# Simulation-based Impact Analysis for Sustainable Manufacturing Design and Management

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*Doctor of Philosophy* 2018

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# List of Abbreviations

| | |
|---|---|
| ABC | Activities Based Costing |
| AE | Auxiliary Energy |
| BIC | Best-In-Class |
| CAD | Computer-Aided Design |
| CAM | Computer Aided Manufacturing |
| CIA | Cost Impact Analysis |
| CIA | Cost Impact Assessment |
| CNC | Computer Numeric Code |
| CSM | Competitive Sustainable Manufacturing |
| CSR | Corporate Social Responsibility |
| DE | Direct Energy |
| DES | Discrete Event Simulation |
| DEMATEL | Decision Making Trial and Evaluation Laboratory |
| DfE | Design for Environment |
| EDA | Exploratory Data Analysis |
| EIA | Environmental Impact Analysis |
| EIA | Environmental Impact Assessment |
| EPA | Environmental Protection Agency |
| EPE | Embodied Product Energy |
| EPE | Environmental Performance Evaluation |
| eLCA | Environmental Life Cycle Assessment |
| eLCC | Environmental Life Cycle Costing |
| FU | Functional Unit |
| GHG | Green House Gas |
| GRI | Global Reporting Initiative |
| GSSB | Global Sustainability Standard Board |
| IE | Indirect Energy |
| ISO | International Standard Organisation |
| JIT | Just-in-time |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Analysis |
| LCC | Life Cycle Costing |
| LCSA | Life Cycle Sustainability Assessment |
| LCSA | Life Cycle Sustainability Analysis |
| LCT | Life Cycle Thinking |
| MCDA | Multi-Criteria Decision Analysis |
| MDGs | Millennium Development Goals |
| MET | Materials Energy and Toxicity |
| MFP | Multi-Factor Productivity |
| OECD | Organisation of Economic Co-operation and Development |
| OEM | Original Equipment Manufacturer |
| OR | Operations Research |

| | |
|---|---|
| PF | Productivity Factor |
| PFP | Partial Factor Productivity |
| PhD | Doctor of Philosophy |
| REACH | Registration Evaluation Authorisation and restriction of CHemicals |
| RIDDOR | Reporting of Injuries, Diseases and Dangerous Occurrences Regulations |
| SD | Sustainable Development |
| SDGs | Sustainable Development Goals |
| SDP | Sustainable Product Development |
| SET | Social Exchange Theory |
| S-LCA | Social Life Cycle Assessment |
| SA | Sustainability Analysis |
| SETAC | Society for Environmental Toxicology and Chemistry |
| SIA | Social Impact Analysis |
| SIA | Social Impact Assessment |
| SIC | Social Impact Coefficient |
| SM | Sustainable Manufacturing |
| SPA | Sustainability Performance Assessment |
| SPD | Sustainable Product Development |
| SS | Sustainability Science |
| TE | Theoretical Energy |
| TFP | Total Factor Productivity |
| TSCMC | Total Supply Chain Management Cost |
| UNEP | United Nations Environmental Programme |
| VSM | Value Stream Mapping |
| WIP | Work In Progress |

# List of Notations

| | |
|---|---|
| $\alpha$ | Aggregated negative social impacts |
| $\gamma$ | Aggregated positive social impacts |
| $\beta$ | Social Impact Coefficient (SIC) where $\beta = f(\alpha,\gamma)$ |
| $M_t$ | Machine Setup and Teardown Time |
| $N_t$ | Manual Operation Time |
| Y | The output of a process |
| $Y=\beta(M,N)$ | Cobb-Douglas production function |
| P | Power generated |
| V | Voltage |
| I | Current (A/C) |
| t | Time of operation |
| $\cos\varphi$ | Electrical power factor |
| $\varphi$ | The phase angle between voltage and current |
| $E_{cons}$ | Energy consumed |
| U | Machine or resource efficiency in percentage |

# Declaration

The study outlined in this dissertation was carried out in the College of Engineering and Technology of the University of Derby, under the supervision of Doctor Kapila Liyanage and Doctor Sabuj Mallik. This is to declare that the work stated in this thesis was done by the author, and no part of the thesis has been submitted in a thesis form to any other university or similar institution. No human or animal participation have been included in this research, and the research presented in this thesis has been ethically approved. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. Parts of this thesis have previously appeared in the papers listed in the list of publications.

Mijoh, Ayodele Gbededo

University of Derby

2018

# List of Publications

## Journals

1. ***Gbededo, M. A.*** and Liyannage, K. (2018) 'Identification and Alignment of the Social Aspects of Sustainable Manufacturing with the Theory of Motivation', Sustainability Journals, pp. 1–23. doi: 10.3390/su10030852.
2. ***Gbededo, M. A.,*** Liyanage, K. and Garza-reyes, J. A. (2018) 'Towards a Life Cycle Sustainability Analysis: A Systematic Review of Approaches to Sustainable Manufacturing', Journal of Cleaner Production. Elsevier Ltd, 184, pp. 1002–1015. doi: 10.1016/j.jclepro.2018.02.310.
3. ***Gbededo, M. A.,*** Liyanage, K. and Oraifige, I. (2016) "Simulation Aided Life Cycle Sustainability Assessment ( LCSA ) Framework for Manufacturing Design and Management", Int. Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, vol. 10, no. 7, pp. 1–3.

## Conference Papers

1. ***Gbededo, M. A.,*** Liyanage, K. and Mallik, S. (2018) "Holistic Simulation-Based Impact Analysis Framework for Sustainable Manufacturing" Proceedings of the ICSIM 2018 : 20th International Conference on Sustainable Intelligent Manufacturing to be held in Paris, France during June, 25-26, 2018.
2. ***Gbededo, M. A.,*** and Liyanage, K. (2017) "Sustainable Manufacturing Assessment: Approach and the Trend Towards Life Cycle Sustainability Analysis" Proceedings of International Conference on Manufacturing Research (ICMR) – September 2017
3. ***Gbededo, M. A.,*** Liyanage, K. and Oraifige, I. (2016) "Simulation Aided Life Cycle Sustainability Assessment ( LCSA ) Framework for Manufacturing Design and Management" Proceedings of International Conference on Sustainable Manufacturing (ICSM)- July 2016

# Abstract/ Synopsis

This research focuses on effective decision-making for sustainable manufacturing design and management. The research contributes to the decision-making tools that can enable sustainability analysts to capture the aspects of the economic, environmental and social dimensions into a common framework. The framework will enable the practitioners to conduct a sustainability impact analysis of a real or proposed manufacturing system and use the outcome to support sustainability decision.

In the past, the industries had focused more on the economic aspects in gaining and sustaining their competitive positions; this has changed in the recent years following the Brundtland report which centred on incorporating the sustainability of the future generations into our decision for meeting today's needs **(Brundtland, 1987)**. The government regulations and legislation, coupled with the changes in consumers' preference for ethical and environmentally friendly products are other factors that are challenging and changing the way companies, and organisations perceive and drive their competitive goals **(Gu *et al.*, 2015)**. Another challenge is the lack of adequate tools to address the dynamism of the manufacturing environment and the need to balance the business' competitive goal with sustainability requirements. The launch of the Life Cycle Sustainability Analysis (LCSA) framework further emphasised the needs for the integration and analysis of the interdependencies of the three dimensions for effective decision-making and the control of unintended consequences **(UNEP, 2011)**. Various studies have also demonstrated the importance of interdependence impact analysis and integration of the three sustainability dimensions of the product, process and system levels of sustainability **(Jayal *et al.*, 2010; Valdivia et al., 2013; Eastwood and Haapala, 2015)**.

