highlight the impacts on environment without considering the impacts on societal aspect.

Organization for Economic Co-operation and Development (OECD)

The Organization for Economic Co-operation and Development (OECD) developed an extensive toolkit to analyze processes and products to identify opportunities for improvement. This toolkit provides a moderate level of technical expertise for small and medium companies. This toolkit can also be used by companies to calculate and interpret a set of 18 core indicators in terms of materials and processes shown in Figure 2.5. These indicators have been developed to help measure the environmental impact relating to the production activities of a single facility in the business (e.g. site, factory, office) as a starting point for sustainable manufacturing. However, the performance can also be monitored and evaluated the performance at the overall organizational level by aggregating the data obtained to calculate the indicators (OECD 2011).

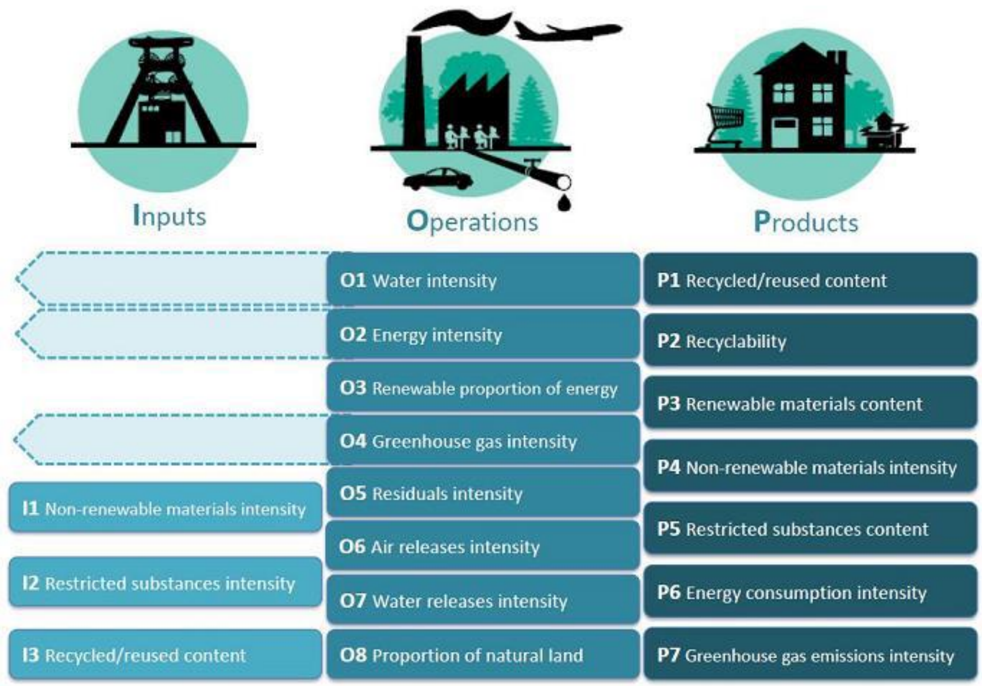

Figure 2.5 OECD sustainable manufacturing indicators (OECD, 2011)

Walmart Sustainability Index (Walmart Qs)

As one of the top Global 500 companies, Walmart has developed a marketability-based environmental product sustainability index, which is information-driven by customer demand on product sustainability. This index is dedicated to delivering sustainable products for customers. Three aspirational goals of this work are to achieve energy supplied by 100% renewable energy, zero waste creation, and to sell products that sustain people and environment (Walmart, 2009). This developed Walmart product sustainability index does not cover the total life-cycle stage for sustainability assessment.

The EU Eco-Management and Audit Scheme (EMAS)

The EU Eco-Management and Audit Scheme (EMAS) is a premium management instrument developed by the European Commission for companies and other organizations to evaluate, report, and improve their environmental performance. EMAS is open to every type of organizations that are eager to improve its environmental performance. It spans all economic and service sectors and is applicable worldwide. EMAS supports organizations in finding the right tools to improve their environmental performance. Participating organizations voluntarily commit to both evaluating and reducing their environmental impact. EMAS is credible where third party verification guarantees the external and independent nature of the EMAS registration process. In addition, EMAS is transparent to provide publicly available information on an organization’s environmental performance with which organizations can achieve greater transparency both externally through the environmental statement and internally through employees' active involvement (EUEMAS, 2011).

ISO 14031: Environmental Performance Evaluation (EPE)

The International Organization for Standardization (ISO) 14031 Environmental Performance Evaluation standards sets out a process to help an organization improve environmental performance. It provides a set of tools to identify, measure, assess and communicate environmental performance using key performance indicators (KPIs), based on reliable and verifiable information (ISO, 1999; ISO, 2009). The ISO 14031 can provides guidance on the design and use of EPE within an organization. It is applicable to all organizations, regardless of type, size, location and complexity.

General Motors: Metrics for Sustainable Manufacturing

A set of sustainability metrics for green or sustainable manufacturing were proposed by General Motors Corporation in 2009. These metrics are proposed based on a survey of available literature, best practices by other manufacturing firms in automotive manufacturing as well as other industries. Following the survey of existing and proposed metrics, the suitability of the metrics were determined by comparing the effort and effectiveness of each, and suggesting the best of these to implement at GM's various manufacturing operations. There are fifty metrics from six major aspects for sustainability performance evaluation: environmental impact (11 metrics); energy consumption (6 metrics); personal health (13 metrics); occupational safety (5 metrics); waste management (9 metrics); manufacturing cost (6 metrics). The criterion given was to maximize the positive environmental impact relative to the other needs of a large public company (Dreher et al., 2009).

Global Reporting Initiative (GRI)

The most well-known set of corporate sustainability indicators are the 91 measures included in the GRI G4 reporting guidelines (GRI 2014). The GRI guidelines have been voluntarily applied in over 1000 companies worldwide by corporations in various sectors, such as automotive, chemicals, construction, energy, supermarket, mining, etc. It includes sustainability metrics covering three dimensions – economic, environmental and social categories – where social is further broken down into four sub-categories. As known, the sustainability reporting is the focal point of guidelines. These guidelines help reporting organizations disclose most critical impacts on environment, society and economy; they can provide reliable, relevant and standardized information to assess opportunities and risks. They can further help to make well-informed decisions for the business and other stakeholders. The highlight of GRI guidelines is that they are universally applicable to all organizations of all types and sectors, large and small across the world.

Dow Jones Sustainability Index (DJSI)

In 1999, the Dow Jones Sustainability Index in association with SAM sustainability Group developed the first set of global sustainability indices. These indices provides a benchmark for corporate to evaluate their sustainability performance.

There are five criteria's sustainability principles on which the ranking of the companies are done as shown in Table 2-3 (Dow Jones/SAM, 1999). It is a weighted set of general and industry-specific criteria according to which the companies are ranked within their industry. Only the leading company for each industry can be selected for the DJSI. This tool is especially used as a benchmark where investors can integrate sustainability consideration to support sustainable investment (DJSI, 2013).

Material Flow Analysis

Material flow analysis is used for analyzing material and substance in product systems which is performed through life cycle stages for discovering where the inflows and outflows of material occurs. This analysis enables the identification of the source of the environmental impact where corresponding reduction of the environmental impact can be directed. Material flow analysis could be used for analyzing a product life cycle but it is often used for analyzing industries (Antikainen et al., 2004)

Table 2-3 Sustainability principles of DJSI (Dow Jones/SAM, 1999)

Criteria	Content
Technology	Assess adoption of innovative technology, efficient, effective and economic use of financial, natural and societal resources
Governance	Corporate governance, management responsibility, organizational capability, corporate culture and shareholder relations
Shareholders	Sound financial return, long-term economic growth, long-term productivity, enhanced global competitiveness and contributions to intellectual capital
Industry	Focus of industry towards sustainable value creation and demonstrating commitment and publishing superior performance with respect to sustainability
Society	Stakeholder engagement, promote societal well-being by understanding the needs and expectations of stakeholders

Ecological Footprint

The Ecological Footprint (EF) is defined as "quantifies for any given population the mutually exclusive, biotically productive area that must be continuous use to provide its resource supplies and to assimilate its wastes" (Wackernagel and Rees, 1997). The ratio of required resources to available resources is interpreted as a measure of ecological sustainability where ratio exceeding one is considered as unsustainable. Calculation of the EF is based on data from national consumption statistics. Therefore, the EF primarily relies on normalization where any consumption is converted into land use. The footprint accounts the resource supply chains and disposal management options. EF is used to evaluate environmental sustainability performance at the national and global levels.

Environmental Pressure Indicators for the European Union (EPI-EU)

Environmental Pressure Indicators for the European Union (EPI-EU) is developed in the project of the Environmental Pressure Indices which aims to provide a comprehensive description of the most important human activities that have a negative environmental impact. The EPI-EU consists of 60 indicators which provide ab overview of the pressure of human activities on environment in 10 policy fields. These indicators cover air pollution, climate change, bio-diversity and dispersion of toxic substances (Eurostat, 1999).

Pollutant release and transfer registries (PRTRs)

A Pollutant Release and Transfer Register (PRTR) is a publicly accessible database or inventory of chemicals or pollutants released to air, water and soil and transferred off-site for treatment. It brings together information about which chemicals are being released, where, how much and by whom. PRTRs typically require facility owners or operators who release chemicals (e.g., in such industries as manufacturing and mining) to quantify their releases and to report them to governments on a regular basis. Reporting can be both on emissions from fixed sources (e.g., factory smokestacks) as well as from diffuse sources (e.g., mobile sources such as automobiles, trucks, aircraft and trains). Depending on the threshold a government sets for reporting, facilities can range from large industrial sites to small operations (OECD, 2005).

UN Commission's Sustainable Development (UN-CSD)

The United Nation Commission's Sustainable Development (UN-CSD) developed a hierarchical framework for sustainability evaluation. This framework consists of 38 subthemes, 15 main themes and 4 main areas. Compared to the traditional view of three dimensions (Economy, Environment and Society), the UN-CSD considers institutional aspect as an additional main area. This framework measures sustainable development mainly from a society or national perspective and therefore not all of them are relevant to industrial and business organizations (Labuschange et al., 2005).

OECD Environmental Indicators (OECD Env.)

The OECD developed the core Environmental Indicators which are considered as the most relevant indicators at the global level. These indicators can be used to measure environmental performance to report the progress towards sustainable development and monitor the integration of economic and environmental decision making as well as societal response (OECD, 2001 & 2003). The indicators set contains about 50 indicators with a strong focus on environmental issues. This indicators set also integrates economic and societal aspects (OECD 2001).

2.3 Requirements for sustainability assessment tools

There are several works attempting to develop guidelines to identify successful sustainability metrics and frameworks at different application domains.

Labuschagne (2005) stated that the sustainability assessment frameworks should satisfy the requirements below when assessing industry sustainability. The sustainability assessment frameworks should be developed based on the following:

(a) The indicator framework includes a set of (measurable) indicators.

(b) The indicator framework addresses all three dimensions of sustainability, i.e. environmental, social, and economic indicators are part of the framework.

(c) The indicator framework has a wide focus, i.e. at a national, community or company level.

(d) The indicator framework is not strongly based on another framework or guidelines, Seven guidelines for choosing an appropriate set of measurements in industrial applications were proposed by Fiksel et al. (1998) as follows:

(1). Comprehensive: Does the set of performance indicators address all of the organization's major aspects and objectives?

(2). Controllable: Can the organization, group, manager or employee significantly influence the desired results?

(3). Cost-Effective: Can the necessary data be obtained from existing sources or otherwise easily collected?

(4). Manageable: Is the set of indicators limited to the minimal number required to meet the other criteria?

(5). Meaningful: Will individuals throughout the organization and external stakeholders easily understand the indicators?

(6). Robust: Do the indicators address inputs and processes (leading indicators) and outcomes (lagging indicators)?

(7). Timely: Can measurement occur with sufficient frequency to enable timely, informed decision-making?

Eaton (2009) contended five key metrics characteristics as follows:

(1). Address the needs of all stakeholders -- community, government, and business.

(2). Facilitate innovation and growth; continuous improvement must be the cornerstone.

(3). Be harmonized at the local, state, national, and international levels.

(4). Be fully compatible with existing business systems and add value.

(5). Measure the right things -- what is measured is what gets managed.

In order to determine the suitability of metrics, Dreher et al. (2009) stated that the best criteria for choosing which metrics to implement depend on identifying the specific "hotspots" for a company and industry. They also stressed that the effort required to implement the metrics depended on the existence of at least one of the following:

1) Reason for the assessment
2) Scope of the tool
3) Resources for the assessment
4) Time frame
5) Data availability

Feng et al. (2010) also identified seven characteristics of the sustainability performance indicators as follows:

(1). Measurable: Indicator must be capable of being quantitatively measured in a phenomenon that is of a sustainability concern, e.g., economic benefit, social well-being, environmental friendliness, and technical advancement.

(2). Relevant and Comprehensive: Indicator must provide useful sustainability information on manufacturing processes. It must fit the purpose of measuring performance and addressing all of the organization's major aspects and objectives.

(3). Understandable and Meaningful: Indicator should be easy to understand by the community, especially, for those who are not experts.

(4). Manageable: Indicators are limited to the minimal number required to meet the measurement purpose.

(5). Reliable: Information provided by indicator should be trustworthy.

(6). Cost-Effective Data Access: Indicator has to be based on accessible data. The information needs to be available or can be gathered when it is necessary from existing sources or otherwise easily collected.

(7). Timely manner: Measurement takes place with the frequency to enable timely, informative decision-making

Sala et al. (2015) sought to delineate the principles and requirements of sustainability assessment. Eight principles were discussed and analyzed in this work. These principles are crucial, because they can very fruitfully guide the practitioner performing the assessment by ensuring that what is performed is not just a simple integrated assessment but an effective sustainability assessment (Pinter et al., 2012).The descriptions for the different principles are as shown in Table 2-4.

Table 2-4 Eight Principles and requirements of sustainability assessment (Sala et al., 2015)

Principles	Description
Guiding vision	Progress towards sustainable development should be guided by the goal of delivering well-being within the carrying capacity of the biosphere and ensuring it for future generations
Essential considerations	Underlying social, economic and environmental components of the system as a whole should be taken into account as well as the interactions thereof. This includes issues related to governance; the dynamics of current trends and drivers of change, and interactions thereof; the risks, uncertainties, and activities that can have an impact across boundaries; and the implications for decision making (including trade-offs and synergies).
Adequate scope	The assessment of progress towards sustainable development should adopt an appropriate time horizon, to address both short- and long-term effects of current policy decisions and human activities, and an appropriate geographical scope, to capture both their local and their global effects.
Framework and indicators	sustainability assessment should be based on: a conceptual framework as basis for identifying core indicators and related reliable data, projections and models; the most recent data in order to infer trends and build scenarios; standardised measurement methods wherever possible, to ensure comparability. Finally, the comparison of indicator values with targets and benchmarks has to be performed, where possible.
Transparency	In the context of sustainability assessment, transparency of data and data sources, models, indicators and results is crucial, as well as public accessibility to the results. Choices, assumptions and uncertainties which determine the results of the assessment have to be clearly reported and explained. Equally, sources of funding and potential conflicts of interest have to be disclosed.
Effective communications	sustainability assessment should be required to use clear and plain language, to ensure effective communication and to attract the broadest possible audience as well as minimise the risk of misuse; for building trust and aid interpretation, information should be presented in a fair and objective way as well as supported by innovative visual tools and graphics;
Continuity and capacity	sustainability assessment require that they are complemented by a continuous monitoring phase. Therefore, repeated measurement as well as responsiveness to change are needed. Investments are therefore necessary to develop and maintain adequate capacity (via, for example, continuous learning and improvement).
Broad participation	sustainability assessment should find appropriate ways to strengthen legitimacy and relevance, engaging early on with users of the assessment, reflecting the views of the public while providing active leadership.

2.4 Product/Process Sustainability Index (*ProdSI*/*ProcSI*)

Two comprehensive product and process sustainability indices have been presented recently in literature. These two sustainability performance evaluation methods at product/process level are developed from a holistic perspective, which cover the TBL, total life-cycle, and 6Rs approaches. Therefore, these two methods can be used as the foundation to develop sustainable manufacturing metrics at systems levels. In this section, *ProdSI* and *ProcSI* methods are reviewed in detail to provide the basis for the later, system level, metrics development.

2.4.1 Product Sustainability Index (ProdSI)

A product sustainability assessment method, known as the Product Sustainability Index (*ProdSI*), is proposed by Shuaib et al. (2014). This product sustainability metrics system is developed by building on some earlier work. In the product sustainability metrics system, each individual metric is generated to measure a specific feature of a product's sustainability. There are more than seventy individual metrics covering all aspects of TBL, which are categorized into sub-clusters based on the particular characteristics of product sustainability. The individual metrics are customized according to the features of a specific product. The sub-clusters are grouped into thirteen clusters, in which three clusters are under the economic domain to form the economic index, five clusters are under the environmental domain and generate the environmental index; five clusters are under the societal domain to calculate the societal index. Finally, the overall Product Sustainability Index is calculated by aggregating economic, environmental, and societal indices. The product sustainability metrics in *ProdSI* were developed after reviewing and studying all existing product metrics (Shuaib et al., 2014). It is important to note that the *ProdSI* was developed from a holistic sustainability perspective including TBL, total life-cycle and 6Rs consideration. For each individual metric, the measured data is normalized onto a 0-10 scale, where the score 10 represents that the best case is assigned when a theoretically perfect case is achieved. A score of zero means the worst conditions happened for a product. The clusters for *ProdSI* under economic, environmental and societal domains are shown in Figure 2.6, Figure 2.7 and Figure 2.8 respectively.

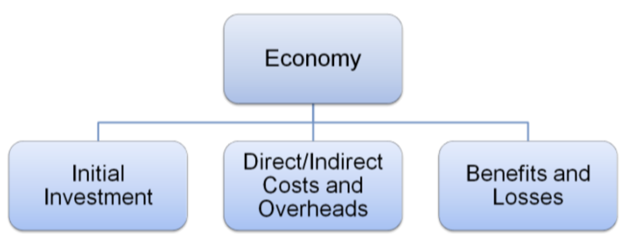

Figure 2.6 *ProdSI* cluster in Economy domain (Shuaib et al., 2014)

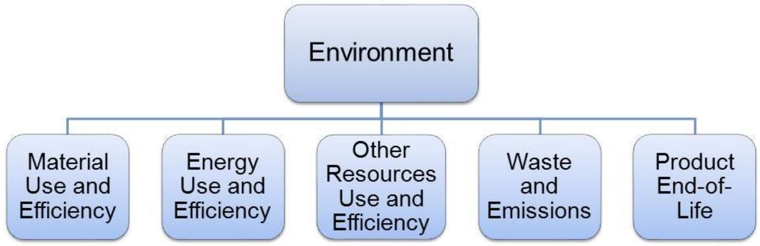

Figure 2.7 *ProdSI* clusters in Environmental domain (Shuaib et al., 2014)

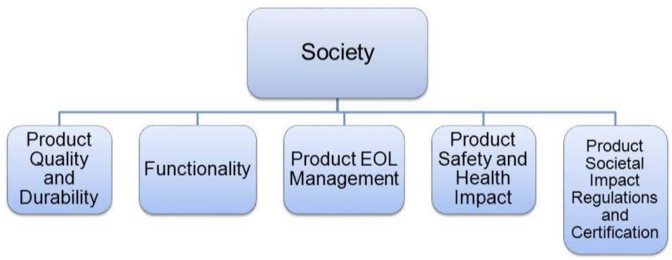

Figure 2.8 *ProdSI* clusters in societal domain (Shuaib et al., 2014)

Finally, the overall Product Sustainability Index is calculated by aggregating economic, environmental, and societal indices. The overall *ProdSI* can be calculated using equations (2.1) and (2.2). In this case equal weighting is applied to each aspect of TBL. In each aspect of TBL, subjective weighting methods are used to determine the relative importance of each cluster.

$$\mathrm{Pr}odSI = \frac{1}{3}(Ec + Ev + Sc)$$
$$= \frac{1}{3}\left(\sum_{i=1}^{3} w_i^c C_i + \sum_{i=4}^{8} w_i^c C_i + \sum_{i=9}^{13} w_i^c C_i\right) \quad (2.1)$$

$$C_m = \sum SC_j w_j^{sc} \ \forall j$$
$$SC_n = \sum M_k w_k^{m} \ \forall j$$

(2.2)

Where:

Ec - Sub-index score for economic impact

Ev - Sub-index score for environmental impact

Sc - Sub-index score for societal impact

w_i^c - Weighting factor for the i_{th} cluster

w_j^{sc} - Weighting factor for the j_{th} sub-cluster

w_k^m - Weighting factor for the k_{th} metric

Cm - Score for m_{th} cluster. C_1 to C_3 are the clusters in the economy sub-index, C_4 to C_8 are the clusters in the environment sub-index and C_9 to C_{13} are the clusters in the society sub-index.

SC_n - Score for the n_{th} sub-cluster

M_k - Score for the k_{th} metric

2.4.2 Process Sustainability Index (ProcSI)

As manufacturing is one of the four life-cycle stages of the product life-cycle, data used in process sustainability assessment can be used for product sustainability assessment. The process sustainability assessment system is established in a four level hierarchical structure (similar to *ProdSI*) that segregates the overall process sustainability into process-level quantifiable individual metrics. The four levels considered are Process Sustainability Index (*ProcSI*), Clusters, Sub-clusters, and Individual metrics (Lu, 2014). The *ProcSI* is also a single score on a scale of 0 to 10 that provides the overall sustainability assessment of the manufacturing process. The *ProcSI* is divided into six clusters that represent the six elements of process sustainability originally identified by Wanigarathne et al. (2004) as shown in Figure 2.9. The six clusters are manufacturing cost, energy consumption, environmental impact, waste management, operational safety, and personnel health. These clusters provide a comprehensive representation of the process sustainability that covers every aspect of the TBL including economy, environment, and society. The overall *ProcSI* is then calculated using a similar method to the one that is used to calculate *ProdSI*.

Figure 2.9 Clusters of *ProcSI* (Wanigarathne et al., 2004 & Lu, 2014)

Chapter 3 Methodology

Research on developing a new methodology for assessing sustainability performance started over two decades ago. Since then, many methodologies have been proposed to measure various aspects of sustainability performance. All these methodologies are valuable and provide unique insights for improving sustainability performance in specific domains. The focus of this research is sustainability performance assessment specifically for the systems level. There are several existing indicators and methodologies that have been presented for the systems level sustainable manufacturing performance evaluation from production line, plant to enterprise. However, few methods are available, which covers all three pillars of sustainability, an emphasis on the total life-cycle stages of products, and the 6Rs concept to assess systems level performance from a sustainable manufacturing perspective. In this research, a three phase approach is followed to answer the research questions raised as shown in Figure 3.1 where:

- Phase I: Developing sustainable manufacturing performance measurement evaluation framework.
- Phase II: Developing index-based methods for sustainable manufacturing performance evaluation at the systems levels (including

production line, plant and enterprise levels), respectively, using the framework developed in Phase I.

- Phase III: Developing value-based method to evaluate enterprise level sustainable manufacturing performance.