Although there are tools capable of assessing the performance of either one or two of the three sustainability dimensions, the tools have not adequately integrated the three dimensions or address the holistic sustainability issues. Hence, this research proposes an approach to provide a solution for successful interdependence impact analysis and trade-off amongst the three sustainability dimensions and enable support for effective decision-making in a manufacturing environment.

This novel approach explores and integrates the concepts and principles of the existing sustainability methodologies and frameworks and the simulation modelling construction process into a common descriptive framework for process level assessment. The thesis deploys Delphi study to verify and validate the descriptive framework and demonstrates its applicability in a case study of a real manufacturing system. The results of the research demonstrate the completeness, conciseness, correctness, clarity and applicability of the descriptive framework.

Thus, the outcome of this research is a simulation-based impact analysis framework which provides a new way for sustainability practitioners to build an integrated and holistic computer simulation model of a real system, capable of assessing both production and sustainability performance of a dynamic manufacturing system.

# Acknowledgement

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# CHAPTER 1

## 1. INTRODUCTION

This chapter introduces the PhD research on "Holistic Simulation-based Impact Analysis for Sustainable Manufacturing Design and Management". The section describes the overviews of the research context in section 1.1, aim and objectives in section 1.2, the scope in section 1.3, the methodology in section 1.4, and the Thesis layout in section 1.5.

### *1.1.* Overview of Research Context (Motivation for the study)

In the past, the objectives of manufacturing industries were based solely on increasing competitiveness, economic efficiency, and acquiring material wealth without much consideration for the limited natural resources **(Stevens, 2005; Almeida *et al.*, 2015)**. The advent of Brundtland report tagged ***"our common future"*** has, however, sparked a new need of approach to the evaluation of industries' performance towards "meeting the needs of the present generation without compromising the ability of future generations to meet their own needs". The US Department of Commerce, defined Sustainable manufacturing as "the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" **(US EPA, OA, no date)**.

The definition clearly emphasised on the environmental protection, social development, and economic development as the three sustainability dimensions required for achieving the objectives of sustainable manufacturing **(Consultants, 2000; Hutchins and Sutherland, 2008a)**. Various assessment tools have been proposed by the international standard organisations to assess the impacts of each of this sustainability aspects such as the ISO 14040 Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) **(ISO 14040:2006, no date; ISO 15686-5:2017, no date; ISO 26000:2010, no date; Leckner and Zmeureanu, 2011)**. There are also contemporary quantitative assessment frameworks that are capable of assessing the combination of one or two of the three dimensions **(UNEP Setac Life Cycle Initiative, 2009; Guinée *et al.*, 2011; Leckner and Zmeureanu,**

**2011)**, however, the frameworks have neither adequately integrated all the three dimensions nor considered the effects of their interdependencies, and the dynamism involved in the manufacturing production processes. Other researchers have proposed the use of LCA in parallel with performance optimisation tools such as simulation, value stream mapping, lean manufacturing, Activity Based Costing (ABC), and Decision Making Trial and Evaluation Laboratory (DEMATEL**)** **(Sumrit and Anuntavoranich, 2012; Deng, Liu and Liao, 2015).**

Although these tools have contributed to the development of sustainable products, the primary scientific challenge remains the lack of interdependent analysis of the economic, environmental and social aspects for effective decision-making. Further, many companies claim activity towards sustainability at the strategic and operational levels, however, the frameworks used to support these activities are out of balance, being economically oriented and do not adequately account for environmental or simultaneously acknowledge the social issues **(Takata *et al.*, 2004a; Nambiar, 2010; Luong, Liu and Robey, 2012).** There is, therefore, the need for a robust sustainability evaluation process that enhances effective decision-making.

Recently, in consideration of possible unintended consequences of the effects of sustainable manufacturing decisions, the joint organisation of United Nations Environmental Programme (UNEP) and Society for Environmental, Toxicology and Chemistry (SETAC) launched a holistic and integrated Life Cycle Sustainability Analysis (LCSA) framework. This framework is to enable researchers from different disciplinary fields of study, to discuss and develop methods that integrate life cycle thinking and sustainability analysis in manufacturing design **(United Nations Environmental Program (UNEP), 2011; Valdivia *et al.*, 2013; Zamagni, Pesonen and Swarr, 2013).** Many authors have emphasised on the analytical requirement of LCSA as against the independent assessment of each of the three dimensions and summing the result**s** **(Heijungs, Settanni and Guinée, 2013; Sala, Farioli and Zamagni, 2013a; Valdivia *et al.*, 2013)**. Various approach and analytical methods have also been posited by many researchers in support of the LCSA framework; these include Data Envelopment Analysis, Mathematical modelling, and other sustainability methodologies that incorporate Simulation model **(Seow, Rahimifard and Woolley, 2013; Tsai *et al.*, 2013; Cortes, 2017).** The analytical requirement is to enable a holistic interdependent analysis of the aspects of the three sustainability dimensions and provide support for effective decision-making.

The simulation approach to sustainable manufacturing is currently gaining preference due to the inherent analytical functions and ability to support effective decision-making in a dynamic manufacturing environment. Also, simulation has been used to model and improve manufacturing systems' behaviour, drive competitive advantage and predict production performance **(Robinson, 2013)**. However, the case study and review of existing simulation applications to sustainable manufacturing shows the approach still lacks integration of the three sustainability factors **(Paju *et al.*, 2010; Thiede *et al.*, 2013)**. In addition, the current simulation software in the market, as reviewed by **(Thiede *et al.*, 2013)** do not have environmental or social functions by default. This research, therefore, seeks to develop a framework that combines existing sustainability assessment tools, life cycle thinking, and inherent values of simulation to analyse the impacts of the manufacturing process in a dynamic production environment. The outcome of the research will enable sustainability practitioners to build a holistic simulation model that support effective decision making at the design phase of sustainable product development. The model will enable the capture of the aspects of the three sustainability dimensions and impact analysis of their interdependencies.

## *1.2.* Overview of Research Aim and Objectives

The main aim of this research is:

> **To develop a holistic, integrated simulation-based impact analysis framework that supports decision-making for sustainable manufacturing design and management**

In order to realise this aim, the study seeks to achieve the following objectives:

a) Assess the existing sustainability methodologies and frameworks, evaluate their decision supporting strengths and weaknesses, and develop an effective strategy for the proposed framework.
b) Determine an appropriate approach to capture the aspects of the three sustainability dimensions for an analytical model.
c) Develop a descriptive framework that allows companies to build an integrated computer simulation model of a real system which is capable of assessing both production and sustainability performance of a dynamic manufacturing system.

d) Verify and validate the descriptive framework by a Delphi method, and demonstrate its applicability by modelling a real manufacturing environment.

The terms used in this thesis includes **“sustainability”** which indicate the state and the presence of the three dimensions of sustainable development as defined by the Brundtland report **(Brundtland, 1987).** These are **environmental protection, economic development and social development**. While the use of “**sustainability aspects**” refers to the “**impact categories”** of the sustainability dimensions, for example; energy, GHG emission and raw materials are environmental aspects. Operations’ costs, productivity, throughput and production wastes represent economic aspects, and child labour, health and safety, and workers’ training represent the social aspects. The **“sustainability dimensions**” are also referred to as “**sustainability pillars”** or “**sustainability factors**”. The last two, are seldom used in this study. A **“holistic**” approach implies total consideration that includes the aspects of the three sustainability dimensions, while “**integrated**” refers to the simultaneous consideration of the aspects of the three sustainability dimensions.

An **“analytical model”** refers to a logical mathematical system or framework capable of calculating the behaviours of different elements in a **“what if**” scenario and over a finite period **(Caliri, 2000).** The Discrete Event Simulation (DES) model is an example of an analytical model used in the manufacturing to gain an understanding of the current operations’ activities and predict the impacts of production elements on the operation. The development of a holistic, integrated analytical model will provide a sustainability analyst with the opportunity to study, understand and predict the various behaviour pattern of both production and sustainability performance of a dynamic manufacturing system.