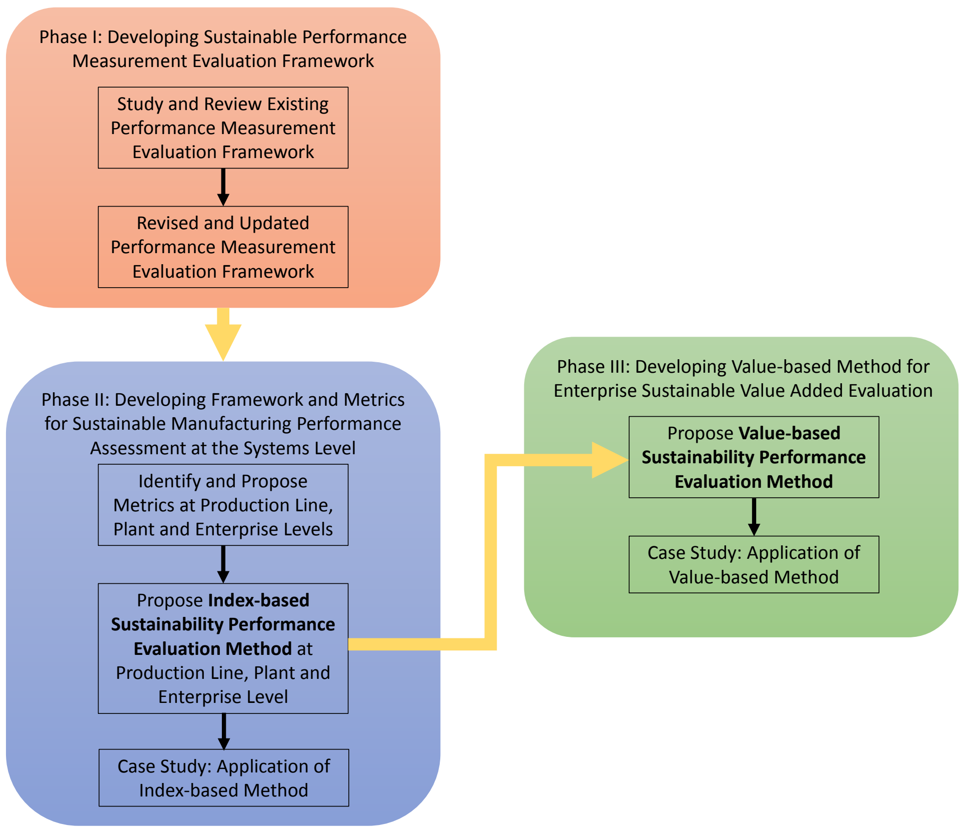

Figure 3.1 Research methodology flow chart

The research questions and details of the steps followed in each phase to answer the research questions are described below.

3.1 Research Outline

3.1.1 Sustainable performance measurement evaluation framework development

Research Question: What key factors should be considered for developing a framework for sustainable manufacturing performance assessment at systems level?

Ultimately, the goal of the research is to create a framework for companies that can help managers and engineers to measure and evaluate the sustainability performance at the systems levels. In order to answer the research question and create a comprehensive performance measurement evaluation framework, several steps will be followed. In phase I, existing performance measurement evaluation framework will be reviewed. A revised and updated performance measurement evaluation framework will be developed to assess measurement system and metrics considering various characteristics such as timeliness, measurability, etc. The development of sustainability performance measurement evaluation framework will be introduced in Chapter 4.

3.1.2 Development of framework and metrics for sustainable manufacturing performance evaluation at the production line, plant and enterprise level

Research question 2*: What metrics should be used and how should they be integrated to measure sustainable manufacturing performance at the systems levels?*

In Phase II of this research, all relevant literature will be reviewed to investigate current research progress on sustainability performance measurement, including existing sustainability indicators as well as sustainability performance evaluation methods at product, process, and system levels. By considering the strengths and shortcomings of these current approaches and considering the requirements for sustainable manufacturing performance evaluation, a comprehensive and holistic systems level hierarchy and metrics will be proposed for the production line level, plant level, and finally for the enterprise level. Subsequently, an index-based sustainable manufacturing performance evaluation method will be proposed for production line, plant and enterprise levels respectively. Finally, the application of the proposed index-based methods will be demonstrated using industrial case studies. The proposed metrics and index-based method for sustainable manufacturing performance evaluation at the line and plant levels will be presented in Chapter 5. The sustainability metrics for enterprise manufacturing performance evaluation and index-based method will be presented in Chapter 6.

3.1.3 Development of sustainable value added assessment approach at the enterprise level

Research Question 3: How can enterprise sustainable value added be measured from a value perspective?

In the third part of research an attempt is made to develop an approach for evaluating enterprise sustainable value added based on the proposed enterprise sustainability performance measurement framework and metrics. Existing work on value and sustainable value definition as well as strategies for their quantification will be studied. These, and insights from other sources will be used to formulate an approach to quantify and evaluate enterprise sustainable value. Then, the application of the approach will be demonstrated using an industrial case study to present the detailed implementation procedures. This part of the dissertation research will be presented in Chapter 6.

Chapter 4 Sustainable Performance Measurement Evaluation Framework

4.1 Development of Sustainable Performance Measurement Evaluation Framework

The purpose of a performance measurement evaluation framework is to provide a consistent approach to systematically collect, analyze, utilize and report performance. In this case, the performance to be reported is sustainable manufacturing performance at the systems level. A thorough review of different frameworks that have been presented in literature was presented in Section 2.1. Compared to other existing performance measurement evaluation frameworks, Prism explores performance evaluation from a much broader perspective of considering all the stakeholders.

The Prism approach is not a prescriptive measurement framework, which can be used by management teams to influence their thinking about what key questions must be raised when managing their business; little information is provided on the process of the actual design of a performance measurement system or how the performance measures are going to be measured. Another weakness is that no consideration is given to existing performance measurement system that companies may already have in place. However, Prism considers performance measurement from a new and broad stakeholder perspective which is highly relevant for sustainable manufacturing from a sustainability point of view. As Prism does not consider the sustainability perspective, sustainability factors will be incorporated to develop a Sustainable Prism (Sus-Prism) performance measurement evaluation framework.

As a first step to proposing a comprehensive sustainability performance measurement evaluation framework, the existing Prism framework is analyzed and critiqued below to subsequently incorporate TBL, total life-cycle stages, and 6Rs approaches consideration.

Stakeholder Perspective

Stakeholder theory was proposed by Freeman (1984) in his book strategic management. This theory looks at the relationship between an organization and others in its internal and external environment. For the systems level and, particularly, corporate sustainability evaluation, stakeholder theory should be applied when developing the theoretical performance evaluation framework. A stakeholder is considered as a person or group that can affect or be affected by an organization. Stakeholder theory implies that corporations have obligations to individuals and groups from inside and outside of the business, including customers, employees, shareholders, suppliers, non-profit groups, government, and the local community, among many others as shown in Figure 4.1. Effectively implementing the Stakeholder Theory will allow corporations to be more successful and perform better than competitors who do not adopt this approach.

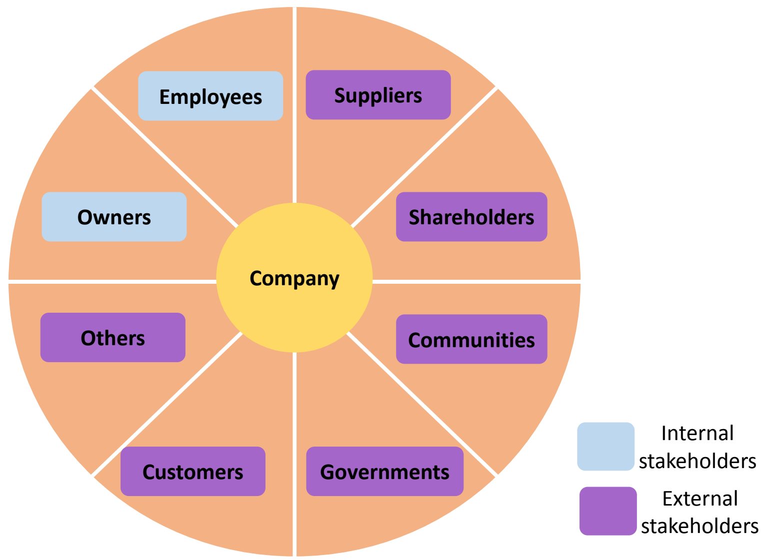

Figure 4.1 Examples of a company's internal and external stakeholders

The stakeholder satisfaction and contribution are mentioned in Prism, where stakeholder's consideration is broadened to all relevant stakeholders. At this point, the question is asked "who are the important stakeholders in the organizations and what do they want and need?" Following that, stakeholders' contributions are discussed. It is recognized that not only organizations deliver value to their stakeholders, but also the stakeholders contribute to the organizations. For instance, the employees want to have a safe and secure place to work. They also want have a decent salary. In return, the organization wants its employees to contribute to the business, such as offer ideas and suggestions, remain loyal to the organization, etc. The interrelationship between organizations and stakeholders is better recognized in Prism compared to other measurement frameworks, and should also be incorporated for sustainable manufacturing. Therefore, the ***framework and metrics development at systems level from sustainable manufacturing perspective should consider all related stakeholders instead of merely considering customers and shareholders***.

Strategies

The second aspect of the Prism framework relates to strategy. Organizations have strategies to deliver value to some set of stakeholders. Before developing such strategies, stakeholder groups of interest and their need/wants must be identified. Therefore, strategy development requires ensuring the needs of stakeholders are satisfied. For sustainable development, in general, and for sustainable manufacturing in particular, the strategic decision-making process should incorporate the environmental and societal dimensions as well as economic profitability considerations. The strategies should be developed to support sustainable business management and as well as innovation. The strategy development should be made from a sustainability perspective for long-term corporate success. To innovate for sustainable manufacturing, corporate strategy development requires incorporating the three pillars of sustainability including economy, environment, and society. Moreover, the total life-cycle focused approach should be reflected in the strategy development, which can help communicate and emphasize the vision across the supply chain. For 6R approach, it reflects the extent of product end-of-life activities (reuse, recycle, recover, redesign, etc.) implementation at the management and operational fields. In addition, all positive and negative impacts to all related stakeholders should be reflected in the strategy development. As listed factors above, ***strategy development for product, process and systems should incorporate the TBL factors, total life-cycle emphasis and 6Rs approach simultaneously for achieving sustainable manufacturing***.

Processes

At this phase, the Prism asks the question of "what are the processes we have to put in place in order to allow our strategies to be delivered?" As sustainability strategies are developed, the processes of implementing these strategies internally and externally should be developed. From a manufacturing perspective and for developing a performance measurement evaluation framework for sustainable manufacturing, these processes can be thought from a hierarchy such as the production line level, plant level, enterprise level, and supply chain level all of which, together cover the entire system necessary to produce and deliver products to customers.

For better supply chain management, at enterprise level and across the supply chain, eight key processes should be considered, including, customer relationship management, supplier relationship management, customer service management, demand management, order fulfillment, manufacturing flow management, product development and commercialization, and return management (Lambert, 2008). This is visually represented in Figure 4.2. For each of these processes, it should be possible to identify specific measures which allow management to evaluate their performance. If an enterprise within this supply chain is considered (shown for example as the 'manufacturer' in Figure 4.3) the functional units within it can be represented as shown in Figure 4.3. When the manufacturing function is considered and further divided, it can be classified into different plants and production lines within those plants, as also shown in Figure 4.3. When performance measures are being developed for sustainable manufacturing all these different levels, that is the production line, plant, enterprise and supply chain levels, must be considered. Also, at these levels, total life-cycle focus, 6R approach and TBL should be taken into account simultaneously.

At the plant and production line levels, the manufacturing flow management process is the most relevant process. For example, in manufacturing processes, clean production, pollution prevention, and environmental compliance must be incorporated to develop specific measures. The application of the 6R approach to reduce resource consumption and negative impacts on stakeholders and the environment are essential to be considered as well. Therefore, the company that has aligned its processes perfectly has potential to provide benefits to overall company performance.

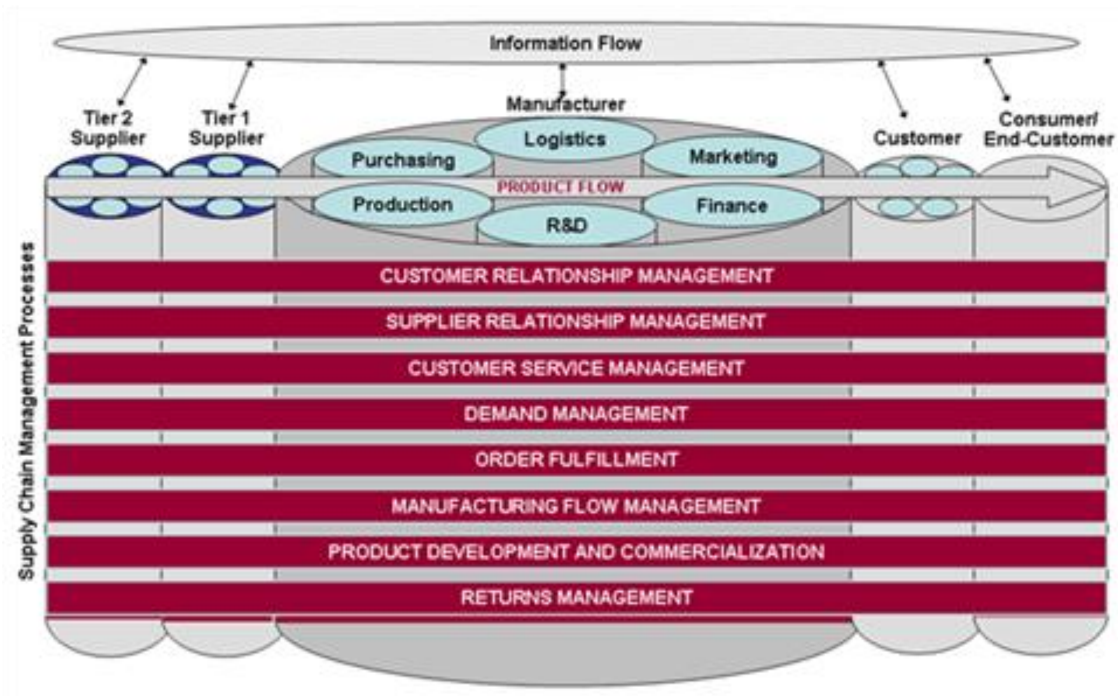

Figure 4.2 Eight key processes of supply chain (lambert, 2008)

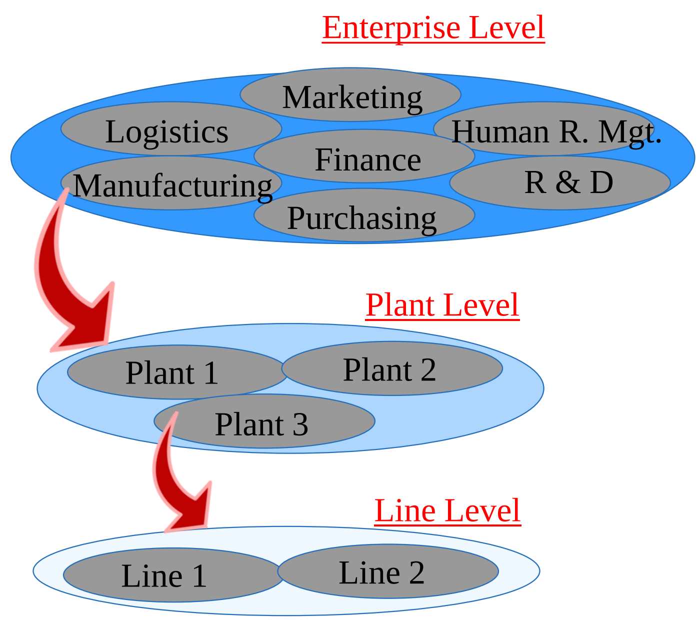

Figure 4.3 Functional units at enterprise level, plant level, and line level

Figure 4.4 better reflects the total life-cycle and 6R approaches that should be applied to suppliers (pre-manufacturing), manufacturer (manufacturing), customers (use), and reverse logistics provider (post-use) from a supply chain perspective (Badurdeen et al., 2009). The supply chain network consists of a focal company, and multiple tiers of both suppliers (leading from the left to the center) and customers (leading from the center to the right). It is important for the focal company to recognize its relative position in the supply chain and to determine with which supply chain members it is most critical to establish links. The network of companies is categorized into four life-cycle stages. The elements of 6R methodology are distributed to each life cycle stage correspondingly. As shown in Figure 4.4 total life-cycle and 6R approaches are connected with supply chain network efficiently, which play an important role for ensuring the success of both the focal company and its partners.

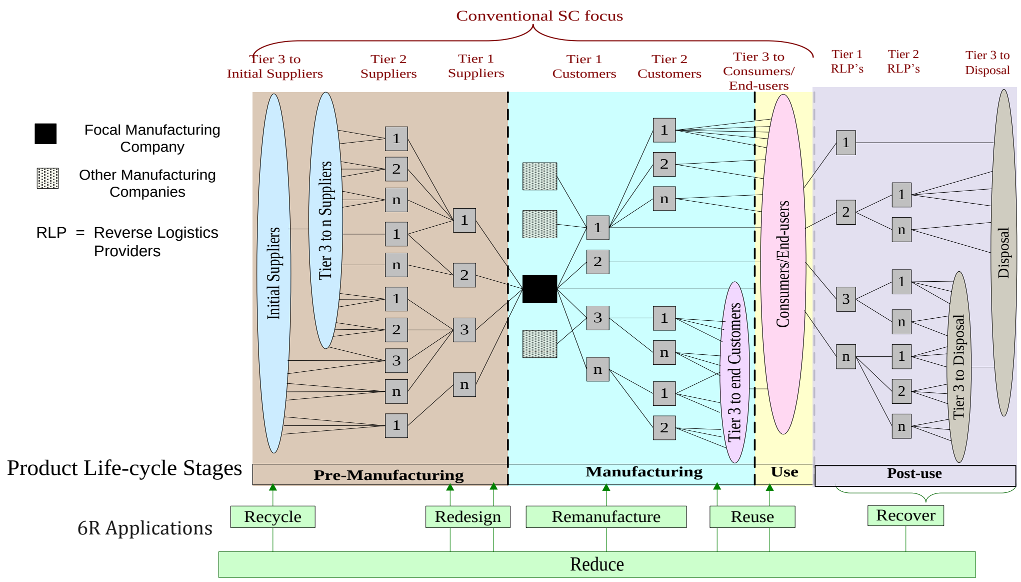

Figure 4.4 Sustainable supply chain structure (Badurdeen et al., 2009)

Capabilities

The designed processes cannot function independently; they require people with skills, the technology, and physical infrastructure to enable them. Thus, in the Prism framework, capabilities refer to the combination of people, practices, technology and infrastructure that enable operating the processes. By developing capabilities, a company can ensure that employees' skills and efforts are useful and directed to achieve corporate goals and strategies. In this phase, capability development needs to integrate business, environmental and societal problems. For instance, developing employees' environmental protection and safety awareness, improving employees' skills, improving infrastructure energy and resource consumption, coordinating the relationship with stakeholders, and implementing advanced technologies can promote the overall corporate sustainability performance. Therefore, here needs to emphasize that ***capabilities development not only focuses on employees' skill, technology, physical infrastructure improvement, but also need to enhance employees' understanding of the requirements of sustainability development such as TBL, total life-cycle focus and 6Rs approach***.

Based on the discussion in previous sections, considering the Prism framework and the specific requirements for sustainable manufacturing, the following modifications must be incorporated when a modified performance measurement evaluation framework is developed:

- Integrate corporate objectives with operational performances indicators
- Include sustainability concept into strategies development
- Implement TBL, total life-cycle, 6R approaches in the process design phase
- Identify key performance indicators for sustainable manufacturing
- Provide detailed information for performance measures implementation

4.2 Performance Measurement: Product, Process and Systems Levels Integration

As discussed in the previous section of sustainable performance measurement evaluation framework, the stakeholder's perspective, strategies, processes and capabilities should be considered to enable developing sustainable manufacturing performance measurement. To achieve this, a metrics hierarchy represented as a house that incorporates considerations at product, process, and systems levels is proposed here. The ideology to represent it as a house is borrowed from the Toyota House used to represent the principles in the Toyota Production System (Ohno, 1988). This metric hierarchy house is developed to creatively organize all sustainability requirements for sustainable manufacturing.

Sustainable manufacturing has been defined as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" by the United States Department of Commerce (USDC, 2009). Therefore, this sustainable manufacturing philosophy forms the foundation of the house. Analogous to a physical building, the steadiness of a building depends on whether the foundation is steady or not; therefore, the success of a company depends on the extent of understanding, appreciating and implementing sustainable manufacturing. To better achieve sustainable manufacturing, there are three important factors that should be considered as basic pillars shown in the house. These three basic pillars are the TBL, 6R approach, and total life-cycle focus. TBL has been highly emphasized for general sustainable development, which considers economic impacts, environmental impact, and societal impacts. Total life-cycle approach must be focused from upstream suppliers to downstream customers, which includes pre-manufacturing, manufacturing, use and post-use. The innovative 6R approach should be implemented for metrics development as well, which ensures closed-loop material flow. Then in the middle is performance measurement framework, which will provide a consistent and acceptable approach to systematically collect, analyze, utilize and report the sustainability performance. This Sus-Prism framework, modified from the Prism (Neely et al., 2002) should be included here as the performance measurement framework.

The definition of sustainable manufacturing clearly emphasizes the need for creating manufactured products using processes. Therefore, the two main pillars of the house are presented as product metrics and process metrics. In the pillar of product metrics, the metrics developed in the previous *ProdSI* are taken into consideration from systems level metrics development. In the pillar of process metrics, process metrics developed in the previous study of *ProcSI* are also incorporated for systems level metrics development. Thus, in this research, *ProdSI* and *ProcSI* are both reviewed and studied as related works for systems level metrics development.

In the middle of the house are the stakeholders, who should be considered for sustainability metrics development. The stakeholder's activity will affects the decision making of a company. Meanwhile, the company's activity will also have positive and/or negative to stakeholders. The interrelationship between the company and stakeholders should be identified and analyzed. Then, in the roof of the house is systems metrics which can be formulated at four levels ranging from line level, plant level, enterprise level, to supply chain level. At a line level, it is structured of several machines, which can manufacture products using processes. Line level is considered as the start point of system level. Following the line level is plant level, which consists of several lines in each plant. The plant can be considered as production department in a company, which can work with other functional departments of a company. The company requires cooperating with its upstream suppliers and downstream customers to achieve company goals, which build the networks of companies known as supply chain. Therefore, the systems metrics need to consider from a broad point of view including line level, plant level, enterprise level, and supply chain level. Therefore, the metrics hierarchy at product, process, and system levels should be integrated as shown in Figure 4.5.

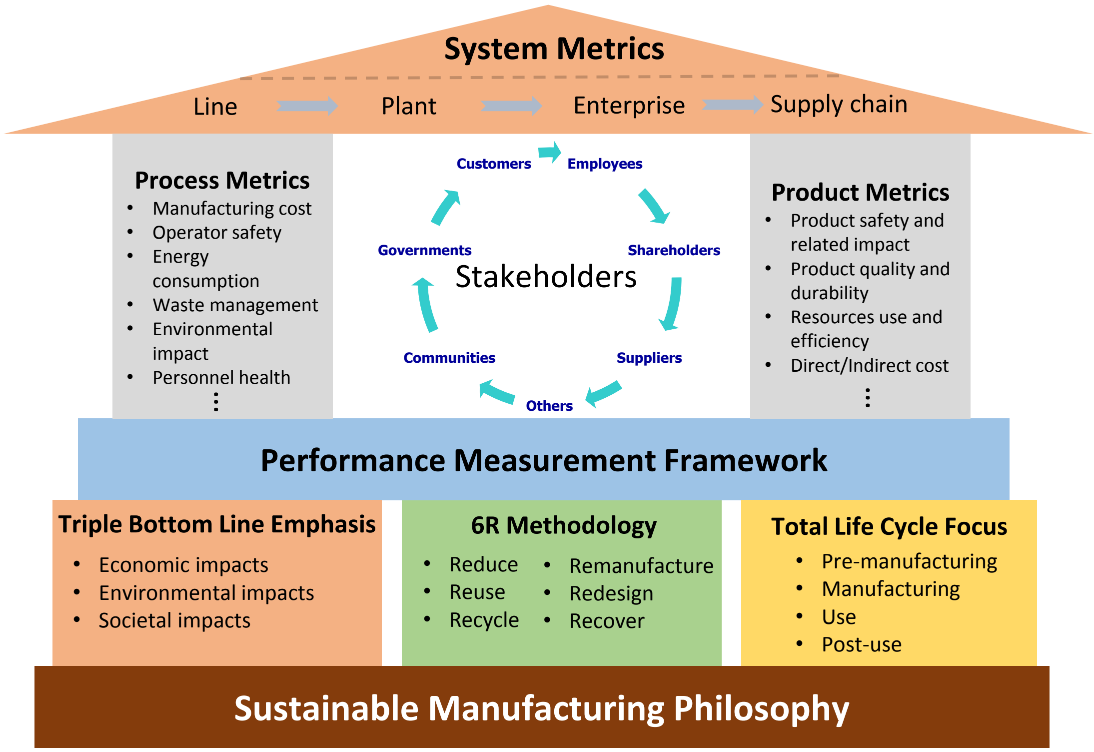

Figure 4.5 Sustainability Performance Measurement House: product, process and systems level integration (Huang and Badurdeen, 2016)

Chapter 5 Metrics-based Approach to Evaluate Sustainable Manufacturing Performance at the Production Line and Plant Levels

5.1 Introduction

Promoting sustainability in manufacturing requires a holistic view covering not just the product, and the manufacturing processes used for its production, but also the systems, the scope of which varies from the production line, to the plant, to the enterprise and finally to the supply chain.

At the product level, major changes are needed to move away from the traditional approach of designing products for end-of-life disposal; sustainable products must be designed and produced considering impacts that span the entirety of its life-cycle, and ultimately, even multiple life-cycles to enable near perpetual material flow.

At the process level, it is necessary to make manufacturing processes more environmentally friendly and safer which can be achieved by using cleaner energy and renewable material, reducing hazardous material usage, etc. A number of process steps are combined to create a workstation and several of those workstations are then combined to form a production line which can be considered the fundamental unit that forms the systems level. Hence, the process performance and system performance both affect product sustainability performance ultimately. Thus, when developing metrics for sustainability performance evaluation at the system level, product sustainability also has to be considered. Whether products can meet the customer's preferences, comply with relevant environmental regulations, or not, can directly affect its sustainability performance. These aspects are directly affected by how a product is manufactured and made available to the customer using the production lines, plants, the enterprise and supply chain. Therefore, when developing metrics for the system level, criteria/clusters related to, and affecting, a product's performance must be considered; system level capabilities necessary to enable product sustainability and to what extent the system can meet those requirements must be determined.

The paradigm shift from an open-loop life-cycle focused system to a closed loop material flow system for sustainable manufacturing is facilitated through the 6R methodology (Jawahir et al., 2006). Implementing the 6R's of (Reduce, reuse, recycle, recover, redesign, remanufacture) can enable minimizing material and energy consumption, eliminating wastes and emissions. The 6Rs is a mechanism to enable closed-loop material flow for sustainable products. But most of the Rs cannot be enabled without emphasis on improving performance of the manufacturing processes or systems aspects. Therefore, to promote sustainable manufacturing it is necessary to concurrently improve sustainability performance of the product, process and system aspects. To improve sustainability performance of any product, process or system, the extent to which 6Rs practices are enabled must be measured accurately and comprehensively.

Metrics can be used to assess the efficiency, performance, progress or quality of a plan, process, product or system. When multiple aspects of performance must be evaluated, such as economic, environmental and societal aspects for overall sustainability, a variety of metrics will be necessary and they must be organized into an effective format to aid with improvement decision making. Thus, to evaluate sustainable manufacturing performance, comprehensive frameworks and metrics are necessary at the product, process and system levels. As per the definition of sustainable manufacturing presented earlier, framework and metrics development must focus on the total life-cycle that spans pre-manufacturing, manufacturing, use and post-use stages, the 6Rs and the TBL. A set of evaluation methods has been presented starting with the early work of Fiksel et al. (1998) who presented a product sustainability indicator focusing on economic, environmental and societal performance, several other studies since have addressed product sustainability. More recently, a more comprehensive approach for a Product Sustainability Index that incorporates all required facets (TBL, total life-cycle stages and 6Rs) have been presented by Shuaib et al., (2014). Similar studies have been done for manufacturing process sustainability performance evaluation by Lu

(2014) who presented a very comprehensive approach covering all required facets. The system levels range from the production line to plant, enterprise, and supply chain levels. However, system level sustainable manufacturing performance evaluation across all levels (from line to supply chain) that covers all the TBL aspects as well as the satisfaction, or not, of system level criteria that will enable 6R implementation and closed-loop material flow practices, are still limited. To address this gap, in this paper, our focus is on production line and plant level sustainability performance evaluation. The term 'plant' and 'factory' have been used interchangeably in literature to refer to a manufacturing facility that could have one or more production lines. We will use the term 'plant' in this paper to refer to the manufacturing facility. Several indicators and methodologies have been presented for sustainability performance evaluation at the line and plant levels (Faulkner and Badurdeen, 2014; Zhang and Haapala, 2015; Despeisse et al., 2012; Despeisse et al., 2013, Winroth et al., 2012). However, none cover all the three pillars of sustainability, the extent to which total life-cycle aspects and implementing the 6Rs is enabled to comprehensively assess sustainable manufacturing performance at the production line and plant levels. In most cases, prior work has addressed only one or two TBL domains, rather than a more comprehensive TBL assessment. Moreover, almost all literature addressing production line and plant level metrics for sustainable manufacturing performance evaluation ignore evaluating the line- and plant-level attributes that enable capabilities to better practice life-cycle focused practices or 6R implementation. In an effort to address this gap, this part of the research will identify comprehensive metrics and develop an assessment methodology for line and plant level sustainable manufacturing performance evaluation. Extensive literature review of line and plant level metrics are conducted to identify suitable metrics for sustainable manufacturing performance evaluation. The identified metrics are organized into a five-level hierarchical structure by integrating the metrics from lower levels--product and process levels. An index-based methodology is proposed to evaluate the production line sustainability performance via data normalization, weighting and score aggregation. An industry case study is used to demonstrate the application of the index-based method to evaluate the production line and plant sustainability performance.

The remaining sections of the chapter are organized as follows. Section 5.2 provides a literature review, primarily focusing on process, line, and plant (factory) sustainability performance evaluation. Section 5.3 describes the methodology followed to identify metrics and develop the index-based method for line and plant level sustainable manufacturing performance evaluation. Section 5.4 presents the application of the proposed method to an industrial case study. Concluding remarks are covered in Section 5.5.

5.2 Curent State of Art

Sustainability has been the subject of growing emphasis over the past three decades. In published literature, the focus on sustainable manufacturing performance measurement is a more recent phenomenon. The discussion presented below reviews the measurement tools offered in existing research, in order to identify gaps and propose a comprehensive performance measurement and evaluation method to assess sustainable manufacturing performance at the production line and plant levels.

Feng and Joung (2009) proposed a framework for sustainable manufacturing performance measurement, which has three key interrelated components: sustainable indicator repository, sustainability measurement methodologies, and performance report. The shortcoming of this work is that metrics and measurement methods are not presented. A comprehensive review of metrics and indicators for sustainable manufacturing performance evaluation was subsequently presented by Feng et al., (2010). They also summarized publicly available sets of sustainability and environmental indicators developed by a wide range of entities such as the Organization for Economic Co-operation and Development (OECD), Ford, General Motors, Walmart, etc. These sustainability evaluation methodologies were classified based on the level of technical detail and the application domains which ranges from product, process, facility, corporation, sector and country level to the global level. (Feng et al., 2010). Given that manufacturing processes are grouped to form a workstation in a production line, we start the discussion below with a review of sustainable manufacturing process evaluation methods.

Sustainable manufacturing performance evaluation at process-level: In some early work, Wanigarathne et al. (2004) identified six performance clusters to evaluate sustainability of manufacturing processes: manufacturing cost, energy consumption, environmental impact, waste management, operational safety, and personnel health. These clusters provide a comprehensive representation of criteria that affect process sustainability covering TBL aspects. The shortcoming of the work of Wanigarathne et al. (2004) is that they did not present any metrics for evaluation. Another early study by Khan et al. (2004) proposed a Life cycle iNdeX (LInX) for product and process design and decision making, which is generated through a four-level system, involving sub-indices and multiple parameters for each of them. The LInX is comprised of four important sub-indices or attributes-environment, health and safety (EHS); cost; technical feasibility; and socio-political factors. Yuan et al. (2012) present another study where they consider technology, energy and material as the three major factors to evaluate manufacturing process sustainability. A case study is carried out on an Atomic

Layer Deposition process where material and energy efficiency, greenhouse gas (GHG) emissions and material toxicity are used as the metrics. The limitation of these review works is that there are no comprehensive metrics presented and 6Rs concept is not fully considered.

The Organization for Economic Co-operation and Development (OECD) presented one of the earliest toolkits to analyze sustainability performance of processes and products to identify opportunities for improvement. The toolkit includes a set of 18 core indicators classified in terms of materials and processes. The indicators are developed to help measure primarily the environmental impact relating to production activities of a single facility in the business (e.g. site, factory, office) as a starting point for sustainable manufacturing. However, the performance can also be monitored and evaluated at the overall organizational level by aggregating the data obtained to calculate the individual indicators (OECD 2011). The major shortcoming of this toolkit, however, is the limitation to evaluating sustainable manufacturing performance purely from the environmental point of view without consideration of economic and societal aspects.

Lu (2014) proposed one of the most comprehensive manufacturing process sustainability performance evaluation tools called the Process Sustainability Index (*ProcSI*) which aims to evaluate the sustainability performance of a manufacturing process. The *ProcSI* is established in a four level hierarchical structure that determines the overall process sustainability starting with process-level quantifiable individual metrics. The four levels considered are Process Sustainability Index (*ProcSI*), Clusters, Sub-clusters, and individual metrics. Once metrics are progressively aggregated, it provides the *ProcSI* as a single score on a scale of 0 to 10, for overall manufacturing process sustainability. As manufacturing processes are the foundational unit used to create workstations that form the production lines, sustainability metrics at the process level can be considered as a basis when developing production line metrics. Given the comprehensive set of metrics considered, *ProcSI* is used in this paper as one of the bases to identify metrics for production line sustainability performance evaluation.

Sustainable manufacturing performance evaluation at line-level: One study highly relevant in the context of sustainable manufacturing performance evaluation at line level is presented by Faulkner and Badurdeen (2014). They propose the development of a comprehensive methodology, known as sustainable value stream mapping (Sus-VSM), extending the widely used concept of VSM from lean, to assess manufacturing sustainability performance at production line level. To develop the Sus-VSM tool, authors identify suitable metrics to evaluate sustainable manufacturing performance at the line level and propose methods to visualize them. Since the intent of Faulkner and Badurdeen's (2014) work is to extend the VSM tool to develop the Sus-VSM, they emphasize the focus on identifying a core set of metrics that can be visually presented without cluttering an essentially visual tool. In addition, this work presents a case study and details about how data can be gathered for each metric. Therefore, while the metrics included cover the TBL aspects, they are limited and not adequate for a comprehensive assessment of production line sustainability performance.

Workstations in a production line can be organized in different layouts, with one alternative being a U- or C-shaped manufacturing work cell. Zhang and Haapala (2015) present an approach to assess work cell sustainability impacts by conducting economic, environmental, and social impact assessments. In this work, four aspects are considered for economic assessment: facility cost, labor cost, material cost and utility cost; environmental assessment is carried out by conducting life cycle assessment (LCA) of the work cell without detailed metrics development; societal assessment is based on wages, workload and injuries. The results for each TBL aspect are then integrated into a sustainable manufacturing assessment framework with weighting methods. To demonstrate the proposed approach is applied to a case study for producing steel knives at a machining work cell level. The results for three production scenarios are compared to investigate the largest production cost contributor, which is proved to be cutting tool cost. While simple, the limitation of this work is that the number of metrics considered is limited not permitting a comprehensive sustainability performance assessment at the line level. Table 5-1 summarizes the line level sustainability metrics identified in the aforementioned studies, organized along the three pillars of sustainability.

Table 5-1 Summary of metrics for line-level sustainability evaluation

Evaluation Aspect	Metrics	
	Faulkner and Badurdeen (2014)	Zhang and Haapala (2015)
Economic Sustainability	Cycle time	Facility cost
	Changeover time	Labor cost
	Uptime	Material cost
	Inventory	Utility cost
Environmental Sustainability	Raw material usage	Life Cycle Assessment (without detailed metrics)
	Process water consumption	
	Process energy consumption	
	Transportation energy consumption	
Societal Sustainability	Physical load index	Wages
	Noise	Workload
	Risk Circle	Injuries

Sustainable manufacturing performance evaluation at plant-level: One of the earliest studies that are relevant in the context of evaluating plant level sustainability performance is presented in the Barometer of Sustainability (Danis, 1997) which emphasizes two aspects of sustainability: Human Well-being and Ecosystem Well-being. A five step rating scale from "unsustainable" to “sustainable” is used in the model which allows for a rapid qualitative assessment. Although the tool has not been created explicitly for manufacturing plant assessment, the approach is flexible and adaptable. Cross-industry comparison can be enabled depending on the adaption procedure (Danis, 1997). The limitation of the Barometer of Sustainability is that the 6Rs are not considered and total life-cycle stages are not fully emphasized. In another study, a set of core indicators of sustainable production was proposed by Veleva and Ellenbecker (2001). The Lowell Center for Sustainable Production (LCSP) indicator framework, proposed by Veleva and Ellenbecker (2001) is organized into five levels, from compliance to effectiveness, supply chain and system performance. The proposed core indicators combine measurements related to energy and material use, natural environment, economic performance, community development and social justice, workers and products. Although the work of Veleva and Ellenbecker (2001) considers the total life-cycle stages, it does not address 6Rs implementation. No detailed guidance is provided on how to construct and calculate supplemental indicators. Goodson (2002) proposed a tool for Rapid Plant Assessment (RPA) that is based on a questionnaire of twenty Yes-No-Questions addressing aspects of leanness in a manufacturing plant. The questions are related to a framework with eleven assessment categories, which are qualitatively rated on a 6-step scale from “poor” to “best”. Both the questionnaire and the framework, however, focus is only evaluating the economic aspect from a flow manufacturing perspective and is inadequate for a sustainability performance evaluation (Goodson, 2002).

In a more recent study, Winroth et al. (2012) proposed a set of sustainable performance indicators at factory (plant) level. Although the authors mention that the proposed indicators can measure progress as well as comparative performance between factories, only the indicator list was presented without details on how they should be used to evaluate factory sustainability performance. Also, the proposed indicators do not consider the 6R concept; for instance, the waste and emission aspect only focuses on the negative impact to the environmental without any post-use treatment assessment. In addition, the societal dimension only considers the impact to the employee; impact on other relevant stakeholders such as customers, communities, etc. is not incorporated. Despeisse et al. (2012) proposed a conceptual manufacturing ecosystem model at the factory (plant) level to improve environmental performance by analyzing environmental principles and industrial practice. The developed model focuses only on material, energy and waste flows between manufacturing operations, supporting facilities and surrounding buildings. In order to improve the resource efficiency, five indicators are considered: prevention by avoiding resource use, reduction of waste generation, reduction of resource use by improving efficiency, reuse of waste as resource, substitution by changing supply or process. However, this work provides only a theoretical model without details for performance evaluation. In addition the societal aspect is not reflected in the proposed conceptual model. A continuing work on factory modelling has been done by Despeisse et al. (2013) where guidelines for manufacturers to undertake the sustainability journey were provided. The cross-functional factory modelling and resource flow analysis was presented via a prototype tool, but the TBL aspects were covered only partially; enabling of 6R concepts incorporation at the plant level is also not evident.

As discussed above, none of the methods in published literature incorporate assessment of plant level capabilities that enable better implementation of 6R aspects. For a comprehensive sustainability performance evaluation, it is necessary to assess whether the system enables implementing the capabilities to conduct 6R activities. Some literature identifies metrics to partially incorporate total life-cycle stages and often the post-use stage is not addressed. Of the plant level work reviewed, those of Veleva and Ellenbecker (2001) and Winroth et al. (2012) are more comprehensive and relevant to the study presented in this paper. Thus, those approaches are thoroughly reviewed for the plant level metrics identification in this study.

5.3 Metrics-based Approach Development at the Production Line and Plant Levels

In order to better measure and evaluate the sustainable manufacturing performance at the production line and plant levels, a framework and metrics must be identified. This section will introduce a framework for the system level that enables addressing TBL, total life-cycle focus, and 6R consideration simultaneously during performance metrics development. Based on this framework and existing metrics/indicators for production line/plant levels, a set of comprehensive sustainability metrics will be identified and summarized for the production line and plant levels. Then, an index-based method is proposed to evaluate the sustainable manufacturing performance at the two levels.

5.3.1 Background

In a manufacturing system, the manufacturing processes are combined into workstations that are then combined to create a production line. Many production lines are used within a plant. Therefore, the manufacturing process can be taken as the fundamental unit to consider when identifying metrics for evaluating sustainable manufacturing performance for production line and plant levels. Being one of the most comprehensive manufacturing process sustainability assessment tools, we review further here the Process Sustainability Index (*ProcSI)* as a first step. The *ProcSI* (Lu, 2014) considers all the aspects of TBL and incorporates 6R aspects during manufacturing process metrics development and consists of six clusters: manufacturing cost, energy consumption, environmental impact, waste management, operational safety, and personnel health as previously shown in Figure 2.9. Since each cluster represents a wide range of impacts that might not be directly related and/or measurable, clusters are divided into sub-clusters which capture the specific areas of impact that each cluster covers. The detailed description of the clusters used in *ProcSI* is summarized in Table 5-2.

Product sustainability has to be mentioned here because manufacturing processes are used to make products. Although product sustainability is not directly related to the process, line, plant or enterprise sustainability, the system's sustainability performance affects product sustainability; a product's pre-manufacturing and manufacturing stage performance is affected by line, plant, enterprise performance. Therefore, when developing metrics for line, plant and enterprise levels, criteria/clusters related to, and affecting, a product's performance primarily during pre-manufacturing and manufacturing stages must be considered. Therefore, when the objective is to improve overall sustainability, there is a need to understand what system level capabilities are necessary to enable product sustainability and measure to what extent the system can meet those requirements. As discussed previously, Shuaib et al. (2014) propose a method for product

Table 5-2 *ProcSI* clusters and description (Lu, 2014)

Clusters	Description
Manufacturing cost	The costs incurred during the manufacturing process. The costs are calculated on a $/unit basis to maintain connectivity with different metrics. This cluster involves three sub-clusters: direct cost, indirect cost, and capital cost.
Energy consumption	The energy consumed by the manufacturing process. This includes the energy consumed during the various manufacturing activities, e.g., machine tool operation, product transportation, facilities operation and maintenance. It also covers energy efficiency and renewable energy use. The sub-clusters identified for this cluster are: production, transportation, facilities, production supply system, maintenance, efficiency and renewable energy.
Environmental impact	The negative environmental impacts resulting from the manufacturing process. The environmental impact considers the manufacturing facilities in addition to the overall eco-system. The sub-clusters are categorized to various types of environmental impacts: energy, water, restricted material, disposed waste, noise pollution and heat
Waste management	All types of wastes produced during the manufacturing operations. It also incorporates waste management operations and the 6R application for waste reduction. The sub-clusters are categorized according to the type of wastes: consumables, packaging, raw material wastes and scrapped parts.
Operational safety	Operator safety risks, working conditions and incident occurrence. The two sub-clusters involved are: working environment conditions and injuries.
Personnel health	This cluster focuses on the operator health. It examines factors that can impact health, e.g., hazardous materials concentration, ergonomics, etc., and it tracks the health-related incidents. The sub-clusters involved are: working environment conditions (health), Physical Load Index (PLI) and absentee rate.

sustainability evaluation where a set of comprehensive sustainability metrics are identified. *ProdSI* will also be relevant when identifying metrics, sub-clusters, and clusters assessment criteria for line and plant levels.

Based on the background described above, the development of index-based methods to evaluate sustainable manufacturing performance evaluation at the production line and plant levels is investigated in the remainder of this chapter. While performance must be evaluated from the TBL perspective, first it is necessary to define the core criteria, or 'clusters', that must be evaluated to assess economic, environmental and societal sustainability. Once the clusters, as well as, sub-clusters have been defined, specific metrics must be determined. In many studies, different names have been used for metrics that measure the same criteria. To avoid duplication, existing similar metrics were all reviewed to assign most suitable titles for measuring the criteria of interest. Moreover, many existing metrics used at the line and plant levels were somewhat vague and needed refinement. It is important to identify the most essential and sufficient number of metrics to evaluate all necessary aspects which is another consideration when identifying metrics. The well-defined prior work such as *ProdSI* and *ProcSI* were used to draw insights on what aspects must be assessed for each sub-cluster and identify the minimum required metrics without duplication.

The following two sections present the measurement clusters and sub-clusters chosen to evaluate production line and plant level sustainability performance, respectively. For each level, specific metrics identified to evaluate each of the sub-clusters is also presented.

5.3.2 Production line sustainability assessment

The following describes the details of sustainability clusters sub-clusters, and metrics for a production line performance evaluation from economic, environmental and societal assessment aspects. All the metrics are identified by studying and reviewing existing literature about production line and relevant work. The collection of all the metrics gathered is presented in Appendix A.

5.3.2.1 Line level economic sustainability performance assessment

To evaluate economic sustainability, performance must be evaluated along two main clusters: manufacturing cost and operational performance. Manufacturing cost is a primary aspect of assessment and will include any cost incurred during the manufacturing stage. This cluster has been included in *ProcSI* (Lu, 2014) to capture the cost for the manufacturing processes. The costs are calculated on a $/unit basis to maintain connectivity with different metrics. The cluster of manufacturing cost must be determined consolidating performance for two sub-clusters: direct cost and indirect cost. Direct cost is a cost that can be completely attributed to the production of specific products on the line such as operational energy cost, material cost, direct labor cost (operator cost) and packaging material cost. Indirect costs are costs that are not directly assignable to a cost object, in this case the production line. Indirect costs may be either fixed cost such as equipment maintenance costs or variable cost such as repair costs. The metrics to evaluate direct cost are discussed in many studies (Winroth et al., 2012, Lu, 2014; OECD, 2011; Zhang and Haapala, 2015). Variations considered for labor cost include average employment cost, employee cost per hour, total employment cost, base wage, bonus, total wage, etc. In order to avoid duplication, we consolidate the metrics into direct labor cost and indirect labor cost. In addition, another cluster 'operational performance' is considered to capture the operational efficiency for the production line. A similar measure has been used by Faulkner and Badurdeen (2014) in their work in Sus-VSM to evaluate production efficiency by measuring lead time, productivity and labor utilization. Table 5-3 shows the hierarchy of line level economic sustainability performance assessment where metrics, sub-clusters, clusters and sub-index are included.

Table 5-3 Line level economic sustainability performance assessment

Sub-Index	Cluster	Sub-cluster	Metrics
Economy	Manufacturing Cost	Direct cost	Operational energy cost
			Direct labor cost (operation labor)
			Product raw material cost
			Packaging related cost
		Indirect cost	Scrap cost
			Process-related consumables cost
			Processing tools-related cost
			Water cost
			Maintenance cost
			Cost of PPE, jigs/fixtures, equipment
			Other non-operational energy cost
			Indirect labor cost (maintenance, cleaning, material handler. labors)
			Training cost
			Cost of waste disposal treatment
			Other related costs
	Operational Performance	Operational efficiency	Lead time
			Productivity
			Utilization of manual labor (labor efficiency)

5.3.2.2 Line level environmental sustainability performance assessment

To comprehensively evaluate production line environmental sustainability, assessment must be carried out along four different clusters: material use and efficiency, energy use and efficiency, other resources use and efficiency, waste and emissions. These four major elements are considered to reflect the inputs to, and outputs from, a production line from the environmental impact perspective (Veleva and Ellenbecker, 2001; Despeisse et al., 2012; Despeisse et al., 2013, Lu, 2014; Shuaib et al., 2014). The clusters of material use, energy use, and other resources use (major focus on water) and corresponding efficiencies reflect the quantity of natural resources used and the efficiency with which they are used, reflecting commonly used measurement aspects in the manufacturing industry. Under the different (material, energy, other) resource use clusters, the amount of each natural resource usage, the types of each resource used (such as renewable material/energy, recycle/reused water), and the efficiency of each resource usage are captured. Waste and emissions are unavoidable outputs of a manufacturing line that can result in negative environmental impacts (such as atmospheric acidification, carcinogenic effects, photochemical smog and eutrophication, etc.). This is covered in the last cluster and sub-clusters within that. Moreover, the application for waste reduction practices to promote 6Rs is also reflected by the inclusion of the sub-cluster of—waste recovery and disposal treatment. An appropriate waste recovery activity and disposal treatment can help to provide waste (such as metal scrap during the machining processes) a second life with recycle/reuse instead of directly disposing to the landfill to finally achieve closed-loop material flow. Table 5-4 illustrates the metrics for line level environmental sustainability performance evaluation.