A “**descriptive framework**” is a **conceptual framework** developed from both theoretical concepts and empirical data of existing studies. The descriptive framework is developed to guide the construction of a holistic, integrated simulation-based impact analysis model that supports effective decision-making. To **“verify**” implies testing the correctness and completeness of the theories, and the conciseness and clarity of the developed framework. The term **“validation”** is used to demonstrate the authentication of both the theoretical and pragmatic application of the framework.

The terms “the framework”, “the simulation-based framework”, “the integrated-simulation-based framework”, “the holistic simulation-based framework”, “the simulation-based sustainability impact analysis framework”, and “the developed framework” are used interchangeably in the thesis to refer to the **“Holistic Integrated Simulation-based Impact Analysis Framework for Sustainable Manufacturing Design and Management**”.

### *1.3.* Overview of the scope of this research

Sustainable manufacturing (SM) is defined as “the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” **(US EPA, OA, no date).** The concept of SM cuts across the lifecycle of a manufactured product that is; from the cradle to the grave or the end-of-life choices. This often transverses the supply networks of the suppliers’ supplier and customers’ customer thus making the data collection process for sustainability assessment very complex and daunting. In order to set the scope for this study, investigations were carried out into various types of approaches, methodologies, and strategies for sustainable manufacturing. Contemporary research covers eco-innovations, clean production, products’ lifecycle assessment, and impact assessments of the economic, social and environmental aspects of the sustainability dimensions.

SM can also be categorised into three types of assessment levels:

1. **Process-level assessment** which involves the assessment of a processing stage in a product lifecycle such as the manufacturing production processing stage **(Jayal *et al.*, 2010; Parent, Cucuzzella and Revéret, 2013)**.
2. **Product-level assessment** includes the assessment of all the stages of a product life cycle from the cradle to the grave or end of life choice
3. **System-level assessment** includes the assessment of an entire supply chain of a product development process or an entire manufacturing site.

With further investigations, this research adopts the gate-to-gate approach **(Jiménez-González, Kim and Overcash, 2000; Puettmann and Wilson, 2005; Russell-Smith and Lepech, 2015)** for a **process level assessment**. The context of this research is set to focus on the sustainability impact analysis of the production process within a manufacturing gate-to-gate boundary with emphasis on the **discrete manufacturing process.**

## *1.4.* Overview of research methodology

The context of this research describes operational research or system analysis due to the emphasis on sustainability impact analysis and the need to support effective decision-making. Operations Research (OR) involves the use of mathematical and quantitative techniques to provide a rational basis for decision-making, especially in the absence of complete information.

This research deploys a multi-methodological approach corresponding to the stated research objectives. These are discussed further in chapter 3 under research programme development.

## *1.5.* Thesis Layout

This thesis is organised into 3 phases consisting of 8 chapters (Figure 1-1) including this introduction **(Chapter 1**) which provides an overview of the research context with the highlight of the motivation for the study, aim and objectives of the research, scope of the research, research methodology and the layout of the thesis.

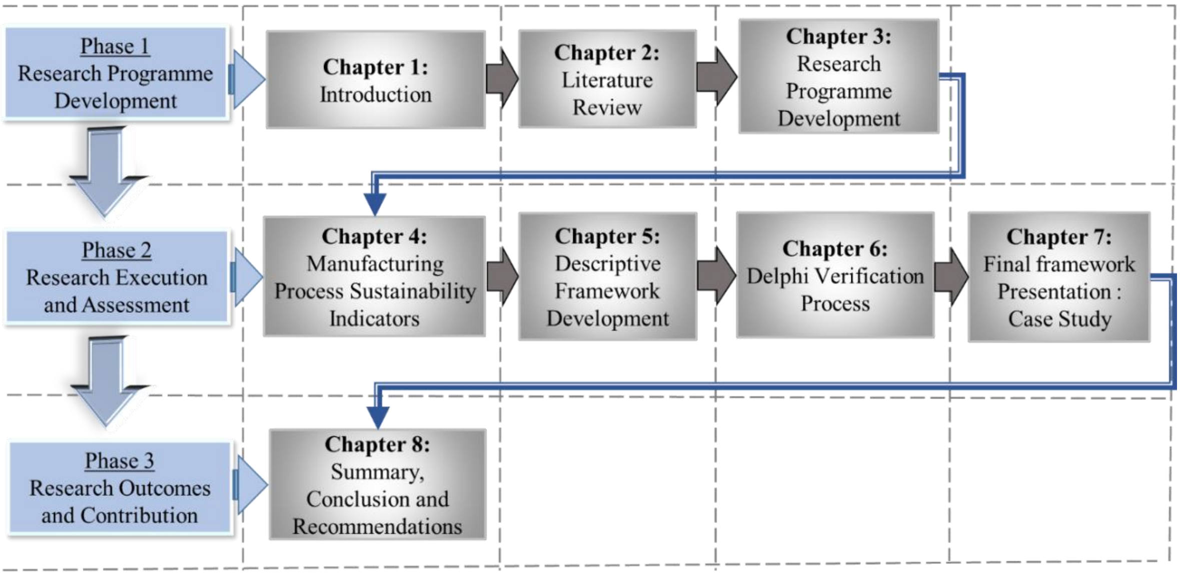


*Figure 1-1 The layout of the thesis*

In **Chapter 2** - The literature review - is presented first to clarify the impact of manufacturing on the environment, economy and society as a significant global challenge, and the issues associated with adopting holistically sustainable manufacturing as lack of appropriate approach and practical tools. The second phase of the literature review and analyses the existing sustainable manufacturing approaches through a systematic literature review to identify gaps in the research and examine the strengths and weaknesses of the existing methods. The analysis inspires the research question and underpins the development of a holistic simulation-based sustainability impact analysis framework.

In **Chapter 3** – The research programme development and methodology – expatiates on the aim and objectives of the research, the scope, and boundary for the study and the various research methodologies adopted in realising each of the objectives of the research. The chapter formulates the applied research multi-methodology adopted in this research.

In **Chapter 4**- Sustainability indicators for sustainable manufacturing process – streamlines the impact category indicators for a product lifecycle assessment to a process level category indicators. The chapter adopts the Global Reporting Initiatives (GRI) category indicators to capture relevant sustainability aspects for the impact analysis. The chapter also presents a strategy for capturing and translating the social aspects into sustainability analytical equation.

**Chapter 5**- The conceptual framework development – presents a step-by-step approach to the development of the initial descriptive framework for building a holistic simulation-based sustainability impact analysis model. Beginning with the outcome of the systematic literature review of chapter 2, this chapter deploys an inductive analytical approach for the emergence of the new holistic simulation-based framework.

**Chapter 6** – Delphi Study Validation Process– presents the process of verifying the framework developed in chapter 5 base on four defined criteria: correctness, completeness, conciseness, and clarity of the framework. The study deploys the knowledge of 24 experts in the field of sustainable manufacturing and relevant field to examine the set criteria in a Delphi format until a consensus is reached amongst the panel of the selected experts.

**Chapter 7** – Presentation of the final framework- presents the verified framework of chapter 6 through a validation process. A case study based validations process is presented in this chapter alongside a step-by-step simulation modelling description and a detailed application of the integrated simulation-based sustainability impact analysis framework.

**Chapter 8** – The Summary, Conclusion and Future Work Recommendation - This chapter summarises the thesis by discussing the research findings, contributions of the research and research limitations. The chapter concluded with the evaluation of the thesis achievement against the set objectives, and the recommendation for the future research works.