Table 5-4 Line level environmental sustainability performance evaluation

Sub-Index	**Cluster**	**Sub-cluster**	**Metrics**
Environment	Material use and efficiency	Material content	Total weight of product raw material use
			Packaging material use efficiency
			Total weight of packaging material use
			Mass of restricted material use
		Material efficiency	Product raw material use efficiency
	Energy use and efficiency	Energy content	Total energy consumed at line
			Transportation energy use
			Idle energy losses
			Percentage of renewable energy usage
		Energy efficiency	Energy use efficiency
	Other resources use and efficiency	Water content	Total amount of water consumed at line
			Percentage of recycled water use
		Water efficiency	Water use efficiency
	Waste and Emission	Waste	Amount of solid waste generated
			Amount of liquid waste generated
			Residue generation intensity
		Emission	Amount of GHG generated
			Hazardous gas emission
		Waste recovery and disposal treatment	Percentage of restricted material recovered (reused, recycled if info available)
			Percentage of consumables recovered (reused, recycled if info available)
			Percentage of used packaging material recovered (reused, recycled if info available)
			Percentage of used raw material/scrapped parts recovered (reused, recycled, remanufactured if info available)

5.3.2.3 Line level societal sustainability performance assessment

The societal assessment must be considered from the related stakeholder's perspective. At the production line level, the most direct and relevant stakeholder is the employees that are working on each station. Therefore, societal sustainability assessment needs to evaluate the impact on the health and safety (cluster) of employees working in the production line.

Similar criteria are discussed and considered in previous literature (Veleva and Ellenbecker, 2001; Winroth et al., 2012; Shuaib et al., 2014; Lu, 2014; Zhang and Haapala, 2015). Therefore, health and safety is an important factor to capture societal performance for a production line. Two sub-clusters can be considered when identifying metrics for this aspect: employee's work environment and work-related injuries and illness, both of which will have a direct effect on the employee health and safety. The metrics are identified by considering the employee's work environment and work-related injuries. The work environment is analyzed by considering the exposure to toxic chemicals, high temperature, high speed components, high voltage, high noise, etc. The injuries are considered from the injury rate and absence due to injuries and illness. Table 5-5 illustrates the metrics for line level societal sustainability performance evaluation.

Table 5-5 Line level societal sustainability performance evaluation

Sub-Index	Cluster	Sub-cluster	Metrics
Society	Health and safety	Employees' work environment	Exposure to corrosive/toxic chemicals
			Exposure to high temperature surfaces
			Exposure to high speed components and splashes
			Exposure to high voltage electricity
			Exposure to high decibel noise
			Physical load index
		Work-related injuries and illness	Injury rate (OSHA incident rate)
			Absence due to injuries or work related illness

5.3.3 *Plant level sustainability performance assessment*

A manufacturing plant consists of multiple production lines all housed under one facility. Therefore, plant level performance can be considered as an aggregation of the performance of all the production lines. However, in addition to the individual production lines, a broader scope, that considers capital, human, and other resources, as well as support services necessary to operate the plant, must be considered. Thus, the clusters and sub-clusters used at the plant level must include all of those considered at the production line level, and more, if necessary. Similarly, the metrics at the plant level, too, will be very similar to that at the line level; additional metrics will be necessary to cover aspects due to the broader scope at the plant level. Figure 5-1 illustrates the relationship between multiple production lines and a plant and how multiple plants could be aggregated to form the enterprise level. A discussion on selecting clusters, sub-clusters and metrics for plant level sustainability performance assessment is presented in the following sections. All the plant sustainability metrics are identified and grouped by studying and reviewing the existing literature about plant sustainability performance evaluation. A detailed list is presented in Appendix B.

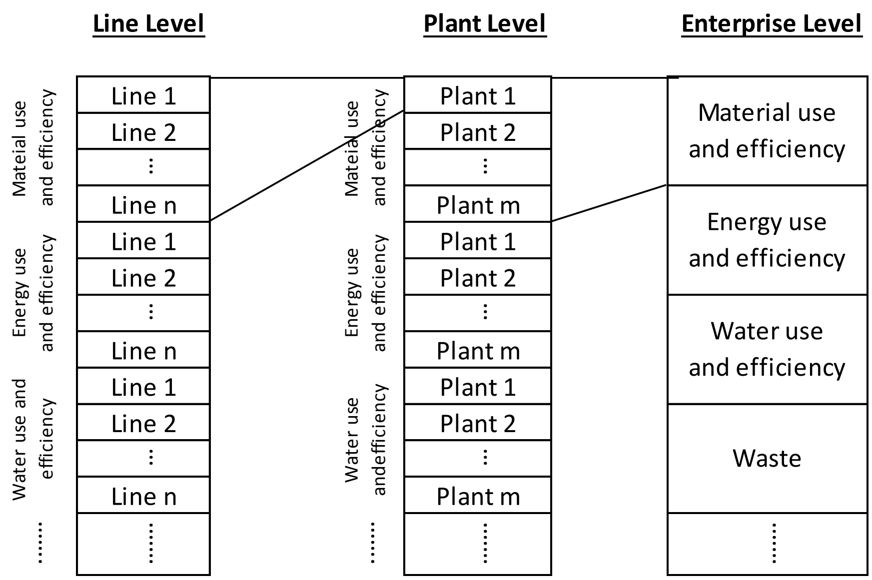

Figure 5.1 Relationship and metrics aggregation among the line, plant and enterprise levels

5.3.3.1 Plant level economic sustainability performance assessment

The clusters and sub-clusters for plant level economic sustainability assessment are the same as those at the line level. As discussed before, several production lines combined together forms a production plant. Therefore, the difference between line and plant levels is the extended boundary over which the data must be collected. The metrics at the plant level are the same as that at line level as shown in Table 5-3.

5.3.3.2 Plant level environmental sustainability performance assessment

In addition to the clusters included at the production line level for environmental sustainability assessment, one more cluster -- product end-of-life (EOL) -- necessary at the plant level. This cluster is included to reflect and evaluate the 6R application for waste reduction at the plant level as discussed in the work of Winroth et al. (2012) and *ProdSI* (Shuaib et al., 2014). Facilitating 6R activities can help to reduce the waste directly disposed to landfill and improve material/component reusability; this can also reduce energy and other resources usage at the plant level. Under this cluster, it measures the percentage of products designed for EOL management and the percentage of products/components recovered can reflect plant level environmental performance. Table 5-6 illustrates the metrics for plant level environmental sustainability performance evaluation.

Table 5-6 Plant level environmental sustainability performance evaluation

Sub-Index	Clusters	Sub-cluster	Metrics
Environment	Material Use and Efficiency	Material Content	Total amount of product material usage
			Total amount of packaging material usage
			Percentage of hazardous material usage
			Percentage of renewable material usage
		Material efficiency and compliance	Product material use efficiency
			Number of notices of violation for hazardous material usage
	Energy Use and Efficiency	Energy content	Total amount of energy usage
			Idle energy losses
			Percentage of renewable energy usage
		Energy efficiency	Energy intensity
	Other resources use and efficiency	Water content	Total amount of water consumption
			Percentage/amount of water reused/recycled
		Water efficiency	Water intensity (water use/unit)
	Waste and Emissions	Waste	Total amount of solid waste generated
			Total amount of hazardous waste generated
			Percentage of waste recovered
			Total amount of liquid waste generated
			Residual generation intensity
			Number of notices of violation for waste generated
		Emissions	Total amount of GHG generated
			Total amount of hazardous gas generated
			GHG intensity
			Number of notices of violation for emission generated
	Product EOL	Product EOL	Percentage of product designed for EOL management
			Percentage of product/component recovered

5.3.3.3 Plant level societal sustainability performance assessment

To evaluate societal sustainability performance at the plant level more comprehensive clusters and sub-clusters, compared to that at line level, must be considered. In addition to the health and safety cluster, now a cluster for stakeholder engagement is included. The stakeholder theory (Freeman, 1984) should be considered when developing the metrics for plant sustainability performance evaluation.

A stakeholder is considered as a person or group that can affect or be affected by an organization. Stakeholder theory implies that corporations have obligations to individuals and groups from inside or outside of the business, including customers, employees, shareholders, suppliers, non-profit groups, government, and the local community, among many others. Because the plant is considered as the unit which manufactures the product without direct involvement in sales, the customers (another stakeholder) are not considered here; it will be relevant when evaluating performance at the enterprise level (Huang and Badurdeen, 2016). Thus, when identifying the metrics for plant level sustainability performance evaluation, employees and other related stakeholders (major focus on community) are considered. Table 5-7 show the metrics for plant level societal sustainability performance evaluation.

Table 5-7 Plant level environmental sustainability performance evaluation

Sub-Index	Clusters	Sub-cluster	Metrics
Society	Health and Safety	Employee health and safety	Work-related incident rate
			Absence due to injuries or work-related illness
			Percentage of workers with work-related disease
			Percentage of workstations with noise level exceeding 85db
			Percentage of workstations with corrosive/toxic chemicals
			Percentage of workstations with high voltage electricity
			Percentage of workstations with high temperature surfaces
			Percentage of workstations with high speed components/splashes
			Percentage of employees receiving safety training
			Number of OSHA citations
	Stakeholders Engagement	Employee diversity and development	Percentage of Employee turnover
			Percentage of employee satisfaction
			Fair and equal treatment for workers
			Average number of hours of employee training per year
			Employee diversity
		Other stakeholders diversity and development	Community quality of life
			Community outreach activities
			Community spending and charitable contributions

5.3.4 *Index-based Sustainability Assessment Method*

To evaluate the line/plant sustainability we define a five-level hierarchical structure starting from metrics, to sub-clusters and clusters to calculate sub-indices, one each for each TBL; finally the sub-indices are aggregated to determine an index that reflects performance. This procedure is followed to compute a Production Line Sustainability Index (*LiSI*) and Plant Sustainability Index (*PlaSI*) via four steps: metrics measurement, normalization, weighting and aggregation. The sequence of steps is illustrated in Figure 5.2 and explained below.

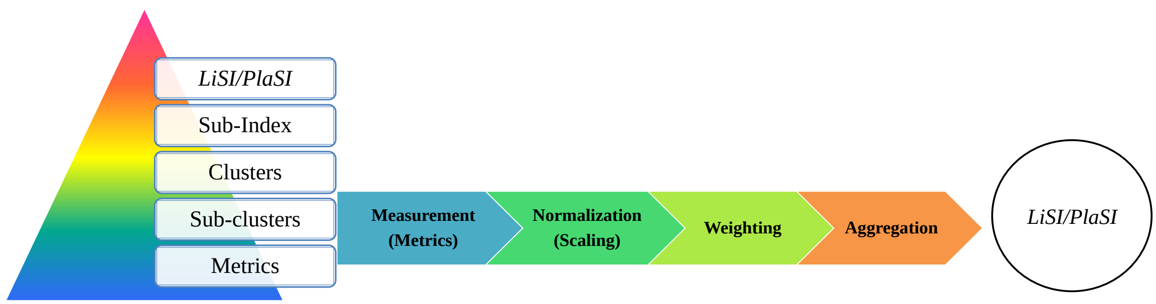

Figure 5.2 *LiSI*/*PlaSI* hierarchy structure and evaluation process

Measurement and normalization

Data measurement is the first step to collect data for each of the metrics. These measured data cannot be summed up together directly due to the inconsistent units of measurements. As a result, normalization is required and has been utilized in most sustainability assessment methodologies (WWF, 1998; Esty et al., 2005; SOPAC, 2005). The normalization method converts the physical measurements into dimensionless scores. There is no single standard normalization method available which can be applied for all the metrics; the normalization of each metric is case-specific and depends on several factors such as the unit of measure, the limits of the measured value, the existence of benchmark or standard reference, etc. The most commonly used normalization methods are benchmark normalization, minimum-maximum and worst-best scenario (Zhou et al., 2012; OECD, 2008). Once the normalization methods are determined, the metrics are normalized to a single scale from 0 to 10, where 0 represents the worst case and 10 represents the best case. Generally, one can assume that a score of 0-4 would indicate a "poor" status, "average" a score of 4-6, "good" a score of 6-8 and "excellent" a score of 8-10. In this work we use the benchmark normalization method and the normalized value of the benchmark is set up as 5, representing average performance. When a quantitative measurement is difficult, subjective normalization can be utilized. The normalized score can be assigned by subjective surveys from industrial experts, customers, academic researchers and/or governmental/non-governmental organizations. Discrete scores can be given from 0-10 based on the subjective evaluation. The measured metrics can be transformed to a normalized value by utilizing the selected normalization methods be it objective or subjective. In the following, a number of normalization methods and the main procedures are presented.

- **Benchmark normalization**

This normalization method calculates the ratio between the indicator and an external benchmark. The normalized indicators can be described in the equation

(5.1), where $I_{ij}^{benchmark}$ is the benchmark for the indicator I from the group of indicator j. In this normalization method, the normalized value is higher than 1 which indicates that the performance of the metric is better than the benchmark. (Zhou et al., 2012; OECD, 2008)

$$I_{N_{i,j}} = \frac{I_{ij}}{I_{ij}^{benchmark}} \quad (5.1)$$

Another benchmark normalization method is also available which can be called percentage over annual difference. This method focuses on the development of the metrics over time which is demonstrated in equation (5.2). The normalized metric is dimensionless. The disadvantage of this method concerns the case t=t_0 which cannot be normalized the given equation. In this case the previous performance of considered metric is set up as the benchmark (Zhou et al., 2012)

$$I_{N_{ijt}} = \frac{I_{ijt} - I_{ij,t-1}}{I_{ij,t-1}} \quad (5.2)$$

- **<u>Minimum-Maximum</u>**

This normalization method normalizes metrics with a positive impact on sustainability by the equation (5.3). When the metric has a negative impact on sustainability, the metrics can be normalized by the equation (5.4). In this normalization method, $I_{i,j,t}^{+}$ and $I_{i,j,t}^{-}$ are the values for metric i from the group j in the year t with positive and negative impacts on sustainability respectively, while the $I^{+}_{N,i,j,t}$ and $I^{-}_{N,i,j,t}$ are the normalized positive and negative indicators respectively. Although the normalization can transform results in a clear compatibility of different metrics, it requires a valid database to be carried out (Zhou et al., 2012)

$$I^{+}_{Nijt} = \frac{I^{+}_{ijt} - I^{+,min}_{ij}}{I^{+,max}_{ij} - I^{+,min}_{ij}} \tag{5.3}$$

$$I^{-}_{Nijt} = \frac{I^{-}_{ijt} - I^{-,min}_{ij}}{I^{-,max}_{ij} - I^{-,min}_{ij}} \tag{5.4}$$

- **Best-worst case scenario**

In this method, a purely best/worst case scenario is considered. Scores are given based on the severity of impact. In order to represent this method clearly, an example of product material recycling is given. The product material recycling ratio could vary from 0% to 100% and the normalized value varies from 0 to 10 respectively. In other words, when the product material recycling ratio is zero, score 0 is given; meanwhile, when the recycling ratio is 100%, score 10 is assigned. Any percentage between 0-100, the corresponding normalized value is assigned.

Weighting

The next step when developing a sustainability index focuses on weighting the individual elements (metrics, sub-clusters, clusters and indices). Weighting is done to assign importance for each element based on their relative importance. Weighting is a very sensitive process which can lead to different results due to different importance assigned. Therefore, it affects the accuracy of the sustainability assessment. Objectivity should be used when in assigning weights for different elements. While there are a number of weighting methods presented in the literature, no standard or universally applied weighting methods can be found in sustainability assessment studies. Many studies use equal weighting (Hermans et al., 2008; Zhou et al, 2012; Shuaib et al., 2014)); others have used the Analytic Hierarchy Process (AHP) (Satty 2008) to obtain weights (Singh et al., 2007). These widely used weighting methods will be introduced in the following part.

- **<u>Analytic Hierarchy Process</u>**

The analytic Hierarchy process was developed by Satty in the early 1970s and is a widely accepted technique for multi-attribute decision making. This method is far more complex and consists of a mathematical approach. It can translate a complex problem into a hierarchy where the top element of the hierarchy is the overall goal of the decision model and the criteria and indicators contributing to the decision are represented at the lower levels. This method requires a pair-wise comparison between each pair of elements. The comparison requires experts to judge how important one element is relative to another element. Based on the comparison the overall weighting factors can be generated. Due to this judgement, inconsistency can be always occurred in this method. Because it is based on people's briefs and it is human nature that they may be inconsistent (Satty 1980, Singh et al., 2007). Moreover, AHP allows both quantitative and qualitative criteria to be in the model and further to assess different levels of criteria.

- **Equal Weighting**

Equal weighting is simple and transparent which assigns the same weight to each element. This implies that all the metrics/sub-clusters/clusters/sub-indices have the same importance. The value of the weights can be calculated by $\frac{1}{N}$ where N is the number of elements at each hierarchy in $LiSI/PlaSI$ and 1 indicates the total weights for considered elements (Hermans et al., 2008; Zhou et al, 2012). Although this method is simple from a scientific perspective, several sustainability evaluation methods have utilized equal weighting method such as Environmental Sustainability Index and European Innovation Scoreboard (Environmental Sustainability Index, 2005; Hermans et al., 2008). The main disadvantage of this method is that it does not truly reflect the relative importance of the aggregated elements and does not reflect reality. However, when there is no other weighting methods that represents valid results, equal weighting method can be considered as a solution.

- **Budget Allocation Process (BAP)**

This weighting method determines the indicator importance based on expert opinion. Generally, the BAP has four different phases: first, experts in the relevant field have to be selected for the assessment. It is necessary that the experts represent a wide spectrum of knowledge and experience. Second, based on their personal judgment of the relative importance, the selected experts have to allocate a "budget" of one hundred points to the indicator set. Then, weights are calculated as average budgets. At the last step, the process could be iterated until convergence is reached. (Hermans et al. 2008; OECD 2008) The main advantages of BAP are its transparent and simple application as well as its short duration. However, it also contains several disadvantages: the weights are fairly subjective and could reflect specific conditions that are not transferable from one factory to another (Zhou et al. 2012).

Aggregation

The final step to calculate the sustainability index is aggregation. The normalized data are systematically aggregated into the next higher level based on the weighting factors assigned to finally calculate the overall sustainability index. During the aggregation of the normalized data, weighting is assigned to each element. Table 5-8 describes the aggregation process where the normalized data are aggregated into the higher level based on the weighting factors assigned.

Table 5-8 Equations of *LiSI/PlaSI* computation

<table>
<tr><th>Levels</th><th>Equations</th></tr>
<tr><td>Index/sub-index</td><td>$LiSI/PlaSI = w_{Ec}Ec + w_{En}En + w_{So}So = w_{Ec}\sum_{i=1}^{r} w_i^c C_i + w_{En}\sum_{j=1}^{s} w_j^c C_j + w_{So}\sum_{k=1}^{t} w_k^c C_k$</td></tr>
<tr><td>Clusters</td><td>$C_m = \sum SC_p w_p^{SC} \quad \forall m$</td></tr>
<tr><td>Sub-clusters</td><td>$SC_p = \sum M_q w_q^m \quad \forall p$</td></tr>
<tr><td colspan="2">$w_{Ec} + w_{En} + w_{So} = 1; \sum w_i^C = 1; \sum w_j^C = 1; \sum w_k^C = 1; \sum w_p^{SC} = 1; \sum w_q^m = 1$

w_{Ec}, w_{En}, w_{So} - Weighting factor for economy, environment, society sub-indices, respectively

Ec, *En*, *So* - Sub-index score for economic, environmental and societal impact, respectively

$w_i^C, w_j^C, w_k^C, w_p^{SC}, w_q^m$ - weighting factor for i^{th}, j^{th}, k^{th} cluster, p^{th} sub-cluster, q^{th} metric, respectively

C_m - Score for m^{th} cluster. r is the number of cluster in the economy sub-index, s are the number of clusters in the environment sub-index and t is the number of cluster in the society sub-index.

SC_p, M_q - Score for the p^{th} sub-cluster, the q^{th} metric, respectively</td></tr>
</table>

5.4 Application Case Study

To demonstrate the proposed method for sustainable manufacturing performance evaluation, the case of a company engaged in satellite television dish production is presented in the following sections. Due to space limitations, only the computation of $LiSI$ is demonstrated; the approach for plant level sustainability assessment will be similar but must consider the entire plant (with all production lines) and all relevant metrics at that level.

5.4.1 Case company background

A company located in southeast Kentucky that produces satellite television dishes, also used in some previous studies (Faulkner et al., 2012; Faulkner and Badurdeen 2014; Brown et al., 2014), is considered here. The company produces roughly 20,000 satellite dishes per month. Figure 5.3 shows the steps involved where steel coils, labor, energy and other materials are used as inputs to produce finished dish kits. Steel arrives at the plant in coils which is then stamped per design specifications into a final shape. The dish is then washed in a five-stage wash system to remove any oils or impurities from previous process steps. It is then dried in a dry-off oven, which is considered as specialty storage, before powder paint is applied. Following the application of the powder paint, a cure oven is used for drying. The wash, paint, and cure oven processes all use the same conveyor system. Once the dish is pulled from the conveyor system after the cure oven process, appropriate emblems are then pad printed onto the dish. The dish is then transported to another location to be kitted with other accessories before it is shipped to the customer. The dish is transported via forklift and truck between operations and warehouse location, respectively.

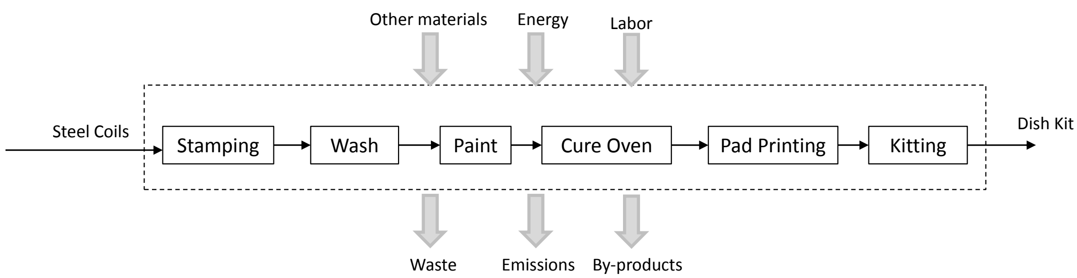

Figure 5.3 Satellite Television Dish Production Line

(Faulkner and Badurdeen, 2014)

5.4.2 *Application of the approach*

In the assessment, the proposed *LiSI* is applied to assess the sustainability performance of the satellite dish production line. Thereafter, the results from each aspect of TBL are presented separately.

5.4.2.1 Economic sustainability assessment

The manufacturing cost for satellite television dishes production includes direct costs such operation energy cost, direct labor cost, product raw material cost, etc., and many indirect costs (cost values are adjusted to mask actual costs) as shown in Table 5-9. Manufacturing cost is calculated by aggregating all the related costs together. For the line operational performance, lead time, productivity, and labor efficiency are considered. All the measured data are compared and normalized with the benchmark (using a score of 5) for normalization. The normalized score is then aggregated to get the score of sub-index by applying the equal weighting method. For the manufacturing cost, all the related costs data are collected and considered together. Table 5-9 shows economic sustainability evaluation of satellite television dished production line.