# CHAPTER 2

# 2. LITERATURE REVIEW

## *2.1. Introduction*

This chapter first presents a literature review of sustainable manufacturing, covering the global challenges and issues associated with sustainable development. This is followed by the importance of the UNEP/SETAC Life Cycle Sustainability Assessment (LCSA) framework for a holistic approach to sustainable development. Then, a systematic review of the current approaches to sustainable manufacturing is presented in order to identify the major gaps in research and examine the strengths and weaknesses of the existing methods. The output of this chapter underpins the formulation of the research questions and the development of a holistic framework for sustainable manufacturing as stated in the aim and objectives of this research. Figure 2-1 shows the outline of the literature review.

In section 2.2, the impact of manufacturing activities is identified as a significant contributor to global warming and other environmental issues. The scope of most product lifecycles, however, made it almost impossible to perform effective product lifecycle assessment. Streamlining the scope of assessment through the goal and assessment boundary definition, thus, becomes inevitable for practical analysis of the impacts of the manufacturing processes. Most especially, the section discussed a “gate-to-gate” approach as appropriate for the aim and objective of this research.

In section 2.3, the importance of Life Cycle Sustainability Analysis (LCSA) and its application in the context of sustainability science and simulation modelling is highlighted. In section 2.4, Sustainable Product Development (SPD) and Sustainability Performance Assessment (SPA) were identified as the two major sustainable manufacturing approaches prevalent in the literature. The two approaches were subsequently categorised either as integrated or segmented. The systematic review of the literature examined literature published on sustainable manufacturing between 2006 and 2015. The review identified 54 relevant contributions within the defined scope, and the analysis indicated 68.5% of the articles focused on SPD techniques, whereas 31.5% on SPA techniques. From the second, 70.4% of these were segmented approaches while only 29.6% incorporated the three sustainability dimensions. Further, the analysis showed that the energy aspect was incorporated into all the approaches, and there is a dearth of holistic approaches to sustainable manufacturing.

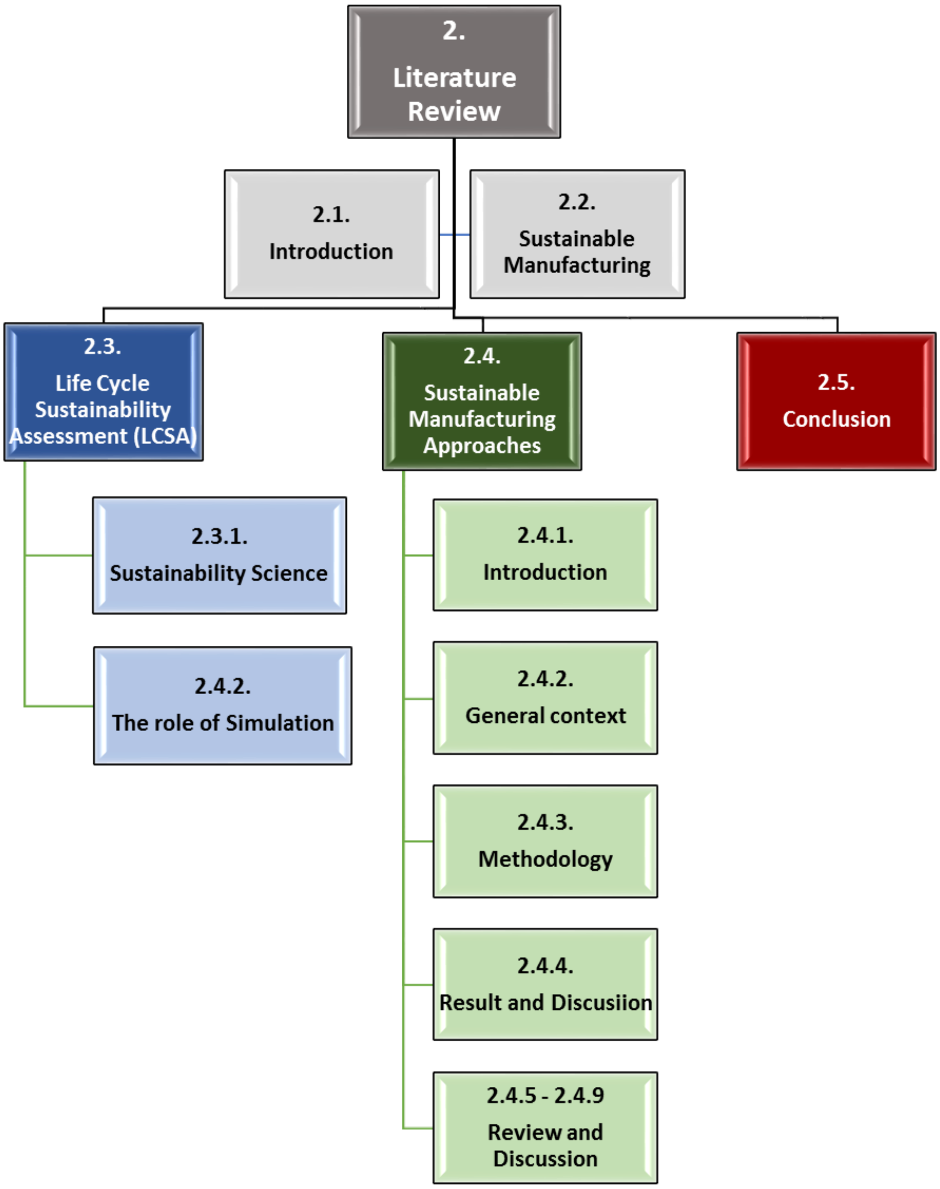


*Figure 2-1 The outline of the literature review – chapter 2*

The outcome of this review chapter underpins the development of a theoretical framework which was further developed into a holistic simulation-based analytical framework that integrates goals that support progressive sustainable product development with methods that focus on the holistic quantitative analysis of the three sustainability dimensions.

### *2.2. Sustainable Manufacturing: The global issues and challenges*

The global society is becoming more concern of the degrading environment and the resulting global warming, increasing sea level, and uncontrollable disasters including the recent heat-wave in India **(BBC News, no date; Takata *et al.*, 2004; Halog and Manik, 2011; LFCP, 2015; United Nations, 2017).** The primary cause of global warming has been attributed to the over-consumption of energy and materials such as coal, fossil oil, water, natural gases and emission of harmful substances during the creation of manufactured products **(Unfccc, 1992).** For instance, the greenhouse effect which is due to the emission of gases caused by industries and human activities has resulted into a temperature rise by over 0.7 degrees Celsius in the last five years **(Nasa, 2015).** Most of these contributions to unsustainable environment occur during the company's supply chain and distribution of products and services to the consumer.

In the past, before the declaration of Brundtland report tagged ***"Our Common Future"*** **(Brundtland, 1987),** the objectives of the manufacturing industries were based on increasing economic efficiency and strengthening their material wealth **(Stevens, 2005; Almeida *et al.*, 2015)**. The advent of Brundtland report places demands on industries to evaluate their performances toward *"meeting the needs of the present generation without compromising the ability of future generations to meet their own needs"* **(Brundtland, 1987).** The report has been interpreted to anchor on three sustainability dimensions: economic development, social development and environmental protection **(Luong, Liu and Robey, 2012; Mastoris, Morgan and Evans, 2013; Sala, Farioli and Zamagni, 2013a)**. The US Department of Commerce defines sustainable manufacturing as *"the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound"* **(US EPA, OA, no date)**. **Widok, Wohlgemuth and Page (2011)** defines sustainability in a capital-based approach as *"the agglomeration of actions/campaigns/processes that have a positive effect on the regeneration of social, environmental and/or economic capital on the one hand, and/or reduce the degradation of this capital on the other"*.