Table 5-9 Economic sustainability evaluation of satellite television dish production line

Sub-Index	Value	Cluster	Value	Sub-cluster	Value	Metrics	Norm-alized	Data	Unit
Economy	7.39	Manufacturing Cost	8.02	Direct cost	8.02	Operation energy cost	8.02	56.34	$/unit
						Direct labor cost (operation labor)			
						Product raw material cost			
						Packaging related cost			
				Indirect cost		Scrap cost			
						Process-related consumables cost			
						Processing tools-related cost			
						Water cost			
						Maintenance cost			
						Cost of PPE, jigs/fixtures, equipment			
						Other non-operational energy cost			
						Indirect labor cost (maintenance, cleaning, material handler. labors)			
						Training cost			
						Cost of waste disposal treatment			
		Operational Performance	6.77	Operational efficiency	6.77	Lead time	5.79	12.64	days
						Productivity	5.11	125	#/hr
						Utilization of manual labor (labor efficiency)	9.4	94	%

5.4.2.2 Environmental sustainability assessment

Environmental assessment is conducted considering the impacts of inputs and outputs of the production line (inputs: material, energy, and water resources; outputs: wastes and emission generated). Based on the proposed approach, the measured data are compared with the benchmark to get the normalized score for each metric. The normalized score is then aggregated to get the score of sub-index by applying the equal weighting method. Table 5-10 shows the environmental sustainability evaluation of the satellite television dished production line.

5.4.2.3 Societal sustainability assessment

Societal sustainability assessment is considered from the health and safety of the employees who are the direct stakeholders of the production line. All the measured data are compared and normalized with the benchmark to obtain the normalized score. The normalized score is then aggregated to get the score of sub-index by applying the equal weighting method. Table 5-11 shows the sustainability evaluation of satellite television dished production at societal aspect.

Table 5-10 Environmental sustainability evaluation of satellite television dish production line

Sub-Index	Value	Cluster	Value	Sub-cluster	Value	Metrics	Norm-alized	Data	Unit
Environment	6.98	Material use and efficiency	7.56	Material content	8.63	Total weight of product raw material use	6.5	8.25	lb/unit
						Packaging material use efficiency	10	100	%
						Total weight of packaging material use	8	2	lb/unit
						Mass of restricted material use	10	0	%
				Material efficiency	6.50	Product raw material use efficiency	6.5	65	%
		Energy use and efficiency	6.45	Energy content	5.60	Total energy consumed at line	5.67	2800	kWh/unit
						Transportation energy use	6.73	980	kWh/unit
						Idle energy losses	10	0	kWh/unit
						Percentage of renewable energy usage	0	0	%
				Energy efficiency	7.30	Energy use efficiency	7.3	73	%
		Other resources use and efficiency	5.35	Water content	2.89	Total amount of water consumed at line	5.79	295	gallon/unit
						Percentage of recycled water use	0	0	%
				Water efficiency	7.8	Water use efficiency	7.8	78	%
		Waste and Emission	8.56	Waste	6.93	Amount of solid waste generated	6.5	2.91	lb/unit
						Amount of liquid waste generated	7.8	64	gallon/unit
						Residue generation intensity	6.5	35	%
				Emission	8.75	Amount of GHG generated	7.5	2.5	kg/unit
						Hazardous gas emission	10	0	kg/unit
				Waste recovery and disposal treatment	10	Percentage of restricted material recovered	-	-	%
						Percentage of consumables recovered	-	-	%
						Percentage of used packaging material	-	-	%
						Percentage of used raw material/scrapped parts recovered	10	100	%

Table 5-11 Societal sustainability evaluation of satellite television dish production line

Sub-Index	Value	Cluster	Value	Sub-cluster	Value	Metrics	Norm-alized	Data	Unit
Society	8.16	Health and safety	8.16	Employees' work environment	6.32	Exposure to corrosive/toxic chemicals	4	3	dimensionless
						Exposure to high temperature surfaces	6	2	dimensionless
						Exposure to high speed components and splashes	6	2	dimensionless
						Exposure to high voltage electricity	10	0	dimensionless
						Exposure to high decibel noise	4.76	89	dB
						Physical load index	7.17	31.7	dimensionless
				Work-related injuries and illness	10	Injury rate (OSHA incident rate)	10	0	#
						Absence due to injuries or work related illness	10	0	#

5.4.2.4 Results Analysis

To calculate the final *LiSI* for the satellite television dish production line sub-indices are aggregated with equal weighting. A spider diagram, with the radial axis on a scale from 0 to 10, to show the sub-indices at the cluster level, is illustrated in Figure 5.4 (baseline line performance, corresponding to a value of 5, is shown using the dashed blue line). When equal weighting is applied, these sub-indices lead to an overall *LiSI* score of 7.51 for the production line. Based on the calculation of *LiSI*, it is not difficult to find that the sustainability performance of the production line is better than that of the benchmark. The performances for manufacturing cost, waste and emission, health and safety are very good, achieving scores of 8. However, there are opportunities to improve the performance along other clusters. For example, potential improvements are feasible by reducing water content (sub-cluster's value of 2.89) and energy content (sub-cluster value of 5.60) to minimize negative impacts to environment. These assessments can help the engineers and managers to identify areas of poor performance in the production line and implement strategies to achieve a more efficient and effective performance.

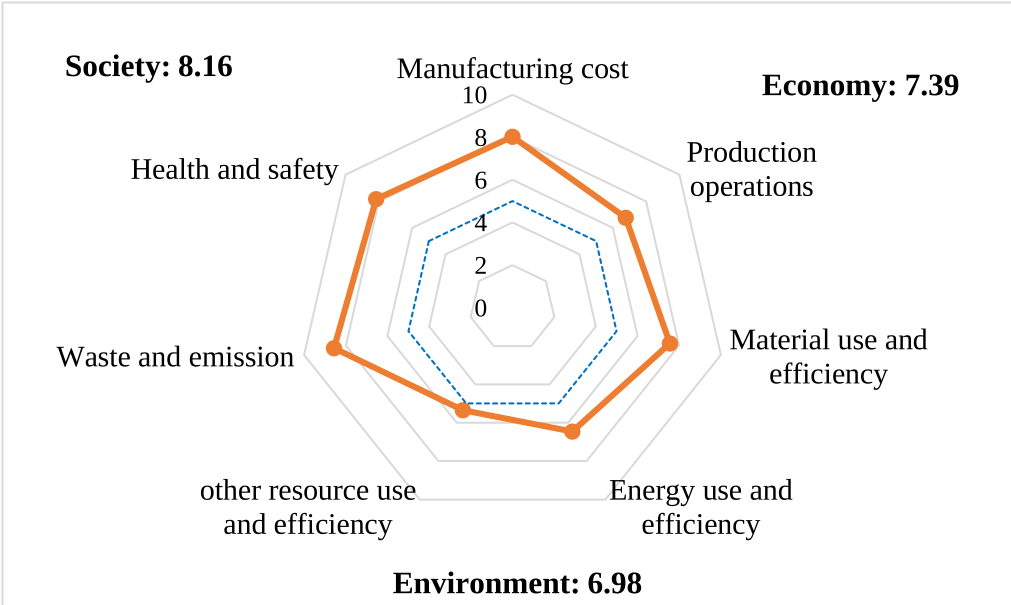

Figure 5.4 Visual representation at the cluster level

As a comparison, the summary of results from Sustainable value stream mapping (Sus-VSM) of the same satellite dish production line from Faulkner and Badurdeen (2014) is shown in Table 5-12. While the Sus-VSM is useful in visualizing sustainability performance of the production line at a high and broader level, it is evident that the results from the Sus-VSM is limited; it is not as comprehensive as that obtained from *LiSI* and does not enable an in-depth assessment, as described above. The *LiSI* provides a more comprehensive evaluation along the three TBL aspects and compares with the benchmark to present the sustainability extent for the evaluated production line in the same manufacturing industry.

Table 5-12 Results from Sus-VSM (Faulkner and Badurdeen, 2014)

Metrics	Value
Total Leadtime	12.64 days
Value Added time	1,952 Secs
Percentage Value Added Time	< 1%
Process Water Consumption	231 gallons/unit (64 gallons/unit lost)
Raw Material Usage	8.25 lbs/unit
Material Utilization Rate	67%
Energy Consumption	3.78 KWh/unit

5.5 Summary

Published literature is lacking comprehensive sustainability performance measurement tools at the production line and plant levels that concurrently consider all aspects of the TBL, enabling capabilities that will facilitate adopting total life-cycle practices, and closed-loop flow enabling 6R practices. This study proposed an index-based method to evaluate the production line and plant level sustainable manufacturing performance. First, a metrics-based framework for production line and plant level sustainability performance evaluation is formulated by assessing and updating currently available sustainability metrics at product/process, production line, work cell and plant/factory levels. The Production Line Sustainability Index (*LiSI*) and Plant Sustainability Index (*PlaSI*) are developed as a five-level hierarchy structure with: metrics, sub-clusters, clusters, sub-indices, index. The indices can be calculated in four steps which are metrics measurement, normalization, weighting, and aggregation. The proposed sustainability indices would help companies measure sustainability performance at the production line and plant levels to find areas to improve the overall sustainability. In future work, more case studies are needed in different industries and types of production lines/plants to validate and improve the proposed metrics and index-based method.

Chapter 6 Sustainable Manufacturing Performance Evaluation at the Enterprise Level: Index- and Value-based Methods

6.1 Introduction

The "system" used for sustainable manufacturing varies in scope from the production line to the plant to the enterprise (and beyond to the supply chain). In this study the focus is on enterprise level sustainable manufacturing performance evaluation. Several indicators and methodologies are available for sustainability performance evaluation at the enterprise level. However, none cover all the three pillars of sustainability known as the Triple Bottom Line (TBL), focus on all stages of a product's life cycle, or the 6R's to comprehensively assess sustainable performance at the systems level.

Most of the widely known methods, including the Global Reporting Initiative (GRI, 2014) are general and not approached from a sustainable manufacturing perspective. Other methods presented in literature, such as those developed by Figge and Hahn (Figge and Hahn, 2004) and Alexandre et al. (2007) are not geared to evaluate sustainable manufacturing performance at the enterprise level by progressively integrating metrics from lower levels (e. g. line, plant). These lower level performances can be evaluated by appropriately combining and consolidating product (Shuaib et al., 2014) and process (Lu, 2014) metrics as discussed in the previous chapter. In an effort to address this gap, this research presents a comprehensive framework for sustainable manufacturing enterprise level performance assessment. The metrics identified using the framework can be used in different ways to evaluate sustainable manufacturing performance at the enterprise level. One approach is to develop an index for enterprise level assessment by progressively consolidating the metrics.

Quantifying sustainable value generated is another way of measuring enterprise sustainable manufacturing performance and requires incorporating environmental and societal value added, in addition to economic value generated. Existing literature on sustainable value measurement is, however, limited. Following a review of value assessment-related literature, we also present a value-based method for sustainable manufacturing performance assessment at enterprise level. An industry case study is then used to demonstrate the application of the index-based and value-based methods to evaluate the enterprise sustainability performance.

The remainder this chapter is organized as follows. Section 6.2 provides a literature review, primarily on enterprise sustainability performance evaluation. Section 6.3 describes the development of sustainable manufacturing performance measurement house by integrating product, process and system metrics. Section 6.4 presents the framework and metrics development for index-based enterprise level performance evaluation. The value-based sustainable manufacturing performance evaluation method is introduced in Section 6.5. Section 6.6 presents the application of the proposed index-based and value-based methods to an industrial case study. Concluding remarks and future work are covered in Section 6.7.

6.2 Current State of Art

Enterprise sustainability has been defined as "meeting the needs of the firm's direct and indirect stakeholders without compromising its ability to meet future stakeholder needs as well" (Dyllick and Hockerts, 2002). Over the last decade, several publications have explored sustainability performance evaluation at the enterprise level. Some of them have been presented by institutional bodies while others are academic efforts. These are briefly discussed in the following sections.

6.2.1 Institutional frameworks

The most well-known set of enterprise sustainability indicators are the 91 measures included in the Global Reporting Initiative (GRI) G4 reporting guidelines (GRI, 2014). The GRI guidelines have been voluntarily applied in over 1000 companies worldwide in various sectors, such as automotive, chemicals, construction, energy, supermarket, mining, etc. It includes sustainability metrics covering three dimensions – economic, environmental and social categories –

where the social category is further broken down into four sub-categories. Guidelines are the focal point of the GRI and they help reporting organizations disclose most critical impacts on TBL aspects; they can provide reliable, relevant and standardized information to assess opportunities and risks. The highlight of GRI guidelines is that they are universally applicable to organizations of all types and sectors, large and small across the world. However, GRI only provides guidelines for sustainability evaluation without detailed measurement steps. In addition, the sustainable manufacturing requirements of total life-cycle and 6R approaches are not explicitly included.

Corporate Responsibility 100 is a ranking compiled by the Corporate Responsibility Magazine (CRM) (CRM, 2016) to evaluate enterprise sustainability performance based on 7 categories: climate change, employee relations, environmental, financial, governance, human rights and philanthropy and community support. The CRM collects and analyzes the data from corporate web sites, sustainability reports, company 10-Ks and other public resources. The relevant performance is then ranked from 1-1000 with 1 being the best. The relative weights for the 7 categories are decided by the methodology committee and the final rank is calculated by aggregating the ranks. The CR100 list and computations are done by the CRM groups, not the company itself. Thus, while the ranking helps the public image as being a sustainability-oriented company, CR 100 does not really help with evaluating enterprise performance to help with sustainable manufacturing decision making. Another measure of enterprise sustainability performance is the Dow Jones Sustainability Index (DJSI), applied in 2500 publicly traded companies. The DJSI includes 12 economic, 12 environmental, and 14 social indicators. A company's total sustainability score ranges from 0-100 and is obtained by summing all question scores. Once the score has been calculated, the relative enterprise sustainability performance within the same industry can be determined (ROBECOSAM, 2015). The shortcoming of this method is that the calculated scores are totally subjective.

One more enterprise sustainability performance evaluation method is proposed by the National Association for Environmental Management (NAEM, 2011). The methodology was applied to 75 members of the NAEM through a survey of relevant metrics. There are 59 identified metrics across six major subject areas: resources consumption, resource reservation, emission and waste management, health and safety, compliance, and management-oriented metrics and several industry-specific sets of indicators have been published. The shortcoming of this method is that not all the stakeholders are considered in the proposed metrics. The Institution of Chemical Engineers (IChemE) has formulated sustainability metrics covering the TBL which are broken down into sub-indicators. This set of indicators can be used to measure the sustainability performance of an operating unit in the process industries (Tallis, 2002). However, no detailed measurement steps for the indicators are presented.

6.2.2 Academic studies

In Dyllick and Hockerts's work (Dyllick and Hockerts, 2002), a conceptual development of enterprise sustainability considering the TBL was proposed where the term of efficiency and effectiveness were considered and compared. In another early work, Azapagic and Perdan (2000) proposed a broadly applicable framework for industrial sustainable development, which consisted of over 30 indicators. The emphasis of this work is that specific indicators should be selected on a case-by-case basis. As a continuing research, Azapagic (2004) published a highly cited paper on a sustainable development index for the mining industry in 2004 which adapted and extended the indicators proposed by the 2000 version of the GRI guidelines. The identification of relevant stakeholders and consideration of their interest were emphasized for indicators development. A total of 24 economic, 63 environmental and 45 social indicators were proposed.

Another set of core indicators for enterprise sustainability evaluation was proposed by Veleva and Ellenbecker (Veleva and Ellenbecker, 2001). This indicator framework composes of five levels which represent the five main steps in moving toward more sophisticated indicators of sustainable production. These five levels are: company compliance/conformance indicators; company material use and performance indicators; company effects indicators; supply chain and product life-cycle indicators; and sustainable system indicators. The proposed 22 core indicators including energy and material use, natural environment, economic performance, community development and social justice, workers and products were accompanied by detailed guidance on their application. Singh et al. (2007) developed a sustainability performance index for the steel industry. This index addressed two additional dimensions, organizational governance and technical aspects except for TBL. Another framework and metrics for enterprise sustainability assessment was proposed by Badurdeen et al. (2012). This work addressed that total life-cycle and 6R methodology should be incorporated for systems level metrics development. A total 26 economic, 17 environmental and 28 societal metrics were proposed. However, their work fell short of proposing how the metrics can be integrated for performance evaluation.

Keeble et al. (2003) presented two case studies for developing enterprise sustainability indicators. The first case study established nine indicators to help measure enterprise sustainability performance through implementing a five-step approach. In the second case study, 69 sustainability indicators applicable to the project-level were developed. The involvement of external stakeholders in the development of the indicators and application of existing standards as reference points were emphasized. In another application work, Krajnc and Glavic (2005) developed a composite sustainable development index for corporations. A seven-step process for developing the composite index was employed. The presented composite index consisted of 6 economic, 22 environmental and 10 social indicators. They also applied the index in a case study to compare two multinational oil companies on the selected indicators, including 4 economic, 6 environmental and 4 social indicators.

The methods reviewed above have been developed by a large variety of organizations such as academia, industry, international communities and nongovernmental organizations. The importance of sustainability at multiple different application domains has been emphasized. Focus was mainly on the sustainability indicators and sustainability performance assessment. All methods quantify or qualify the metrics or indicators. Some methods solely provided the guidelines to improve sustainability performance. Some aggregated the metrics or indicators to calculate an overall index for sustainability evaluation and comparison. However, many of these methods either considered TBL partially and/or ignored the importance of the post-use stage from total life-cycle stage point of view. The extent of incorporating the concept of 6R, which is essential for achieving closed loop of material flow and provide extra value, is not incorporated by any. Table 6-1 summarizes the above reviewed work in terms of the extent of detail involved as well as TBL, 6R, and total life-cycle considerations. There is a need to develop an approach to cover the gap highlighted in Table 6-1 to measure sustainable manufacturing performance at the enterprise level.

Table 6-1 Comparison of Enterprise Level Sustainability Assessment Methods

Source	Year	TBL	TLC	6R
GRI	2014	√	√p	×
CRM	2016	√	√p	×
DJSI	2015	√	√p	×
NAEM	2011	√	√p	×
IChemE	2002	√	√p	×
Dyllick and Hockerts	2002	√	×	×
Keeble et al	2003	√	×	×
Azapagic	2004	√	√p	×
Krajnc and Glavic	2005	√	√p	×
Veleva and Ellenbecker	2001	√	√	×
Singh et al.	2007	√	√p	×
Badurdeen et al.	2012	√	√p	√p
√= concept considered; ×=concept not considered; √p=concept partially considered; TLC=total life-cycle.				

6.3 Integrating Product and Process Sustainability Metrics for Enterprise Sustainability Assessment

A significant amount of research has focused on developing more sustainable products and processes to promote sustainable manufacturing. At the product level, this means moving from the practice of going from cradle-to-grave to cradle-to-cradle (Jawahir et al., 2006). Most previous research focuses merely on pre-manufacturing, manufacturing and use stages of a product life-cycle. The total life-cycle approach which incorporates upstream suppliers and downstream customers through the post-use stage should be considered when sustainably manufacturing more sustainable products.

However, just focusing on the four life-cycle stages alone is not sufficient. Multiple life-cycles, essential for optimal resources utilization and minimal environmental impacts, must also be considered. These emphases on total life-cycle and multiple life-cycles require the implementation of 6R methodology, which was proposed by Jawahir and Dillon (2007). The 6R methodology includes Reduce, Reuse, Recycle, Recover, Redesign, Remanufacture that is an improvement from 3R, which only includes Reduce, Reuse, and Recycle. The 6R shifts material flow from an open-loop, single life-cycle to a closed-loop, multiple life-cycles. Manufacturing processes are used to manufacture the products. More efficient resource consumption, emission reduction, waste management as well as health and safety improvement are all necessary to promote manufacturing process sustainability. Performance at the systems level is affected by processes used; they both affect product sustainability. Therefore, metrics should be aggregated from these two levels, as suitable, to evaluate systems level performance.

The measurement framework design guidelines presented in (Neely et al., 2002) were adapted to develop the sustainable manufacturing measurement approach that is visualized as a 'house', (details are discussed in Chapter 4.2). In the following section, we present two methods to evaluate sustainable manufacturing performance at the enterprise level based on this framework.

6.4 Index-based Sustainable Manufacturing Performance Evaluation Method: Enterprise Sustainability Index (*EnSI*)

In a manufacturing system, multiple manufacturing processes are combined into workstations and several workstations are combined to create a production line. A manufacturing plant can have many production lines. Finally, the plants (production department) and other functional departments together forms the enterprise. Therefore, the manufacturing process can be considered the fundamental unit from which evaluating sustainable manufacturing performance of an enterprise must be started. The Process Sustainability Index (*ProcSI*) developed by Lu (2014) is one of most comprehensive tools available for manufacturing process sustainability evaluation. The *ProcSI* considers metrics in all TBL aspects and incorporates 6R concept for waste reduction and is organized into six clusters: manufacturing cost, energy consumption, environmental impact, waste management, operational safety, and personnel health. In this study, *ProcSI*, its clusters and metrics are used as one of the main inputs to incorporate process-related aspects for enterprise level evaluation.

Product sustainability also has to be considered when developing metrics for enterprise sustainability performance evaluation. The success or failure of an enterprise primarily depends on whether the products can win market share. Whether products can meet the customer's preferences, comply with relevant environmental regulations or not, can directly affect its sustainability performance. These aspects are directly affected by how a product is manufactured and made available to the customer using the production lines, plants, enterprise and supply chain. Therefore, when developing metrics for the enterprise, criteria/clusters related to and affecting a product's performance must be considered; system level capabilities necessary to enable product sustainability and to what extent the system can meet those requirements must be determined.

In order to enable the above, product sustainability evaluation tools have been reviewed. The product sustainability index (*ProdSI*) developed by Shuaib et al.

(2014) has a set of comprehensive sustainability metrics for product sustainability evaluation organized into a five-level hierarchical structure including: metrics, sub-clusters, clusters, sub-indices, and index. The *ProdSI* has thirteen clusters in total. There are: (a). three clusters from 'Economy' as initial investment, direct/indirect cost and overhead, benefits and losses; (b). five clusters from 'Environment' as material use and efficiency, energy use and efficiency, other resources use and efficiency, waste and emission, product end-of-life; (c). five clusters for 'Society' as product safety and health impact, product societal impact regulations and certification, product quality and durability, functional performance, product end-of-life management. In this study, we use *ProdSI*, its clusters and metrics as another main input when determining metrics, sub-clusters and clusters for enterprise performance evaluation.

For enterprise level evaluation, we propose a five-level hierarchical structure in the sequence of individual metrics, sub-clusters, clusters, sub-index, and the index. Following a thorough review of clusters of *ProcSI*, *ProdSI* and all the different enterprise level evaluation schemes presented in the literature, we propose nine clusters for the new enterprise level sustainability performance evaluation. Each cluster represents an area of importance for enterprise sustainability is determined. The nine clusters are: net profit, capital charge from Economy; material use and efficiency, energy use and efficiency, other resources use and efficiency, waste and emission, product end-of-life from Environment; health and safety, stakeholder engagement from Society. To better reflect the context of assessment, they are further divided into sub-clusters and metrics are identified for each sub-cluster. The metrics are sequentially aggregated at sub-cluster and cluster levels to develop sub-indices for economic, environmental and societal aspects. The sub-indices are then aggregated to compute the Enterprise Sustainability Index (*EnSI*). Table 6-2 shows a comprehensive of coverage of the clusters used in the product (from *ProdSI*), process (from *ProcSI*) levels, production line (*LiSI*) level, plant (*PlaSI*) level, and those proposed for the enterprise level.

Table 6-2 Comparison of clusters for sustainability performance evaluation for *ProdSI*, *ProcSI*, *LiSI*, *PlaSI* and *EnSI*.

Clusters	Economy							Environment								Society								
	Initial investment	Direct/Indirect costs and overhead	Benefits and losses	Net profit	Capital charge	Operational Performance	Manufacturing cost	Material use and efficiency	Energy use and efficiency	Other resources use and efficiency	Waste and emission	Product EOL	Energy consumption	Waste management	Environmental impact	Product safety and health impact	Product societal impact regulations and certification	Product quality and durability	Functional performance	Product EOL management	Health and safety	Stakeholder engagement	Operational safety	Personnel health
ProdSI	√	√	√					√	√	√	√	√				√	√	√	√	√				
ProcSI							√						√	√	√								√	√
LiSI						√	√	√	√	√	√										√			
PlaSI						√	√	√	√	√	√										√	√		
EnSI				√	√			√	√	√	√	√									√	√		

As can be observed, some clusters from *ProdSI* and *ProcSI* are included in *EnSI*, directly or with some minor modifications. This reflects the fact that some aspects of product performance and process performance must be integrated (at enterprise level) because enterprise level performance is a reflection of results at the product and process levels.