Since the adoption of Brundtland declaration by the international bodies, regulatory and legislative pressures on manufacturing industries have increased. There are also prevailing changes in consumers' demand pattern towards more sustainable products and practices **(Rahimifard, Seow, and Childs, 2010; Ustainability *et al.*, 2010; Cataldo, Taisch and Stahl,**

**2013; J.K. Simpson and K. Radford, 2014)**. Hence, the current global focus is now on supporting and coercing manufacturing industries to implementing sustainability approaches such as cleaner and more efficient production practices that enable development of products with reduced negative environmental and societal impacts **(Stevens, 2005; Conference, Summit and Sia, 2010; Zeng *et al.*, 2010; Kubota and Da Rosa, 2013; Ribeiro and Kruglianskas, 2013)**. Other stricter environmental regulations and policies are also enacted to hold companies accountable for the lifecycle impact of their products and to be driven into eco-innovations that transform unsustainable development to one that is sustainable **(Sailing *et al.*, 2002; Korhonen and Luptacik, 2004; World Business Council on Sustainable Development, 2010)**. The process involved in the creation and use of a manufactured product, however, extends beyond a geographically located or focal organisation to networks of product lifecycle actors that may cut across geographical locations and time zones. Thus the question often asked is to what extent an organisation is responsible for its created product? The life cycle of a product as depicted in Figure 2-2, is generally described as the stages a product goes through from cradle (raw materials extraction) to the grave or end-of-life option. Each of the stages is bounded by two gates: "gate-in" and "gate-out" representing the "start" and "end" of the activities that take place within the stage respectively **(Puettmann and Wilson, 2005)**.

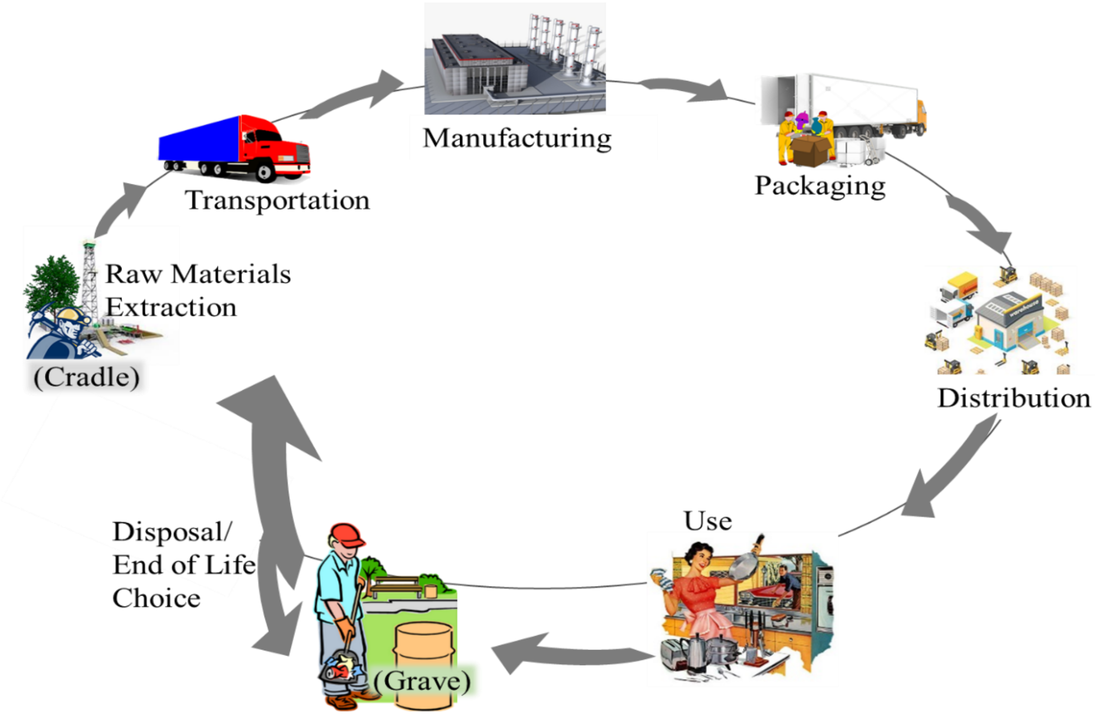


*Figure 2-2 The life cycle of a product and its stages*

The global challenge, however, has been posited to be environmental, social and economic sustainability **(Brundtland, 1987; Mastoris, Morgan and Evans, 2013).** The method deployed for the assessment of the activities involved in the product lifecycle stages is known as the Life Cycle Assessment (LCA) or cradle-to-grave analysis **(Leslie JACQUEMIN, Pierre-Yves PONTALIER, 2012)**. Empirical studies and research have highlighted the efforts of industries in implementing approaches that support sustainable development. Organisations now incorporate processes that enable development and assessment of environmental and social objectives in addition to the economic performance **(Rosen and Kishawy, 2012).** Some of the approaches focus solely on innovative design or continuous improvement of the processes, systems or products in order to enhance economic, environmental and social sustainability. Other approaches focus on the process, system or product's level sustainability assessment in order to support decision-making. However, case studies and research reveal that the adoption of sustainable development is a major challenge due to various factors including the lack of a standard holistic assessment framework to support effective decision-making and for its implementation **(Paju *et al.*, 2010; Bhanot, Rao and Deshmukh, 2015)**. The impacts of this challenge accounted for the current trend of non-holistic approaches to sustainable product development where optimisation of related environmental factors such as materials and energy efficiencies are being integrated with competitive manufacturing strategies **(Kibira and McLean, 2008; Haapala, *et al.*, 2011; Casamayor and Su, 2013; Keskin, Diehl and Molenaar, 2013; Aydin, Kwong and Ji, 2015; Gelbmann and Hammerl, 2015).**

### *2.3.* The Life Cycle Sustainability Assessment (LCSA)

In the recent years, the subject of the Life Cycle Sustainability Assessment (LCSA) has emerged and the United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) under its Life Cycle Initiative, have published a framework to support the development of a holistic LCSA **(United Nations Environmental Program (UNEP), 2011; Valdivia *et al.*, 2013; Zamagni, Pesonen and Swarr, 2013).** The framework provides the platform for scientists from various fields of study to discuss sustainability subject with a holistic life cycle perspective. Though the initial idea to combine LCA, LCC, and S-LCA methodologies into a framework was first postulated by **Klöpffer (2005),** the holistic view of LCSA framework refers to the evaluation of the social, economic and environmental impact and benefit of a product or service throughout its lifespan.

**Valdivia *et al.* (2013)** posited that it is possible to combine LCA, LCC and S-LCA to develop a holistic sustainability evaluation tool. However, the authors stressed that the results of the evaluation should not be added up as portrayed in the classical discipline approach to the LCSA model but rather be jointly analysed (Figure 2-3). The field of analytical science or computation science thus becomes apparent in the development of LCSA. **Valdivia *et al.* (2013)** further state that combining the three methodologies into LCSA have the potential benefits which include cost and risk reduction, consistency in reporting and active engagement of the stakeholder. In the special review of **(Zamagni, Pesonen and Swarr, 2013),** the authors discussed the state and direction of the life cycle approach in the context of sustainability. The authors created an overview of the contribution of some key literature in respect to the development of appropriate tools for the LCSA framework. The authors noted that the enterprises' behaviour of "ability to act on" **(Parent, Cucuzzella and Revéret, 2013),** Life Cycle Thinking (LCT) which is an inherent nature of Sustainability Science (SS) **(Sala, Farioli and Zamagni, 2013a)** and Sustainability Analysis **(Guinée *et al*., 2011)** are vital contributions toward framing a holistic LCSA tool. **Parent, Cucuzzella and Revéret (2013)** emphasised on the importance of LCT, LCA and S-LCA in sustainable development and observed that S-LCA is scarcely discussed under Statistical Process Control (SPC) and the social impact of products on the consumer is hardly mentioned. Thus Corporate Social Responsibility (CSR) and their appropriate effort to act on social and customers' demands are vital to sustainable development.