It is important to note that *LiSI* and *PlaSI* have additional economic clusters as operational performance comparing to *ProcSI*. At the societal aspect, *LiSI* and *PlaSI* combine health and safety impacts as cluster of health and safety. In addition, *PlaSI* considers additional societal cluster as stakeholder engagement. Also note that additional clusters are included in *EnSI* to assess aspects only relevant at the enterprise level (e.g.: net profit, capital charge, stakeholder engagement, etc.). Table 6-3, Table 6-4 and Table 6-5 present the entire set of metrics for enterprise sustainability evaluation including the relevant sub-indices, clusters, and sub-clusters. The metrics were identified following a thorough review of literature and previous work. Relevant metrics from *ProdSI, ProcSI, LiSI* and *PlaSI* were included, in some cases with some modification, to suit the scope at the enterprise level. Coverage of enterprise level operations' influence on pre-manufacturing, manufacturing, use and post-use stages were also considered when selecting metrics. When selecting sustainability metrics for enterprise performance evaluation, it is also important to include metrics that can assess both the concept efficiency and effectiveness. Enterprise long-term sustainability performance depends not only on the efficiency (e.g.: by using less of a certain resource), but also on the effectiveness of the decisions made (e.g.: avoiding use of toxic materials). Therefore, at this stage, an effort was made to identify and include both efficiency and effectiveness of sustainable manufacturing performance. For example, from the environmental point of view, the metrics on material/energy/water intensity is used to measure the resource usage efficiency; metrics for renewable energy usage/ recycled water usage are used to capture the effectiveness.

Table 6-3 Enterprise level sustainability metrics at Economic aspect

Sub-Index	Cluster	Sub-Cluster	Metrics
Economy	Net Profit	Profit from Operations	Sales revenue
			R&D expenditure
			Material cost
			Energy cost
			Labor cost
			Supplies cost
			Water cost
			Transportation cost
			Warehouse cost
			Penalties cost
			Other Expenses
		Taxes	Taxes
	Capital Charge	Current Assets	Inventory
			Other current assets
		Fixed Assets	Facilities
			Equipment
			Other fixed assets
		Cost of capital	Cost of capital

Table 6-4 Enterprise level sustainability metrics at environmental aspect

Sub-Index	Cluster	Sub-Cluster	Metrics
Environment	**Material Use and Efficiency**	Material efficiency	Material intensity
		Material content	Non-hazardous material used
			Hazardous material used
			Recycled material used
			Percentage of restricted material use
			Percentage of recycled material use
			Environmental compliance ratio of restricted material use
	Energy Use and Efficiency	Energy content	Percentage of renewable energy usage
			Renewable energy usage
			Non-renewable energy usage
		Energy efficiency	Energy intensity
	Other Resource Use and Efficiency	Water efficiency	Water intensity
		Water content	Fresh water used
			Water reused/recycled
			Percentage of water recycled/reused
	Waste and Emission	Waste	Mass of non-hazardous waste landfilled
			Mass of non-hazardous waste recycled
			Mass of non-hazardous waste reused
			Mass of hazardous waste generation
			Mass of hazardous waste recycled
			Mass of hazardous waste reused
			Percentage of non-hazardous waste recycled/reused
			Percentage of hazardous waste recycled/reused
			Total waste generation intensity
			Environmental regulatory compliance of waste generation
		Emission	Greenhouse (GHG) gaseous emission
			GHG release intensity
			Hazardous gasous emission
			Ruduction of hazardous gasous emission
			nvironmental regulatory compliance of gaseous emission generatio
	Product EOL	Product EOL	Percentage of products landfilled
			Percentage of product EOL recovered
			Mass/number of product not recovered at EOL
			Mass/number of product recycled
			Mass/number of product reused
			Mass/number of product remanufactured

Table 6-5 Enterprise level sustainability metrics at societal aspect

Sub-Index	Cluster	Sub-Cluster	Metrics
Society	Health and Safety	Employees	Percentage of emloyees receiveing safety trainning
			Employees exposed to high-risk work environment
			Work-related injuries and incidents rate
		Customer	Customer injury rate
		Other stakeholder related	Health/safety risk to community
	Stakeholder Engagement	Supplier diversity and development	Local sourcing
			Supplier support & development
			Percentage of sustainability-oriented suppliers
		Employee diversity and well-being development	Employee training
			Employee diversity
			Employee turnover
		Customer satisfaction and development	Repeat customers
			Product satisfaction rate
			Number of customer compliants (including these affected by recalls)
		Product end-of-life practice	Job creation from product EOL processing
			Reduction of product disposed directly to landfill
			Benefits to society by virgin resource saving
		Other stakeholders diversity and development	Numer of community outreach/volunteering/engagement activities
			Local community hiring percentage

The process for evaluating *EnSI*, which includes data measurement, normalization, weighting, and aggregation is similar to *LiSI* as shown in Chapter 5.3.4. The difference is that methods to evaluate enterprise economic performance are well established. Therefore, we use the method proposed by Lambert (2008) for Economic value added (EVA) to compute enterprise economic sustainability (Ec) or the economic sub-index.

6.5 Value-based Sustainable Manufacturing Performance Evaluation Method: Sustainable Value Added Assessment

As opposed to using an index-based as described in the previous section, a value-based approach can potentially be used to evaluate enterprise sustainable manufacturing performance. Economic value added (EVA) (Lambert, 2008) is a measure that can be applied to assess whether a company operates at a profit or loss and is adding (or losing) economic value. While enterprise sustainable value added is discussed in literature, an acceptable method to measure this has not been proposed. This section will first introduce relevant literature on sustainable value and existing sustainable value measurement methods. From the study of the strengths and drawbacks of these methods, a new sustainable value added assessment approach at enterprise level is proposed.

6.5.1 Related work: value vs. sustainable value

Value has been defined as "the regard that something is held to deserve" (Oxford, 2015). Value is also defined as proportional to the needs/functions of product (process) divided by resources used (Figge and Hahn, 2004; Catarino et al., 2010). Value is whatever the customer feels is valuable, where the unique difference is that value for customer reflects the value-in-use; for a merchant, it reflects tangible value such as economic income, and intangible value such as company and brand reputation. The concept of value has been mentioned a few times in lean manufacturing. As a systematic method used in manufacturing, lean as a long-term philosophy has emphasized the need to generate value for the customer, society, and the economy. Moreover, the quality for customer drives the value proposition. The definition of value in lean is mainly considered from the perspective of customer and the company itself. The company has to take their best information about customer value and translate it into specifications for the product/service they are going to provide. Activities of any organization carried out to meet the customer needs can be divided into three types of work: (1). value-added work; (2). non value-added but necessary to complete value-added work (necessary waste); and (3). non-value added work. The value-added work must be those activities that: (1) the customer is willing to pay for this activity; (2) it must be done right the first time; (3) the activity must somehow change the product or service in some manner. The second category of work is non value-added work but necessary to complete the value added work as required by law or government requirements. Non-value added work involvess activities not necessary for meeting customer's demand and those which can be eliminated through continuous improvement to allow product flow at the pull of the customer in pursuit of perfection. Thus, non-value added activities should be eliminated from the company's processes to streamline the value-added activities. The relationship between value-added and non value-added activities can be identified as increasing the portion of value-added work while reducing the portion of non value-added work (Saito and Saito, 2012). Value analysis, has been defined as a process of systematic review that is applied to existing product designs to compare the product function required by a customer to meet requirements at the lowest cost consistent with the specified performance and reliability needed (Rich, 2000). The value of a product can be improved by considering two elements, the first concerns the use of the product (known as "use value") and the second source of value come from the ownership ("esteem value").

Another perspective to view value is from the shareholders or investors perspectives. Rappaport (1986) provided managers and investors with the practical tools needed to generate superior returns and presented a new and in-depth assessment of the basic principles for generating shareholder value. A case study of Duracell International by Gillette was analyzed which enabled to understand the critical information when assessing the risks. (Rappaport, 1986)

The concept of shareholder value is also mentioned in Hart and Milstein's work (Hart and Milstein, 2003). They proposed a framework of key dimensions of shareholder value applied the time and space concept to demonstrate shareholder value. The vertical axis shows the needs of managing the current business while creating future technology and predicting additional markets. The horizontal axis shows the needs for protecting and improving internal management and operational skills while incorporating new knowledge and technologies from outside.

Based on the framework of shareholder value, they proposed a sustainable value framework. According to Hart and Milstein (2003) corporate sustainable value can be created considering the full range of challenges and opportunities. In the sustainable value framework, each driver of sustainability with associated business strategies and practices was illustrated in Figure 6.1. The strategy of developing the next generation of clean technology to drive future economic growth is applied in a growing number of firms. BP and Shell are ramping up investments in solar, wind, and other renewable technologies that might ultimately replace their core petroleum businesses. In the automotive sector, Toyota and Honda have already entered the market with hybrid power systems in their vehicles, which dramatically increase fuel efficiency.

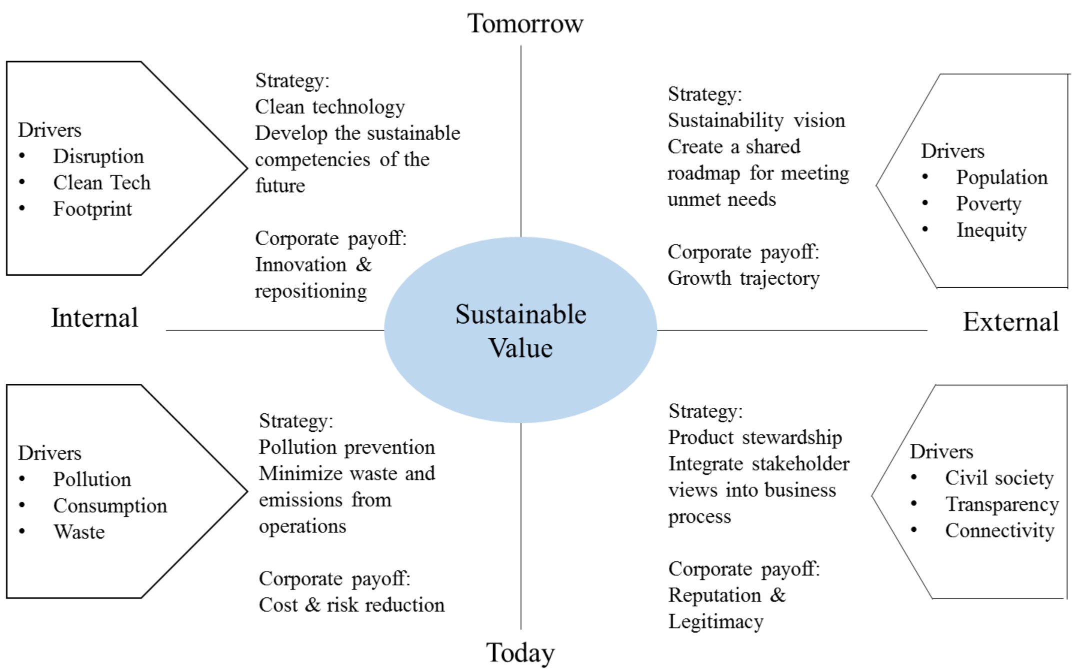

Figure 6.1 Dimensions for Sustainable Value (Hart and Milstein, 2003)

The change in perspective necessary when describing sustainable value is clear from the work of Laszlo (2003). Their sustainable value framework, shown in Figure 6-2, describes enterprise performance using both shareholder value and stakeholder value. According to this framework, sustainable value can be created when companies deliver value to shareholders without destroying value for other stakeholders. In other words, sustainable value is created only when companies deliver positive value for both its shareholders and stakeholders. Any negative value creation for shareholders or stakeholders can be considered as unsustainable. If value is created by transferring it from shareholders to other stakeholders or away from both, it leads also to unsustainable activities. Thus, in a stakeholder-driven business environment, enterprise management must completely understand the impacts of new strategies on all stakeholders to avoid negative value generation.

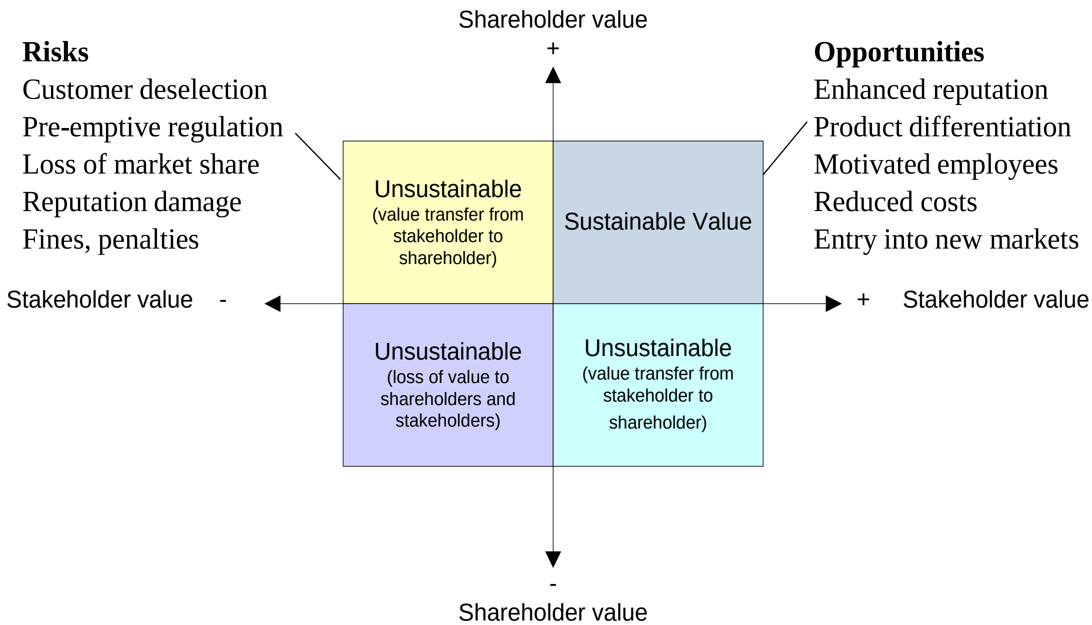

Figure 6.2 Sustainable value framework (adapted from Laszlo, 2003)

Takenaka and Ueda (2008) proposed three service models from the viewpoint of value creation. Their models were shown as service provision model, adaptive service model and co-creative service model. This work showed how to create sustainable value through the service provision and adaptive models by analyzing the studies on services. The study of co-creation service model is not explored, which consists cross-disciplinary for sustainable value creation. Ueda et al. (2009) described the goal of sustainable value creation as a complex problem. Beyond a producer creating an artifact that they feel the consumer will value, values are "co-created" through interaction among systems including natural systems. In manufacturing, value is realized through interactions among suppliers, manufacturers, customers, and other stakeholders (Ueda, et al., 2009). Ueda et al. (2009) also presented value creation models based on emergent systems and co-created decision making. They studied the relationships between natural, social, and artifactual systems. The models were built from three levels: producer, consumer and surrounding environment. This work analyzes the history of value evolution and only provides the guidelines for sustainable value creation without providing detailed method for value measuring. Bilge et al. (2015) presented a conceptual model to show the interactions among all the factors of product, processes, organizations, equipment, and humans. The characteristics of these factors are identified to support decision-making. To estimate value creation along all life-cycle stages, a cumulative value is created by aggregating weighted profitability and sustainability criteria for each factor. The limitation of this work is that no detailed descriptions for how to measure value for each factor are provided.

Figge and Hahn (2004, 2005, and 2009) proposed a sustainable value approach to measure enterprise contribution to sustainability, in monetary terms relative to its benchmark. Conventionally, investors concentrate on the return on capital. Similar to the approach used in financial return on investment (ROI), they compare the company ROI to the ROI of a benchmark. Only an investment that beats the benchmark ROI is considered to create value. This reasoning is built on a very fundamental rule that value is created whenever the return of an investment exceeds its costs. However, from a sustainability perspective, companies use not only economic capital but also environmental and social resources to create a return. To create value, the returns in terms of environmental and social benefits must cover the costs of resources used. The same approach to compare sustainability of agricultural systems by using data envelopment analysis (Hou et al., 2014) and to measure bank's sustainable value in financial crisis (Stankeviciene and Nikonorova 2014). Alexandre et al. (2007) proposed another sustainable value measurement approach developed based on cleaner production and value analysis, where value is defined as proportional to the needs/functions of product (process) divided by resources. This approach does not include characterization and quantification of societal aspects, and has no detailed measurement steps.

Considering the foregoing review and discussion, we propose the following as a definition of sustainable value that will be adopted in this paper.

Sustainable Value: The ability of a product/service to meet customer specific needs, such as quality, durability, functionality, etc., within a specific time and at the most competitive price while not sacrificing the economic, environmental and societal well-being of other stakeholders.

This sustainable value definition is derived by considering stakeholders and broad requirements for sustainable development. In manufacturing, the company creates economic value by using environmental and social resources, which will lead to positive and/or negative impacts on other stakeholders. Therefore, this definition incorporates all relevant stakeholders and TBL for sustainable value consideration.

6.5.2 Return-Risk approach to assess sustainable value added

In this section, we examine several approaches relevant to evaluating and quantifying sustainable value added and present the ideology derived from some early work to develop the proposed value-based method. The sustainable value framework developed by Laszlo (2003) and discussed earlier (Figure 6.4) shows that companies that deliver value to shareholders while sacrificing value for other stakeholders have a fundamentally flawed sustainability business model (upper left quadrant). Potential risks of operating this way include customer deselection, pre-emptive regulation, loss of market share, reputation damage, fines, penalties, etc. In the upper right quadrant, value is created for stakeholders by cultivating sources of extra value that can increase competitive advantages. The potential opportunities for companies by such a practice include enhanced reputation, product differentiation, motivated employees, reduced costs, entry into new markets, etc. These opportunities can be considered as the returns to the company due to considering benefits to all related stakeholders. Value created through such means for both shareholders and stakeholders can make companies improve market opportunities and averse the potential risks. Thus, the potential risks and opportunities (return) to the company affects sustainable value creation. This means that, in order to create more sustainable value, the goal of a company must be to minimize the risks and maximize returns to the company and other stakeholders. In other words, sustainable value can potentially be measured by considering the opportunities/benefits (returns) earned in relation to the risks taken to generate those opportunities.

Aother concept that becomes relevant in the context of sustainable value measurement is the break-even point (BEP), one of the widely used concepts in financial analysis of entrepreneurial decisions. Entrepreneurs and decision makers calculate BEP of proposed projects to evaluate the feasibility. As a risk-measure, lower BEP implies greater probability of the project to break-even, which is less likely to run into losses in adverse circumstances (Singh and Deshpande, 1982; Restifo, 1978; Heath, 1986). Based on BEP concept used in investment management, one can also device a sustainable BEP (Sus-BEP). Such a Sus-BEP can be explored to evaluate the enterprise performance in manufacturing industry. Sus-BEP would be related to resources usage and sustainability consideration in the company as shown in Figure 6.3, which will be further explained later through an example. In the conventional BEP the total revenue is the ‘Return’ earned for the ‘risk’ of incurring the total cost. To elaborate the potential of extending this concept to establish a Sus-BEP, we consider here one of the TBL aspects, environmental sustainability. In the context of environmental sustainability, the ‘risk’ could be the negative environmental outcomes (e.g. through use of non-renewable energy sources, using only virgin materials, etc.). On the other hand, the ‘return’ could be benefits from adopting positive environmental practices (e. g. using renewable energy sources, recycled water, remanufactured components, etc.). The point at which the return and risk are equal could be considered, the BEP from an environmental perspective. Similarly, when the positive and negative impacts/behaviors of TBL aspects are considered, it is possible to envision establishing a Sus-BEP, as very simply illustrated in Figure 6.3.

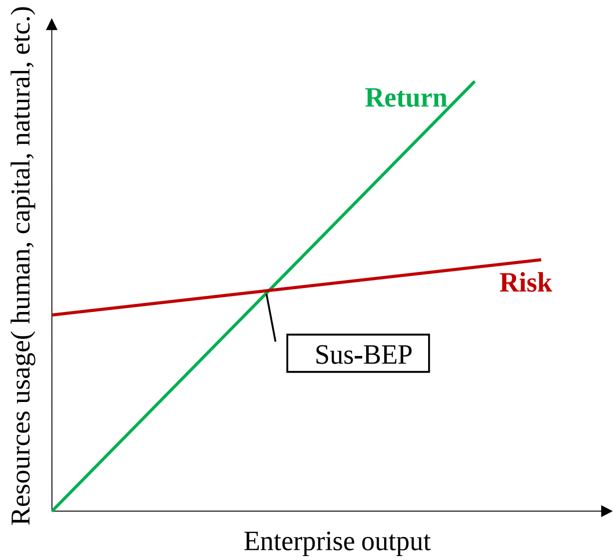

Figure 6.3 Sustainability break-even point considering return and risk

One other relevant approach is the Portfolio Management Theory developed by Harry Markowitz, the Nobel Prize winner for Economic Sciences in 1990. The Portfolio Management Theory studies the effects of asset risk, return, correlation and diversification on probable investment portfolio return and is applied very broadly in the field of investment management. It can help investors optimize the investment portfolio to obtain maximum return and minimize or avoid potential risks. This theory considers the expected return and variance of return to select the optimal portfolio. Using the method the total expected returns for all securities is first calculated to then measure the variance which is considered as risk (Markowitz, 1952, 1991, 1999). The lower the variance is, the better the portfolio will be. The expected return -variance (in other words, Return-Risk) ratio can be used to measure the success or failure of an investment. This theory can be applied to evaluate corporate economic sustainability considering, for example, the profit and cost of capital.

Considering the expected return–variance ratio from an environmental sustainability perspective, expected return (benefit) from environmental perspective could be performance/outcomes that are desired (e.g. renewable energy use, material recycling, etc.). The variance, which represents the risk, can be those environmental performance that are not desired (e. g. toxic emission, fossil fuel usage, etc.). Just as the Portfolio Management Theory, when the returns and risks are taken together, it can represent the value added from an environmental point of view.

6.5.3 Quantifying the measurement of enterprise sustainable value added

The methods discussed above reflect how value added can be measured in the context of the return earned and the risk that is taken to earn that return. The ultimate goal of these methods is to explore a way to earn maximum returns with minimum risks. In this section we extend the ideology presented in these methods for assessing sustainable manufacturing performance at the enterprise level. As mentioned in the previous sections, sustainable manufacturing requires considering all aspects of TBL, the total life-cycle coverage and extent of enabling 6R concepts. Thus, when any one of these concepts is considered, the benefits or the returns could be considered equivalent to the positive performance, and the risk will be the negative performance. Therefore, considering the ratio of 'Return' to 'Risk' from economic, environmental and societal aspects can be a way to assess sustainable value added at the enterprise level. That means overall performance which can improve a company's sustainability level and are advantageous for company sustainable development can be considered as 'Return'. Practices that will have negative impacts on the company and/or other stakeholders can be considered as 'Risk'.

Economic Value Added (EVA): Lambert (2008) uses the term economic value added (EVA) for the difference between net profit (total revenue – total expenses) and the 'capital charge' determined by the amount tied up in assets multiplied by the weighted average cost of capital. . Net profit is calculated by subtracting a company's total expense from total revenue. Capital charge is how much a company has tie up in assets multiplied by the weighted average cost of capital. While it bears the same name (i.e.: EVA), Lambert's (Lambert, 2008) description does not express the return-risk ratio defined earlier. Therefore, following the return-risk definition for value added, we define EVA as the ratio between the net profit and the capital charge as shown in Table 6-6.