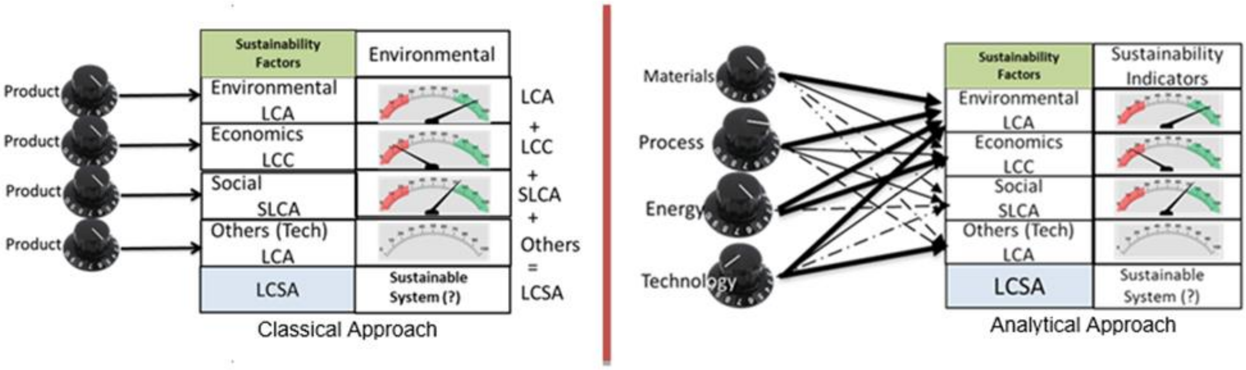


*Figure 2-3 Example of Classical versus Analytical Approach to LSCA*

### *2.3.1. Sustainability Science (SS) and Life Cycle Sustainability Analysis (LCSA)*

In harmony with LCSA development, Sustainability Science (SS) has also been posited as a holistic approach to achieving sustainability **(Sala, Farioli and Zamagni, 2013b)**. This method approaches sustainability development from cultural, historical and institutional perspectives. According to **(Sala, Farioli and Zamagni, 2013b),** its emergence compliments the inadequacies in classical disciplines and scientific approach to the management of sustainability. Application of SS thus made it possible to "scientifically transcend reductionist analysis of classical science through system thinking approach to address sustainability factors within political and sustainability domain" **(Sala, Farioli and Zamagni, 2013b).** One crucial feature of SS is that LCT and LCA are inherently embedded in it; these factors make it possible to explore dynamic activities and interactions between nature, human activities and the society in order to design a holistic sustainability framework **(Sala, Farioli and Zamagni, 2013b; Zamagni, Pesonen and Swarr, 2013).**

**Guinée *et al.* (2011)** expressed the ideology of LCSA (Life Cycle Sustainability Assessment) framework with a similar concept termed Life Cycle Sustainability Analysis (LCSA).This new framework better described the jointly analytical requirements of the combined LCA, LCC and S-LCA methodologies. Sustainability Analysis is core to SS and it interchangeably used with Sustainability Assessment in some literature **(Parent, Cucuzzella and Revéret, 2013; Zamagni, Pesonen and Swarr, 2013)**. According to the observation of **Sala, Farioli and Zamagni (2013)** on the analysis of these two frameworks against SS criteria for addressing sustainability; the authors noted that, LCSA (Assessment) failed to consider the mutual interaction amongst the three sustainability pillars hence, devoid of holistic understanding of the system under consideration, however; LCSA (Analysis) framework overcame this inadequacy through an integrated approach. **Sala, Farioli and Zamagni (2013)** also summarised the development of sustainability analysis framework as characterised by the trans-disciplinary, holistic and system-wide approach. According to the authors, it is a "shift from multi- towards trans-disciplinary; multi-scale (temporal and geographical) perspectives; and better involvement and participation of stakeholders" **(Sala, Farioli and Zamagni, 2013b)**.

### *2.3.2. The Roles of Simulation in Sustainability Decision-Making*

In the past decades, simulation has provided solutions to many challenges that require a high cost of an experiment for a real-life situation. It provides opportunities for testing different approaches and varying indicator compositions to enhance process flow and achieve potential desired measure before a real-life application **(Widok, Wohlgemuth and Page, 2011; Laroque *et al.*, 2012).** There are two major categories or classifications of simulation, these include;

1. Static versus Dynamic simulation model
2. Deterministic versus Stochastic simulation model

***Static versus Dynamic:*** In the Static simulation model, the passage of time plays no meaningful role or affect the structure of the operations and execution of the simulation model **(Kelton, Smith and Sturrock, 2011).**

An example is the use of an Ms Excel to model single-period energy consumption or cost activity. Whereas, in a Dynamic simulation model, the passage of time is crucial and part of the model structure, operations, and execution **(Kelton, Smith and Sturrock, 2011)**. A queuing-type system such as manufacturing and health services where arrival time and operations time changes are examples of a dynamic model. Dynamic models are also often characterised by state variables such as “queuing length”, “time or number in the system”, “idle time.”

A dynamic model can either be Continuous-Change or Discrete-Change, representing another class of simulation model.

***Continuous-Change versus Discrete-Change***: In a Continuous-Change simulation model, the state variables change continuously over continuous time. Whereas, a Discrete-Change model will change at instantaneous and separated discrete points on the time and “busy time” that collectively define the status of a simulation model at a point in the time axis **(Kelton, Smith and Sturrock, 2011).**

**Deterministic versus Stochastic**: When the input parameters into a simulation model are fixed with service time, constant and non-random, then, the simulation model is “Deterministic”. A deterministic situation is rare as it assumes no breakdown of parts or machines with constant input and same result for all the operations. A stochastic model is a non-deterministic model where input parts are assumed to arrive at random intervals from a probability distribution and processes. The focus of this research is on Dynamic, Discrete-Change and Stochastic simulation model.

Discrete Event Simulation (DES) has been used in both supply chain management and manufacturing for optimisation of processes and resource usages **(Perera and Rupasinghe, 2015).** In the recent years, we have experienced various efforts of developers in the application of DES to support decision-making in sustainable manufacturing. The integration of Discrete Event Simulation with LCA (DES-LCA) or DES with Material Flow Analysis as in MILAN software **(Laroque *et al.*, 2012)** promises a solution to environmental and economic dimensions leaving behind the consideration for social dimensions. This issue is common with many other integrated simulation software due to the difficulty to adequately incorporate all the three sustainability dimensions, most especially the social aspects into software **(Heilala *et al.*, 2008; Laroque *et al.*, 2012).** The social indicators are however relatively vast and interdependent on the other sustainable dimensions. According to **(Zamagni, Pesonen and Swarr, 2013),** there is a need for further innovative research and development in the area of Life Cycle Sustainability Assessment (LCSA) to address corporate policy and decision-making. The LCSA framework proposes an integrated approach to balance and enable assessment and trade-off of the three factors for an effective sustainability decision-making process **(Widok, Wohlgemuth and Page, 2011; Zamagni, Pesonen and Swarr, 2013)**. It has been posited that the main challenge of designing and managing a sustainable manufacturing system is the complexity of interdependent aspects and variables to be handled simultaneously **(Heilala et al., 2008; Nambiar, 2010)**

## *2.4.* Sustainable Manufacturing Approaches

### *2.4.1. Introduction*

This section presents a systematic review of the approaches to sustainable manufacturing. The section aims at identifying gaps both in practice and research within the context of the manufacturing sector through a structured literature review. In order to do this, the section systematically identifies and critically analyses current contributions in the field of sustainable manufacturing, with a particular interest in sustainability assessment techniques and Life Cycle

Sustainability Analysis. The review underpins both the development of the research question and a holistic conceptual framework.