Table 6-6 Equations for EVA and EnVA computation

<table>
<tr><th colspan="2">Economic Value Added (EVA)</th></tr>
<tr><td colspan="2">$$\mathrm{EVA} = \frac{E_{c1}}{E_{c2}} = \frac{\text{net profit}}{\text{capital charge}}$$</td></tr>
<tr><th colspan="2">Environmental Value Added (EnVA)</th></tr>
<tr><td>$$\mathrm{EnVA}(En_{c1}) = \frac{\text{renewable energy use}}{\text{non} - \text{renewable energy use}}$$</td><td rowspan="5">$$\mathrm{EnVA} = \frac{\sum_{i=1}^{5} \mathrm{EnVA}(En_{ci})}{5}$$</td></tr>
<tr><td>$$\mathrm{EnVA}(En_{c2}) = \frac{\text{reused material} + \text{recycled material}}{\text{virgin material} + \text{hazardous material}}$$</td></tr>
<tr><td>$$\mathrm{EnVA}(En_{c3}) = \frac{\text{recycled water} + \text{reused water}}{\text{fresh water}}$$</td></tr>
<tr><td>$$\mathrm{EnVA}(En_{c4}) = \frac{\text{recovered waste}}{\text{disposed waste} + \text{hazardous waste}}$$</td></tr>
<tr><td>$$\mathrm{EnVA}(En_{c5}) = \frac{\text{recovered product}}{\text{disposed product}}$$</td></tr>
</table>

Environmental Value Added (EnVA): Five clusters [material use and efficiency, energy use and efficiency, other resources use and efficiency (mainly focus on water), waste and emission management, and product end-of-life] were defined to assess environmental performance in the index-based method (Table 6-4). All clusters include metrics to assess both positive and negative environmental impacts. Therefore, following the return-risk approach, a ratio can be determined for each cluster. The environmental value added can be calculated by summing up all the ratios and dividing by the number of clusters as shown in Table 6-6. To illustrate the approach, consider the example of energy use and efficiency (at cluster level) which can involve two types of energy sources: renewable and non-renewable. The return or benefit can be denoted by how much renewable energy is used and the amount of non-renewable energy used could be considered the risk. The ratio between these two can be used as a measure to evaluate the value added under this cluster. Similarly, for all other environmental clusters, the return or benefit can be denoted as the numerator; the risk can be denoted as the denominator. Thus, the desirable and undesirable performance for the clusters can be used to obtain the ratios shown in Table 4. When the return equals to risk, the ratio will be 1, which can be considered as the baseline to evaluate the value added (greater than 1) or value loss (less than 1).

Societal Value Added (SoVA): For the societal aspect, two clusters health and safety and stakeholder engagement, were defined earlier in Table 6-5. Here again, an approach similar to that described above for environmental value added can be followed. For the health and safety cluster, we can consider employee and customers' health and safety to calculate societal value added. Under the stakeholder engagement cluster, there are five sub-clusters (supplier diversity and development; employee diversity and well-being development; customer satisfaction and development; product end-of-life practice; other stakeholder's diversity and development) and societal value added can be evaluated at the sub-cluster level where metrics are considered from both positive and negative aspects. Each sub-cluster can be calculated using the ratio, and the societal value added can be determined by summing up all the items together and then dividing by the number of sub-clusters as shown in Table 6-7. This ensures that value added score is not affected by the number of clusters. To illustrate the approach, consider the customer satisfaction and development sub-cluster. Customer satisfaction and development can be considered from two aspects: customer satisfaction rate and customer complaint rate. The return or benefit can be the number of satisfied customers and the risk can be the number of customer complaints. Therefore, the ratio between these two can be used as a measure to evaluate value added in this sub-cluster. Similarly, for other sub-clusters, the return or benefit can be denoted as the numerator and the risk as the denominator. Thus, the desirable and undesirable performances can be used for these sub-clusters to obtain the ratios as shown in Table 6-7.

Table 6-7 Equations for SoVA computation

Societal Value Added (SoVA)	
$\mathrm{SoVA}(\mathrm{So}_{sc1}) = \frac{\text{employee safety training}}{\text{injury rate}}$	$\mathrm{SoVA} = \frac{\sum_{i=1}^{6} \mathrm{SoVA}(\mathrm{So}_{sci})}{6}$
$\mathrm{SoVA}(\mathrm{So}_{sc2}) = \frac{\text{sustainability} - \text{oriented supplier}}{\text{non local sourcing}}$	
$\mathrm{SoVA}(\mathrm{So}_{sc3}) = \frac{\text{employee training}}{\text{employee turnover}}$	
$\mathrm{SoVA}(\mathrm{So}_{sc4}) = \frac{\text{customer satisfaction}}{\text{customer complaints}}$	
$\mathrm{SoVA}(\mathrm{So}_{sc5}) = \frac{\text{job creation from EOL processing}}{\text{product disposed directly to landfill}}$	
$\mathrm{SoVA}(\mathrm{So}_{sc6}) = \frac{\text{community outreach activity}}{\text{non local community hiring}}$	

Thus, combining the three aspects presented above, the Sustainable Value Added at the enterprise level can be calculated by the average of Economic Value Added (EVA), Environmental Value Added (EnVA), and Societal Value Added (SoVA) as shown in equation (6.1).

$$\text{Sustainable Value Added} = \frac{1}{3}(\mathrm{EVA} + \mathrm{EnVA} + \mathrm{SoVA}) \tag{6.1}$$

6.6 Case Study: Results and Analysis

The case of a Fortune 500 Company from the consumer electronics industry (due to confidentiality reason the company name cannot be disclosed) is used to demonstrate the application of the two methods for enterprise level sustainability performance evaluation. For the analysis, the data was collected from corporate sustainability reports and annual reports from 2012 to 2015. Data generated from these reports include all economic metrics and metrics for environmental clusters of material/energy/other resources use and efficiency, waste and emission. However, only some societal metrics were available in these reports. The unavailable data are listed in the following. In situations where data was not available, reasonable estimates were assumed. Due to the company does not have the data of total end-of-life (EOL), the calculation of all EOL are estimated. In addition, local sourcing, percentage of sustainability-oriented suppliers, employee diversity, reduction of product disposed directly to landfill, community outreach, percentage of local community hiring are not available and were estimated. The individual values for the metrics are not shown in the paper due to space limitations.

To compute *EnSI* using the index-based method, equal weights are assigned to the metrics, sub-clusters, clusters and sub-indices. A visual comparison of the variation in cluster-level values for the *EnSI* measure, from 2012-2015, are shown in Figure 6.4, Figure 6.5 and Figure 6.6. The sub-indices and overall the *EnSI* for 2012-2015 for the same period are shown in Table 6-8. For these calculations, performance in 2012 was used as the baseline and assigned a score of 5.00 for normalization. The performance in 2013, 2014 and 2015 are then calculated and normalized. Results clearly show that enterprise sustainable manufacturing performance was best in 2013. Ideal enterprise performance would be when economic performance is highest and environmental and societal negative impacts are lowest. However, it is reasonable to expect that improving environmental and societal benefits, at least in the short term, can only be achieved by sacrificing some economic profitability.

From Figure 6.4, it is not difficult to find that the net profit in 2013 is higher than that in other years due to a significant increase in operating income in 2013, primarily driven by cost and expense reductions. Meanwhile, the societal performance score for 2015 is slightly higher than that in other years resulting from the societal benefits due to better environmentally and societally friendly sustainability strategy implementation by the company. The comparison of enterprise sustainability performance in the form of *EnSI*, and the corresponding clusters, helps assess the trade-offs that may have to be made when balancing economic profitability and the environmental and societal impacts simultaneously.

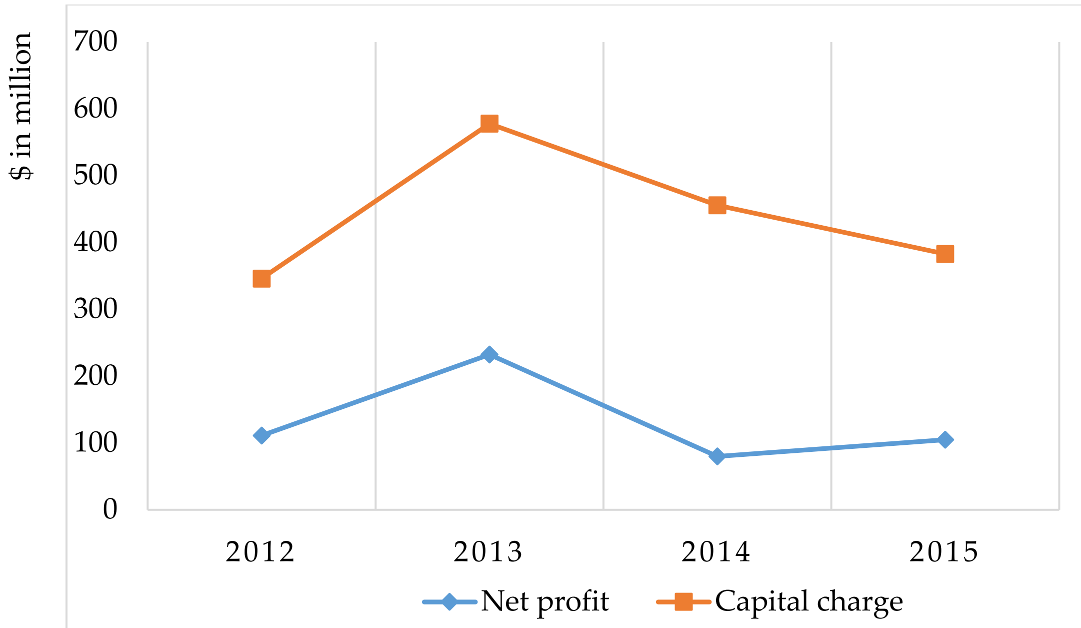

Figure 6.4 Economic clusters comparison

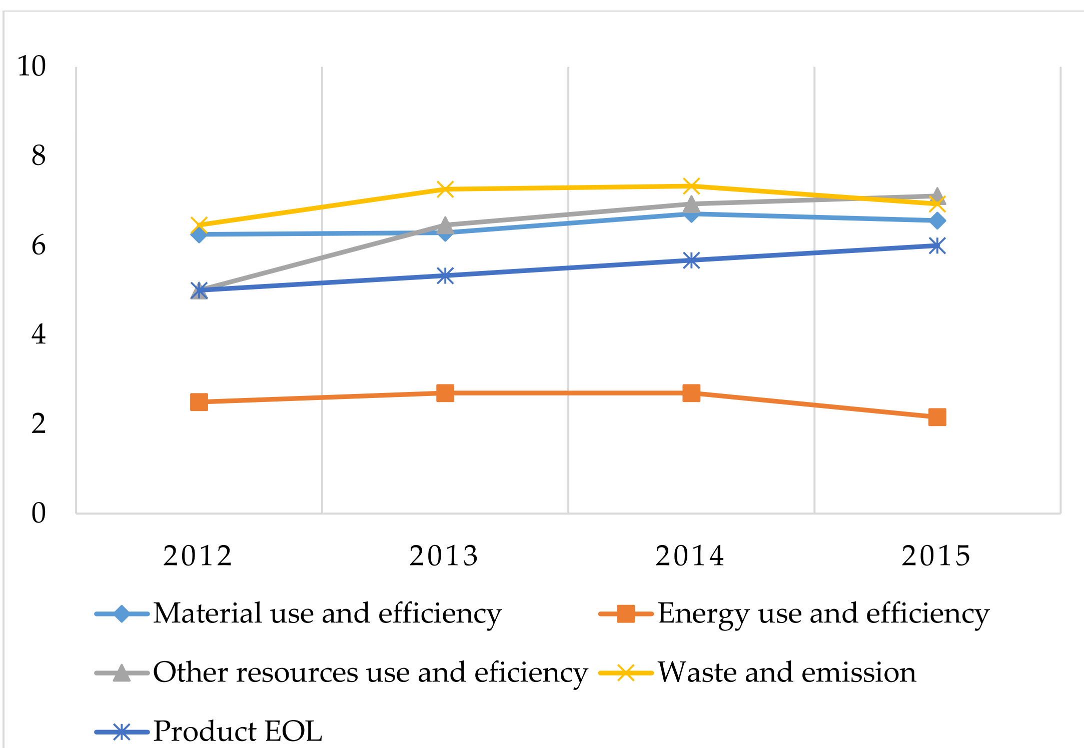

Figure 6.5 Environmental clusters comparison

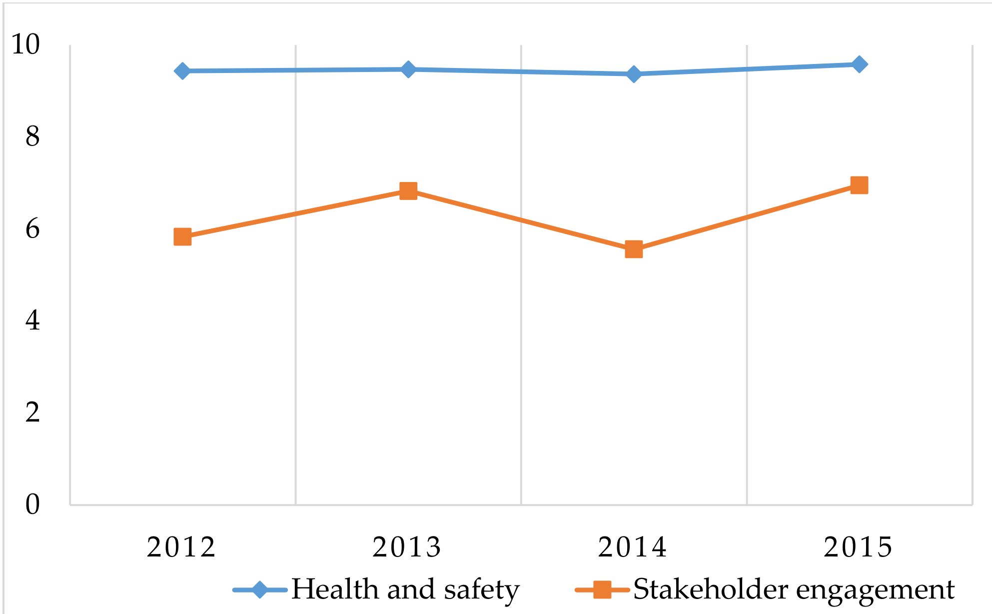

Figure 6.6 Societal clusters comparison

To compute the enterprise Sustainable Value Added (SVA) equations shown in Table 6-6 and Table 6-7 are used. The results are shown in Table 6-8. Based on the return-risk concept, the highest value is added when the return is maximized while risk is minimized, which in Table 6-8 corresponds to 2013, the same year *EnSI* provided the highest score. Also note that EVA is less than 1 for all years, indicating that the net profit is less than the capital charge, a negative economic value added for the period reflecting poor performance. The EnVA score is approximately 2 indicating that company exhibits good environmental performance. The SoVA shows a decline in the last two years.

Table 6-8 Results of Index-based and Value-based methods

<table>
<tr><th>Methods</th><th colspan="2">Aspects</th><th>2012</th><th>2013</th><th>2014</th><th>2015</th></tr>
<tr><td rowspan="4">Index-based</td><td rowspan="3">Sub-index</td><td>Economy</td><td>5</td><td>5.46</td><td>0</td><td>3.06</td></tr>
<tr><td>Environment</td><td>5.04</td><td>5.61</td><td>5.87</td><td>5.75</td></tr>
<tr><td>Society</td><td>7.64</td><td>8.15</td><td>7.46</td><td>8.27</td></tr>
<tr><td>Index</td><td>EnSI</td><td>5.89</td><td>6.41</td><td>4.44</td><td>5.69</td></tr>
<tr><td rowspan="4">Value-based</td><td colspan="2">Economic value added</td><td>0.47</td><td>0.67</td><td>0.21</td><td>0.38</td></tr>
<tr><td colspan="2">Environmental value added</td><td>1.85</td><td>1.97</td><td>1.92</td><td>2.07</td></tr>
<tr><td colspan="2">Societal value added</td><td>2.33</td><td>2.33</td><td>1.27</td><td>1.89</td></tr>
<tr><td colspan="2">Sustainable value added</td><td>1.55</td><td>1.66</td><td>1.13</td><td>1.44</td></tr>
</table>

The final results obtained from the index-based and value-based methods demonstrate that both provide comparable results and can be used to evaluate the enterprise sustainable manufacturing performance. The index-based method requires normalization of metrics, which has to be done by using subjective and /or objective normalization methods. Subjective normalization often cannot reflect the actual situations well due to the preferences of different individuals which can affect the evaluation. Even objective normalization (applied in the index-based method here) has some limitations. In the computations presented, the normalized score for the benchmark was set at 5.00. When normalizing other metrics, if the measure is higher/less than twice the benchmark, the normalized score will be outside the limit for the highest feasible score of 10 (or lower than the worst score of 0). When this happens, the normalized score will not provide a realistic evaluation of the performance. Thus, even objective normalization can pose problems. This challenge can be overcome with the value-based method which uses the absolute values to compute various values added.

A closer examination of the sub-indices and corresponding value added measures, most of them, too, are consistent. However, a few are not consistent, although the overall *EnSI* and SVA are consistent. This needs to be clarified and studied in future work to validate the proposed methods. Results reported in the corporate sustainability reports often only provide a report of how much/many materials/energy/water/wastes/emission are used/generated by reporting values for a lot of metrics. In contrast, the results obtained from the two alternative methods presented here provide a single and straightforward measure. While most of the data necessary in this study were available from corporate reports, however, gathering the required data could be a challenge. Especially if it is a small company, they often will not have all data and methods such as this could be difficult to use. However, if companies are interested in monitoring and improving sustainability performance, data collection needs to begin at some point in time.

6.7 Summary

Although the sustainability issue is omnipresent, a company's contribution to sustainability is hard to measure. While there are some existing guidelines for evaluating enterprise sustainability performance, they are not suited when the goal is to assess the effectiveness of the extent to which an organization is adopting sustainable manufacturing practices. To comprehensively evaluate sustainable manufacturing implementation and help with improvement decision making, a comprehensive framework and metrics that considers all TBL aspects, the total life-cycle emphasis, and 6R method implementation are needed. To be effective, the framework and metrics must enable aggregating metrics from other levels (e.g. product, process) to evaluate the systems level.

This research presents two alternate methods for enterprise level sustainability performance evaluation using the 'Performance Measurement House' as the guiding framework. An Enterprise Sustainability Index (*EnSI*), calculated following four steps of data measurement, normalization, weighting and aggregation, is proposed to evaluate the enterprise sustainable manufacturing performance. Another method to quantify the Sustainable Value Added (SVA) at the enterprise level, as a measure of sustainability performance, is also proposed by drawing on the ideologies presented in previous studies. As presented in the

‘Performance Measurement House’ the different domains (product, process, and system) must be evaluated with different measures. The focus of this paper is the enterprise level and some measures to quantify the influence of enterprise level performance on products and processes are included. The *EnSI* and SVA proposed here must be used together with the more comprehensive product/process sustainability performance evaluation method (*ProdSI*/*ProcSI*) that has been developed in earlier work. Thus, to be a comprehensive sustainable manufacturing evaluation, a company must use *ProdSI*, *ProcSI* and *EnSI*/SVA together. As illustrated through the case study, both methods can be used to evaluate enterprise level sustainable manufacturing performance. The index-based *EnSI* requires the use of a baseline and data normalization, which can pose challenges when the baseline is not chosen carefully. On the other hand, the SVA method provides more of an absolute measurement without the need for quantification.

One of challenges of the methods proposed in this research is getting the required data, particularly for small companies, if companies have corporate sustainability reports, most data can be easily collected for the economic and environmental data. However, the data for societal aspect is still not available in most cases. The index-based method *EnSI* needs to be improved by using more acceptable normalization method to process the collected data. This paper presented a preliminary approach to quantify the sustainable value added through SVA. Further research is necessary to conduct additional case studies for reviewing and updating the method further. One additional issue that cam come up, possibly the ideal case, is when he risk in the SVA ratio (the denominator) becomes zero. This also needs to be addressed in further studies. One more issue is that the results obtained of the sub-indices and corresponding value added measures, most of them, too, are consistent. However, a few are not consistent, although the overall *EnSI* and SVA are consistent. This also needs to be clarified and studied in future work to validate the proposed methods.

Chapter 7 Concluding Remarks and Future Work

7.1 Conclusions

The main research questions to be addressed in this research were (1): What key factors should be considered for developing a framework for sustainable manufacturing performance evaluation at the system level? (2): What metrics should be used and how should they be integrated to measure sustainable manufacturing performance at the system level?, and (3): How can enterprise sustainable value added be measured from a value perspective? Extensive work was conducted to examine how to answer these questions. The contributions of this research derived as a result are described in the sections below.

7.1.1 Sustainable performance measurement evaluation framework and sustainable manufacturing performance measurement house

First of all, the contribution of this research is the development of a sustainable performance measurement evaluation framework based on, and adapting, one of the existing performance measurement evaluation frameworks called Prism. In order to propose a sustainable performance measurement evaluation framework, it was determined that Prism should be modified and updated by (1) integrating sustainability concept into strategies development (2) implementing TBL, total life-cycle focus and 6Rs approach in the process design phase. (3) improving people capabilities by making people better understand sustainability requirements.

Based on the requirements for the development of sustainable performance measurement evaluation framework, *Sustainable Manufacturing Performance Measurement House* is proposed by integrating the elements of sustainable manufacturing at the product, process and systems levels. This measurement house can be used to guide framework development and metrics identification at the production line, plant and the enterprise levels.

7.1.2 Framework and metrics for sustainable manufacturing performance evaluation at the production line, plant and enterprise levels

By reviewing the existing literature for sustainability assessment at different levels, a comprehensive set of sustainability metrics was proposed at production line, plant and enterprise levels, respectively. The metrics are categorized into five-level hierarchical structure organized as metrics, sub-clusters, clusters, sub-indices, and index. Then, an index-based sustainable manufacturing performance evaluation method was proposed as Line Sustainability Index (*LiSI*), Plant Sustainability Index (*PlaSI*), and Enterprise Sustainability Index (*EnSI*), respectively. These proposed *LiSI*/*PlaSI*/*EnSI* methods can be applied at different manufacturing industries for different area of interest. The application of these proposed methods can help engineers and managers identify the shortcomings of the manufacturing systems; further improve the performance by implementing the sustainability strategy.

7.1.3 Enterprise sustainable value added evaluation

One other contribution of this research is the development of a value-based sustainable manufacturing performance evaluation method for enterprise Sustainable Value Added (SVA) assessment. This proposed value-based method considers return and risk to evaluate the value added. The sustainability benefits or desired behavior is considered as the 'return' whereas the 'risk' is the negative impacts or undesired behavior. This method can also guide the engineer and manager to identify the positive performance (return) and negative performance (risk). Another benefit of this value-based method is that it does not require a benchmark for each metric evaluation due to the fact that absolute values of the measures are used for the computation without the requirement of data normalization. It must also be noted that the proposed methods are more suitable to evaluate company performance over time, rather than for comparative performance of different organizations. Based on the case study analysis, the overall results for enterprise sustainability performance from the value-based and index-based are consistent and comparable; however, there are slight differences in how some of the sub-indices compare. This requires further research and must be addressed in the future studies.

7.2 Future Work

The newly developed index-based (*LiSI*/*PlaSI*/*EnSI*) and value-based (SVA) methods have potential for further improvement. In all cases, only one case study was used to demonstrate the application of the tool. Further studies are necessary to apply the tools to more case studies for different types of manufacturing industries which can help validate and improve them. Further study is also needed in improving the metrics setup, data collection and processing, and normalization in the index-based method. In order to be able to apply and benefit from the methods presented here, there is a need for better and more efficient mechanisms for data collection. Normalization, weighting and aggregation methods used in this research are those commonly used.

There are limitations in most of the methods used in normalization; such as the requirements of a benchmark; some assessments are very subjective and do not reflect actual situation; etc. There are issues with weighting as well; the question about what is the best weights to assign to each sub-index, cluster, etc. remains open Results of the sustainability indices proposed here can vary based on what methods are used. Therefore, further research is necessary to study what normalization and weighting methods are most suited for sustainable manufacturing assessment using the variety of indices used.

The value-based method of Sustainable Value Added (SVA) compares the returns (performance desired from a sustainability perspective) to the risks (performance not desired from a sustainability perspective) to assess sustainable value added at the enterprise level. One limitation of SVA method, as proposed, is that when the risks (denominator) reaches the value of zero the SVA becomes indeterminate. While this represents an idealistic scenario, if this happens, the SVA computation does not hold true. Therefore, future work should explore modifying the SVA computation and determine a better way to deal with this situation.

In order to more comprehensively evaluate manufacturing performance at the systems levels, it is also necessary to incorporate the supply chain level – the highest level in the systems hierarchy. For supply chain sustainability performance evaluation, companies at each tier will have to apply *EnSI*/SVA to evaluate their individual sustainability performance. However, in order to evaluate sustainability performance at the supply chain level, it will be necessary to determine how individual supply chain entity performance should be integrated. The extent of the cooperation between the supply chain partner companies and how that will affect the sustainability performance of the entire supply chain will also have to be integrated.

Appendix A: Summary of Production Line Level Metrics

Metrics	OECD	*ProcSI*	Zhang and Haapala	Pinto-Ferreira et al.	Faulkner and Badurdeen	Winroth et al.
Scrap cost						
Coolant cost			x			
Use of process additive						x
Consumable related cost		x				
Cutting tool relatd cost		x				
Tool cost			x			
Packaging related cost		x				
rate of packaging material						x
Number of packages used in the production of a part				x		
Scrap rate		x				x
Maintenance cost		x				
Cost associated to the maintenance and acquisition of EPIs				x		
Audit and legal cost		x				
Cost of EHS complaince		x				x
Cost of PPE and safety investment		x				
Cost of depreciation		x				
Cost of jigs/fixtures investment		x				
Cost of new equipment purchase	x					
Total water cost	x					
Cost of the water consumed for each section of line				x		
Operation energy cost		x				
Total energy cost	x					
Energy cost			x			
Cost of the energy consumed for each section of the line				x		
Average employment cost	x					
Indirect labor cost		x				
Employee cost per hour						x
Labor cost	x		x			
Cost per hour of the RR. HH. Staff				x		

Metrics	OECD	*ProcSI*	Zhang and Haapala	Pinto-Ferreira et al.	Faulkner and Badurdeen	Winroth et al.
Total employment cost	x					
Base wage ($/mon)			x			
Bonus ($/mon)			x			
Total wage ($/mon)			x			
Annual wage ($/year)			x			
Training cost		x				
Cost of the training hour for adaption to the post				x		
Cost of the training hour for safety and health				x		
Cost of by-product treatment		x				
Cost of package disposal				x		
Cost of disposal of solid waste				x		
Cost of the depuration treatment of the emissions in each section of line				x		
Cost of the depuration treatment of the water in each section of line				x		
Lead time					x	
Productivity (#/hr)						x
Performance rate for manual laor (time used/ideal time)						x
Utilization of manual labor						x
Time spent per unit product	x					
Products produced per month			x			
No of workers on each machines				x		
Average worked hours per year	x					
Material usage						x
Raw material usage metric					x	
Total material cost	x					
Total weight of material consumption	x					
Scrap rate						
Water consumed per unit product	x					
Recycled water content (%)	x					
Total weight of water consumed	x					
the amount of water used during the manufacturing process					x	
Recycled water						x
Purification of waste water						x
Water consumption				x		x

Metrics	OECD	*ProcSI*	Zhang and Haapala	Pinto-Ferreira et al.	Faulkner and Badurdeen	Winroth et al.
Total amount of waste water produced during the manufacture of a part				x		
Total water consumption of the line		x				
Water intensity	x					
Quantity of energy consumed per product (units)	x					
Energy content per unit (MJ/unit)	x					
Use of renewable energy						x
Energy use						x
Idle energy losses						x
Renewable energy content (%)	x	x			x	
Power of energy consumption				x		
Energy consumption					x	
Total energy consumed	x					
Renewable proportion of energy consumed	x	x				
Renewable energy consumed	x					
Energy intensity	x					
In-line electricity consumption		x				
In-line fossil fuel consumption		x				
In-line transportation electricity consumption		x				
In-line transportation fossil fuel consumption		x				
Electricity consumption on maintenance		x				
Fossil fuel consumption on maintenance		x				
Releases to air	x					
Releases to surface water	x					
Releases to land	x					
Releases from landfills	x					
Transfers to disposal	x					
Transfers to treatment	x					
Transfers to recycling	x					
Transfers for energy recovery	x					
Transfers to sewage	x					
Mass of non-collected solid wastes		x				

Metrics	OECD	*ProcSI*	Zhang and Haapala	Pinto-Ferreira et al.	Faulkner and Badurdeen	Winroth et al.
Mass of non-collected liquid wastes		x				
Mass of non-collected gaseous wastes		x				
Mass of solid wastes going to landfill		x				
Total solid waste						x
Weight of hazardous waste		x				x
Mass of liquid waste disposed		x				
Additional GHGs released in production process	x					
GHGs released in total energy consumption	x				x	
Amount of emissions discharged into the atomosphere				x		
GHG intensity	x					
Emission of ozone-depleting substances						x
Emission of causing acid rain						x
Emission of particles						x
Emission of CO2 from factory						x
Residual intensity	x					
Total waste (waste outputs)	x					
Total amount of waste produced in the manufacture of a part				x		
GHG emission from energy consumption of the line		x				
Mass of restricted materials in disposed consumables		x				
Mass of restricted material in disposed packaging		x				
Mass of restricted material in disposed raw materials		x				
Mass of restricted material in scrap parts going to landfill		x				
Ratio of consumables recovered		x				
Ratio of consumables reused		x				
Ratio of consumables recycled		x				
Mass of disposed used consumables		x				
Ratio of used packaging recovered		x				
Ratio of used packaging reused		x				
Ratio of used packaging recycled		x				
Mass of disposed used packaging		x				
Ratio of used raw material recovered		x				
Ratio of used raw material reused		x				
Ratio of used raw material recycled		x				
Mass of disposed used raw material		x				

Metrics	OECD	*ProcSI*	Zhang and Haapala	Pinto-Ferreira et al.	Faulkner and Badurdeen	Winroth et al.
Ratio of scrap parts recovered		x				
Ratio of scrap parts remanufactured		x				
Ratio of scrap parts recycled		x				
Mass of disposed scrap parts		x				
Climate change human health			x			
ozone depleting			x			
human toxicity			x			
Photochemical oxcidant formation			x			
Particulate matter formation			x			
Lonising radiation			x			
Climate change ecosystems			x			
Terrestrial acidification			x			
Freshwater eutrophication			x			
Terrestrial ecotoxicity			x			
Freshwater toxicity			x			
Marine ecotoxicity			x			
Agricultureal land occupation			x			
Urban land occupation			x			
Natural land transformation			x			
Metal depletion			x			
Fossil depletion			x			
Exposure to corrosive/toxic chemicals		x			x	
Exposure to high temperature surfaces		x			x	
Exposure to high speed components and splashes		x			x	
Exposure to high voltage electricity		x			x	
Other threatening exposure		x				
Chemical concentration		x				
Mist/dust level		x				
Heat generation		x				
Noise level outside the plant		x				

Metrics	OECD	*ProcSI*	Zhang and Haapala	Pinto-Ferreira et al.	Faulkner and Badurdeen	Winroth et al.
Noise exposure		x			x	
Temperature		x				
Other hazardous exposure		x				
No of training hour for the post				x		
No of training hour per employee						x
No of training hour for safety and health				x		
No. of accidents				x		x
Injury rate		x	x			
Physical load index		x			x	
Absebce due to injuries or work related illness						x
Health-related absenteeism rate		x				

Appendix B: Summary of Plant Level Metrics

Metrics	Veleva and Ellenbecker	Winroth et al.	Dreher et al.
Company market share	x		
Company image	x		
Profit profitability etc according to annual reporting legislation		x	
Growth in shareholder value	x		
Employee cost per hour		x	
% of annual budget to R&D		x	
Total EHS operating costs	x		
Employment cost in relation to income sales		x	
Cost of EHS compliance		x	
Investment in sustainability R&D as percent of a company soending	x		
Cost associated with EHS compliance (e.g. Fines,liabilities, worker compensation, waste treatment, etc.)	x		
Total annual EHS capital cost	x		
Fresh water consumption	x		
Water consumption		x	
The volume of water used by source with a goal of 100% water reuse at all facilities			x
Recycled water		x	
Purification of waste water		x	
Share reuse or recycled		x	
Percent/amount of water reused	x		
Material used (total and per unit of product)	x		
Material usage		x	
Track amount of scrap metal machined away by design, driving engineers to optimize design and fabrication processes			x
Track consumption of compressed air operating fluids identifying and repairing leaks			x
Scrap rate		x	
Rate of packaging material		x	
Use of process additives		x	
Percent of products involving use of GMO (genetically modified organism)	x		
Percent of products involving the use of endocring disrupting substance)	x		

Metrics	Veleva and Ellenbecker	Winroth et al.	Dreher et al.
Percent of products from recycled material	x		
Percent renewable materials used at a rate lower or equal to the rate of renewal	x		
Total mass in (raw material,products,packaging)/$value of product sold	x		
Kg of PBT (Persistent Bioaccumulative Toxic) chemicals used	x		
Kilograms of endocrine disrupting substance used	x		
Kilograms of POP used (persistent organic pollutants)	x		
Percent change in specific local resources(forests,water,coal, oil,metals)	x		
Percent of biodegradable packaging	x		
Toxic use reduction chemicals used at the facility	x		
Energy use (total and per unit of product)	x		
Use of renewable energy		x	
Percentage of energy generated from renewable sources at each facility			x
Amount of energy generated from recapture and reuse			x
Dollars saved in energy efficiency investment			x
Degree of perfection for each unit produced (ratio of energy that actually went into production of final product to the amount of energy actually used)			x
Total energy used annually per unit produced			x
Energy use		x	
Idle energy losses		x	
Quantity of each type of energy used	x		
Percent energy from renewables	x		
Kilograms of waste generated before recycling(emission, solid and liquid waste)	x		
Number/type of reportable release	x		
Ecotoxicity metric	x		
Concentration of specific contaminants in ambient air at selected monitoring locations	x		
Percent of days with poor air quality as result of a facility production	x		
Tons of Toxic Release Inventory releases	x		
The level of contaminants in wastewater			x
The concentration of contaminnants in local and downstream surface and ground waters			x
Local ground and surface water levels			x
Amount of hazardous waste generated	x		

Metrics	Veleva and Ellenbecker	Winroth et al.	Dreher et al.
Local ground and surface water levels			x
Amount of hazardous waste generated	x		
Total solid waste		x	
Weight of hazardous waste		x	
Concentration of specific contaminants in ground waters or surface waters	x		
Quantity of toxic chemicals released	x		
Company-wide waste management system, separating and recycling so as to achieve zero waste in all plants and offices			x
Reuse all production wastewater through filtering			x
Spread dry and near-dry machining to all processes where feasible to reduce waste generated by machining fluids and metal scrap			x
Reduce compensated waste to 30kg/vehicle			x
Reduce waste by avoiding it. Rethink and redesign processes to reduce waste			x
Reuse organic and other suitable waste by generating landfill gas			x
Actively encourage suppliers to put in place active waste management, exploiting if necessary synergies of scale with GM			x
Engage specilists inside the plants to systematically explore ways to reduce waste by optimizing and rethinking manufacturing processes, analyzing sources of waste, and exploring alternative ways of doing things			x
Find applications for waste or by products suitability to sell them into scrap markets			x
Kilogram permitted air emissions	x		
Emission of ozone-depleting substances		x	
Emission causing acid rain		x	
Five-year target of an 8% reduction in co2 emission from 2005-2010			x
Normalize all greenhouse gas emission to lbs/vehicle			x
Carbon footprint of common business practices			x
The emissions from vehicles manafactured			x
Emission of particles		x	
The amount of volatile organic compounds emitted			x
The pollutant levels in local air and downwind areas			x
Emission of CO2 from factory		x	
Liters of biochemical Oxygen Demand discharge	x		
Global warming potential (GWP)	x		
Photochemical ozone depleting potential	x		

Metrics	Veleva and Ellenbecker	Winroth et al.	Dreher et al.
Nutrification potential	x		
Summer smog potential	x		
Heavy metal equivalents	x		
Acidification potential	x		
Number of notices of violation	x		
Amount invested in EHS and community projects	x		
Number of sites certified under ISO14001	x		
Environmental accidents		x	
Environmental impact assessment is used		x	
Comliance with ISO 14001/EMAS		x	
Number of positive/negative press report on the organization's environmental and social performance	x		
Rate of employees' suggested improvements in quality, social and EHS performance	x		
Rate of customer compliants and returns	x		
Rate of customer comliants		x	
No of new customer per year		x	
Rate of defective products	x		
Customer satisfaction level	x		
Percent of products leased opposed to sold	x		
Increase in product durability	x		
Organization's openness to stakeholder review and participation in decision-making process(scale 1-5)	x		
Number of community-company partnerships	x		
Implementation of a program to improve community ouotreach efforts	x		
Income disparity within company and compared to local community abd industry	x		
Community quality of life	x		
Population growth in the local area	x		
Social and recreational benefits provided to community	x		
Number of community outreach activities	x		
Community spending and charitable contributions as percent of revenues	x		
Percent of products designed for disassembly, reuse, or recycling	x		
Rate of internal recycling/energy recapture			x
Type/volume of non-regulated material recycled	x		
Reuse or recycle parts packaging; track reduction			x
Reduce or eliminate protective coating for transport			x

Metrics	Veleva and Ellenbecker	Winroth et al.	Dreher et al.
Collect and recycle process material			x
Percent of products designed to be recycled	x		
Percent of products with take-back policies in place	x		
Percent of work stations with noise level exceeding 85db	x		
Percent of accident-free workstations	x		
No of accidents		x	
Number of near-misses	x		
Number of employees days away due to injury per shift and per manager			x
Number of employees days away due to exposure to toxins			x
Ratio of safety gear and safety shower to employees			x
Ratio of sick days to work days per facility			x
Number of safety measures adopted safety/fail-safe equipment installations and improvements per year and ROI per improvement			x
Health index of onsite foods			x
Percent of employee suggested EHS improvements implemented in practice	x		
Percent of workstations with elimination of the hazards through promary control	x		
Percent of workers woth work-related disease	x		
Number of peer nominations for health and safety improvements per month			x
Absence due to injuries or work related illness		x	
Recordable injury rate			x
Lost workday case rate			x
Elimination of hazardous work places		x	
Injury rate based on injury type, such as puncture, laxeration or strain			x
Working hours not exceeding 48 hours per six day period			x
Health and safety workplace safety based on recognized standards of the ILO and national laws, employee training on safety workplace practices			x
Employee blood lead levels			x
Participation in health education and wellness programs, health certification-related courses completed, monthly on-site fitness equipment use			x
Percent of workers with some level of hearing loss	x		
Percent of employees who believe that company offers equal opportunity to its staff	x		
Worker health status compared to other companies in the industry	x		
Stress level compared to the health level	x		
Percent of products with updatedd and complete MSDS(material safety data sheet)	x		

Metrics	Veleva and Ellenbecker	Winroth et al.	Dreher et al.
Acres of land in the local community used by the company for landfill incineration or any other type of wastedisposal	x		
Land consumption		x	
Value added/employee (productivity)		x	
Access to skilled personnel		x	
No of new products related to total # of products		x	
Overall equipment efficicency		x	
Productivity		x	
Performance rate for mannual labor		x	
Utilization of mannual labor		x	
Delivery precision		x	
Lead time		x	
Monitor machine power consumption and optimize machine usage patterns define metrics to describe and drive machine power usage relative to parts production			x
Flexibility		x	
Maintenance		x	
Stops caused by suppliers		x	
Level of education		x	
Rate of temporary workers		x	
Rate of employees that are shre holders		x	
Equal opportunity		x	
male to female ratios		x	
Cross functional teams for improvements		x	
Percentage of employees trained in sustainability initiatives			x
Non-discrimination		x	
Gendar/age/ethnical/sexual		x	
Company wage in comparison to local minimum wage		x	
Turnover rate or average length of service of employees	x		
Percent of workers who report complete jod satisfaction (based on questionnaire)	x		

Metrics	Veleva and Ellenbecker	Winroth et al.	Dreher et al.
Average number of hours of employee training per year	x		
Number of employees per unit of product or dollar sales	x		
Employee retention rates	x		
No of new employees per year		x	
Voluntary employment			x
Fair and equal treatment for workers			x
Child labor prohibitions for individuals younger than 16 years old			x
Compensation for regular work hours at a minimum to meet governing standards			x
Freedom of association			x
Number of complaints from public or employees			x
Number of paid days off per facility			x
Employee satisfaction rate		x	
Support for employee physical acitivity health care and medicine		x	
Employee turnover		x	
Responsibility and empowerment related to competence		x	
Clear job descriptions		x	
Promotion opportunities for all employees		x	
Employees using public transit/walking/biking			x
Percentage of employees commuting , participating in subsidized public transportation, or car-pooling to work per faciclity			x
Launched an energy citizen campaign to engage employees in energy conservation			x
Engaged employees through energy awareness month and earth day awareness events			x
Increase the energy champion network to more than 2000 employees			x
Apply 6 sigma focus to energy challenges through the enterprise energy team			x
Incidence of specific diseases compared to the national average	x		
Number of OSHA citations	x		
Number of OSHA 200 LOG ENTRIES	x		
Number of recordable injuries/illnesses	x		
No of training hours per employee		x	
Participation ratio in improvement groups		x	
Number of employees receiving EHS training	x		
Human health metric	x		
Lost workday injury and illness case rate (LWDII)	x		

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Zhang, H. and Haapala, K.R., 2015. Integrating sustainable manufacturing assessment into decision making for a production work cell. *Journal of Cleaner Production*, 105, pp.52-63.

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VITA

AIHUA HUANG

EDUCATION

University of Kentucky
Lexington, Kentucky, USA

Ph.D. in Mechanical Engineering July 2017

Jilin University
Changchun, Jilin, China

Bachelor of Industrial Design in Automotive Engineering Sep 2003 - Jul 2007

ACADEMIC EXPERIENCE

Teaching & Research Assistant

Department of Mechanical Engineering, University of Kentucky Aug 2010 - present

- Introduction to Mechanical Engineering (ME101): Prepared and taught experiments to first-year college students, facilitated discussion sections, graded homework and quizzes, maintained grading and attendance records
- ME Capstone Design (ME411&412) and Manufacturing Systems (ME/MFS512): graded homework and quiz, maintained grading and attendance records, distributed and copied course materials
- Lean Manufacturing Principles & Practices (ME/MFS 503): Used online learning management system (Canvas) to organize content, in-line grading of assignments, managing student correspondence. Assisted in set up and conducting hands-on simulations for standardized work, 5S, kanban system. Tested production line online simulation development
- Mechanical Vibrations (ME513) and Computational Techniques in Mechanical Engineering Analysis (ME514): weekly office hours and tutored students, in-line grading of assignments, managed and responded to course-related e-mail
- Assisted with academic research and projects, discussed research assignments with supervisor regularly

INDUSTRIAL EXPERIENCE

Design Engineer

First Automotive Works - CAR Co. Ltd., China Aug 2007- Sep 2008

- Designed automotive interior for new car development
- Optimized the interior design for New Mazda 6
- Collected data and analyzed the assembly line of automotive interior
- Communicated with technicians in the field to improve the parts design

Internship

First Automotive Works - Jiefang Automotive Co. Ltd., China Nov 2006 - Dec 2006

- Prepared Auto CAD drawing for transmission gears
- Analyzed and improved the assembly flow of truck Production
- Collected and analyzed data to improve the manufacturing process

OTHER EXPERIENCE AND TRAINING

Participant

First Academic Research Colloquium, University of Dayton, Dayton, Ohio Apr 2016

- Presented research work, and collaborate with other Ph.D. candidates and faculties
- Learnt how to apply and interview for faculty positions — and what search committees look for in a candidate
- Learnt the keys to writing winning proposals
- Discovered partnership opportunities between industry and academia
- Gained exposure to research opportunities with local companies and organizations

Participant

The 5th Annual Sustainability Forum, University of Kentucky Dec 2015

- Presented research work and collaborate with UK's faculty and students who conduct interdisciplinary research in environmental and sustainability science and policy
- Discussed with the people from the areas of Environmental Science, Public and Environmental Health, Economic and Social Policy, Political Ecology, Manufacturing and Materials Science
- Learnt how to provide creative and innovative ways to bridge the gap between these areas and the general public

Participant

The 2nd, 3rd, 4th, 5th International Forum on Sustainable Manufacturing,

University of Kentucky, Lexington, Kentucky Sep 2010, 2013, 2014, 2015

- Presented research work and collaborate with other academic and industrial attendees
- Learnt recent and on-going work for value creation through sustainable manufacturing
- Helped with venue layout and organization work

Participant

Innovation for Sustainable Manufacturing and Workforce Effectiveness Workshop,

University of Kentucky, Lexington, Kentucky Jun 2011

- Learnt recent and on-going national efforts to develop strategic vision and roadmaps for sustainable manufacturing
- Helped with workshop setup and registration work

RESEARCH PROJECTS

Development of metrics, metrology and a framework for product-process ontology for interoperability in model-based sustainable manufacturing

National Institute of Standards and Technology, USA Jan 2011 – Nov 2013

- Developing metrics and metrology for sustainable products and sustainable manufacturing processes based on the preliminary work done in developing Product Sustainability Index and process sustainability rating
- Developing product and information models for total life-cycle analysis of sustainable products
- Testbed development for validation of predictive models for products and processes
- Worked with three industrial companies: Toyota, GE Aviation, Lexmark
- Two technical paper published

Economic Analysis of Selective Societal Factors Regarding Cryogenic and Conventional Cutting Fluids

Semicon Associates, Lexington, KY, Sep 2012 – Dec 2012

- Study the impact of conventional cutting fluids on the operator health and how it affects the financials of the company
- Compare the human and economic impacts of conventional cutting fluids and liquid nitrogen
- Create a business case to achieve cost reduction

Sustainability Consideration for Separation of Polystyrene Pellets from Other Materials

Nextlife, Frankfort, KY Jan 2012 – May 2012

- Study and prepare sustainability requirements for related material separation
- Separate materials based on the study of materials characteristics
- Develop a separation method to sort materials based on color difference
- Create a business case for sustainable manufacturing of plastic materials

HORNOR AND AWARDS

The Distinguished Paper Award
Oct 2015 *2016 Engineering Lean & Six Sigma Conference*

NSF Travel Grant Award
May 2012 *2012 Life Cycle Engineering Conference*

Excellent Undergraduate Student
Jul 2006 *College of Automotive Engineering, Jilin University, Changchun, China*

Undergraduate Scholarship
Jul 2005 & 2006 *Jilin University, Changchun, China*

PROFESSONAL AFFILIATION

- Institute of Industrial and Systems Engineers
- Society of Manufacturing Engineers

PUBLICATIONS

Journal Papers

- **Huang, A.**, Badurdeen, F., 2017. (Submitted).Framework for production line and plant levels sustainability performance evaluation by integrating product and process metrics. *Journal of Cleaner Production*.
- **Huang, A.**, Badurdeen, F., 2017. (In press).Sustainable Manufacturing

Performance Evaluation at the Enterprise Level: Index- and Value-based methods. *ASTM Journal - Smart and Sustainable Manufacturing Systems*.

- Wijekoon, K., **Huang, A.**, Badurdeen, F., 2014. Model to evaluate and optimize sustainability performance of customizable product service systems. *International Journal of Strategic Engineering Asset Management-Special Issue on Sustainable Manufacturing*, Accepted.

Conference Papers

- **Huang, A.** and Badurdeen, F., 2017. Sustainable Manufacturing Performance Evaluation: Integrating Product and Process Metrics for Systems Level Assessment. *Procedia Manufacturing, 8*, pp.563-570.
- **Huang, A.** and Badurdeen, F., 2016. Framework for Sustainable Manufacturing Performance Assessment at the System Level. *IISE Annual Conference and Expo 2016*, May 21 – 24, Anaheim, California.
- Hogan, B., **Huang, A.**, Badurdeen, F., 2015. Wayfinding in the Graduate School: Structured Problem Solving in a Non-Manufacturing Environment. *Proceedings of the 2015 IIE Engineering Lean and Six Sigma Conference*, Atlanta, Georgia.
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