In the subsequent sections 2.4.2 and 2.4.3, the general context of sustainable manufacturing approaches and research methodology are discussed, followed by the results and discussions of the findings in section 2.4.4. The theoretical development process for the proposed integrated framework is detailed in Chapter 5. Section 2.5 provides the summary, identified research gaps and directions, and the conclusions.

### ***2.4.2.*** *The General Context of Sustainable Manufacturing Approaches*

In the recent years, we have witnessed a plethora of research on sustainable product development and the emergence of new sustainable products and technologies. The integration of sustainability into the product design phases and operations' activities are the current norm in the industries. Eco-innovation, eco-design, clean production, lean-green manufacturing and Corporate Social Responsibility (CSR) are some of the terms used by organisations to demonstrate their commitments toward sustainable development. The multiple criteria and variables of competitive and sustainability to be considered simultaneously thus become more complex and challenging for effective decision-making in sustainable manufacturing **(Cabot *et al.*, 2009)**.

There are contemporary assessment tools used by industries to assess the impacts of each of the three sustainability dimensions, such as the ISO 14040:2006 Life Cycle Assessment (eLCA) framework **(ISO 14040:2006, no date)**. However, the eLCA framework is environmental centric, segmented and does not support effective sustainability decision-making during product development **(Krozer and Vis, 1998; Pryshlakivsky and Searcy, 2013).** The integration of Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA) **(Leckner and Zmeureanu, 2011)** and the eLCA framework have also emerged to sequentially or inter-dependently analyse the impact of the three dimensions throughout a product lifecycle **(Heijungs, Huppes and Guinée, 2009; UNEP Setac Life Cycle Initiative, 2009; Leckner and Zmeureanu, 2011; Hong *et al.*, 2012).** Many researchers have proposed the use of eLCA in parallel with performance optimisation tools such as lean manufacturing, value stream mapping, simulation, Activity Based Costing, and Decision Making Trial and Evaluation Laboratory **(Sumrit and Anuntavoranich, 2012; Deng, Liu and Liao, 2015).**

The existing sustainability decision-making and strategy formulation are anchored on either one or the combinations of the tools mentioned above for the assessment of a product or service lifecycle. However, despite the vast research on the sustainability tools, the leading world challenge remains the integration of the economic, environmental and social features of the life cycle of a product **(Mastoris, Morgan and Evans, 2013).** Further, **Mastoris, Morgan and Evans (2013)** stated that many companies claim activity towards sustainability at the strategic and operational levels, however, the frameworks used to support these activities may be out of balance, economically oriented and do not adequately account for the three sustainability dimensions (Takata *et al.*, 2004b; Nambiar, 2010; Widok, Wohlgemuth and Page, 2011)**.** One other challenge of practical use of the ISO 14040 LCA framework is the overwhelming amount of massive data, and or lack of necessary data and information that cut across a product lifecycle **(Zamagni, Pesonen and Swarr, 2013; Gmelin and Seuring, 2014)**. Data identification and collection process could be daunting, and having inefficient quality data can cause a severe delay and restriction during the development of a simulation model **( Perera and Liyanage, 2000; Bokrantz *et al.*, 2017).** Also, the existing assessment frameworks have neither adequately integrated all the three sustainability dimensions nor considered the effects of their interdependencies, and the dynamism of manufacturing production processes.

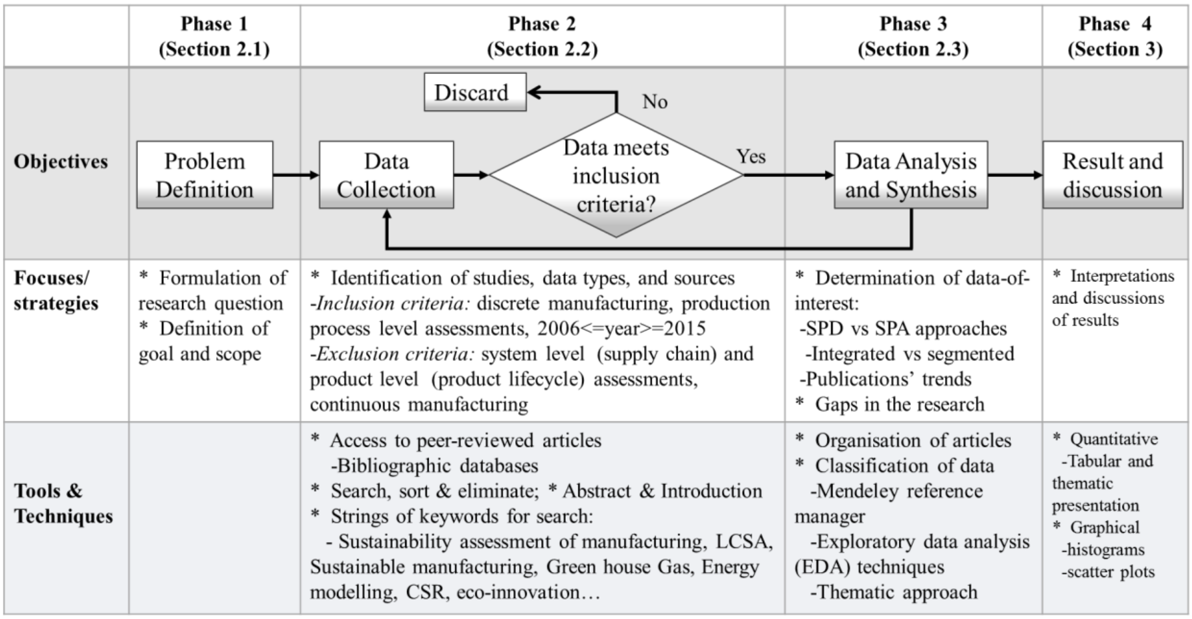
In 2011, the United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) **(United Nations Environmental Program (UNEP), 2011)**, under its Life Cycle Initiative programme, published a framework to support the development of a holistic Life Cycle Sustainability Assessment (LCSA). The framework provides the stage for a new approach to sustainability subject among scientists, researchers, and practitioners to discuss and implement sustainable development with a holistic life cycle perspective **(United Nations Environmental Program (UNEP), 2011; Parent, Cucuzzella and Revéret, 2013; Valdivia *et al.*, 2013; Zamagni, Pesonen and Swarr, 2013)**. Given the above, and in order to facilitate and further the progress of research in this field, the researcher is driven to answer the following questions:

1. What are the current research approaches in sustainable manufacturing?
2. What is the trend and direction from partial or segmented assessment methods to an integrated, holistic assessment of the three sustainability dimensions?
3. How practical are the existing approaches in supporting effective sustainability

decision-making?

### *2.4.3. Methodology for the Systematic Literature Review*

The research methodology adopted to conduct a literature review is critical to the validity of the results, applicability, and outcomes of the review **(Goodall, Rosamond and Harding, 2014; Garza-Reyes, 2015).** This research adopts a structured approach to perform a full literature review; a method that is systematic, transparent, methodical and reproducible to inform policy and decision-making **(Tranfield, Denyer and Smart, 2003; Goodall, Rosamond and Harding, 2014). Tranfield, Denyer and Smart (2003)** espoused three phases of processes which have been adopted by various researchers to systematically review full literature based on a defined research question, goals and scope (e.g**. (Chang, Lee and Chen, 2014; Brones and Monteiro De Carvalho, 2015; Garza-Reyes, 2015; Esmaeilian, Behdad and Wang, 2016; Fakhimi, Mustafee and Stergioulas, 2016)*).*** The three steps process involves data collection, data analysis, and synthesis. **Goodall, Rosamond and Harding (2014)** define the three stages as the scope of the study, search strategy, and evaluation of the material method. **Esmaeilian, Behdad and Wang (2016)** expounded on these in a three-stage qualitative research method as identification, classification, and evaluation. The identification stage, which is the data collection phase, consists in identifying studies through a search of scholarly databases (such as electronics database, and the web of science), limited by the defined goals and scope of the review such as articles date, type, and keywords **(Garza-Reyes, 2015).** The classification stage, similarly to the data analysis phase, is the process of organising articles according to approaches and techniques, and in a way that they can easily be accessed and retrieved. Finally, the evaluation stage involves the analysis and synthesis of the quantitative and qualitative results into an interpretive pattern or summary **(Brones and Monteiro De Carvalho, 2015).** Thus, in reference to the above-reviewed methods, this study adopts a four-phase approach as depicted in Figure 2-4. The phases include: 1) the definition of the research problem, 2) the data collection, 3) the data analysis and synthesis, and 5) the result reporting and discussions phases.



| | Phase 1 (Section 2.1) | Phase 2 (Section 2.2) | Phase 3 (Section 2.3) | Phase 4 (Section 3) |
|---|---|---|---|---|
| **Objectives** | Problem Definition | Data Collection → Data meets inclusion criteria? No → Discard; Yes → | Data Analysis and Synthesis | Result and discussion |
| **Focuses/ strategies** | * Formulation of research question<br>* Definition of goal and scope | * Identification of studies, data types, and sources<br>-*Inclusion criteria:* discrete manufacturing, production process level assessments, 2006<=year>=2015<br>-*Exclusion criteria:* system level (supply chain) and product level (product lifecycle) assessments, continuous manufacturing | * Determination of data-of-interest:<br>-SPD vs SPA approaches<br>-Integrated vs segmented<br>-Publications' trends<br>* Gaps in the research | * Interpretations and discussions of results |
| **Tools & Techniques** | | * Access to peer-reviewed articles<br>-Bibliographic databases<br>* Search, sort & eliminate; * Abstract & Introduction<br>* Strings of keywords for search:<br>- Sustainability assessment of manufacturing, LCSA, Sustainable manufacturing, Green house Gas, Energy modelling, CSR, eco-innovation… | * Organisation of articles<br>* Classification of data<br>-Mendeley reference manager<br>-Exploratory data analysis (EDA) techniques<br>-Thematic approach | * Quantitative<br>-Tabular and thematic presentation<br>* Graphical<br>-histograms<br>-scatter plots |

*Figure 2-4 Phases, objectives, focuses, and tools for a systematic literature review*

### **2.4.3.1.** *Problem Definition Phase*

The Correct identification of a research problem is critical to finding the right path and solution to a phenomenon. This is often explicitly stated in a problem statement or refined in a research question and includes the description of the goals and scope of the investigation **(Gall, M. D., Gall, J. P., & Borg, 2006)**. In respect to the research question, this review focused on identifying the approaches to sustainable manufacturing and determining up to what extent these approaches have transitioned from segmented assessment methods to the holistic and integrated LCSA. The goal was to identify gaps both in practice and research within the boundary of the gate-to-gate manufacturing production domain. The scope was limited to the manufacturing production domain and the literature published between 2006 and 2015 (inclusive) on approaches to sustainable manufacturing. The purpose was to focus on the product and process design phase of manufacturing which is central to sustainability decision-making and most previous and up to date methodologies after UNEP/SETAC launched the LCSA framework in 2011 **(United Nations Environmental Program (UNEP), 2011)**. It is worth noting that the International Standard Organisation (ISO) first adopted LCA standard from the code of practice developed by SETAC in 1990 and the collaboration of SETAC and UNEP further enabled its worldwide acceptance in 2002 **(Klöpffer, 2006; Pryshlakivsky and Searcy, 2013)**. The delimited manufacturing production domain was established to allow focus on methodologies adopted for assessment of a discrete manufacturing production process for a product under design.

### **2.4.3.2.** *Data Collection Phase*

Due to the current global significance of the sustainability subject, there are proliferations of articles and literature on the topic cutting across the boundaries of every field of studies. Hence, the use of a keyword such as "sustainability" or "sustainable" in a search engine will generate an overwhelming volume of data. The main focus of the data collection phase is identifying the data types, sources, and defining the inclusion and exclusion criteria relevant to the problem statement of the review **(Garza-Reyes, 2015).** In this study, a search for peer-reviewed articles on approaches to sustainable manufacturing were conducted using strings of keywords (this is to ensure relevant articles are collected) to search major online bibliographic databases such as World of Science (WoS), the University Library Catalogue, Science Direct, and Google Scholar **(Garza-Reyes, 2015).** The use of Mendeley software enabled the processing and management of overlapped articles collected from the various sources. A further manual checking through the reading of the "abstracts" and "introductions" enabled elimination of irrelevant articles from the collections. The search included articles that used quantitative assessment approach and those that used the qualitative approach to new product development and continuous product improvement. Sustainable manufacturing development can be categorised into three types of assessment levels. 1) System-level assessment which includes the assessment of an entire supply chain of a product development process, 2) Product-level assessment which include the assessment of a whole product lifecycle from the cradle to the grave or end of life choice, and 3) Process-level assessment which involves the assessment of a processing stage in a product lifecycle such as the manufacturing production process **(Jayal *et al.*, 2010; Parent, Cucuzzella and Revéret, 2013).** The system level and the product level assessments were excluded in the data collection as they fell outside the boundaries of the defined scope of this study. The process level assessment is defined by the gate-to-gate boundaries **(Gbededo, Liyanage and Oraifige, 2015)** of a product lifecycle stage. The continuous production process was also excluded in order to focus on the discrete manufacturing process. The ten years range for collection allows for a balance of five years prior to the launch of the LCSA framework and five years from when it was launched. This approach enabled the inclusion or articles published in 2011 to be included as post launched. In addition to the scope defined in the problem statements, the delimited articles enhanced the speed of data collection and ensured analysis of a complete representation of a stage of a manufacturing type.

#### **2.4.3.3.** *Data Analysis and Synthesis Phase*

This phase is characterised by determining the data of interest, that is; what the researcher is looking for in the collected data, this underpins the data coding and choice of analytical tool appropriate for the analysis. Based on the problem statement, the approaches to sustainable manufacturing adopted by the reviewed authors, and the year of publication are of key importance to this study. In addition, the identification of the methods that are segmented and the combination groups of the sustainability dimensions in the segments are also crucial to our analysis. Those articles which included the three dimensions; some authors summed up the three parts while others suggested aggregation in an analytical equation. According to **Brones and Monteiro De Carvalho (2015),** synthesis is the most valuable process that involves the generation of new knowledge, based on complete data collection and meticulous analysis. There are various techniques for the data synthesis of quantitative and qualitative literature reviews that include thematic approach, bibliometrics, meta-analysis, and content analysis **(Brones and Monteiro De Carvalho, 2015; Garza-Reyes, 2015).** Thematic synthesis, as used by **(Garza-Reyes, 2015),** was adopted in this case due to its effectiveness in summarising, synthesising and classifying qualitative research into structured themes as depicted in Figure 2 [A]. With exploratory data analysis (EDA), the trend and relationships between the two major sustainable manufacturing approaches before and after the launch of the LCSA was established as shown in Figure 3. EDA is a robust data analysis technique which provides insight into the underlying structure of a data **(Behrens and Yu, 2003).**

### *2.4.4. Results and Discussion*

The data collection process produced a total of 54 articles relevant to the approach to sustainable manufacturing within the defined goal and scope. The data analysis categorised the literature into the two techniques adopted for sustainable manufacturing, i.e. Sustainable Product Development (SPD) techniques - 36 (66.7%) articles and Sustainability Performance Assessment (SPA) techniques - 18 (33.3%) articles, see Figure 2-5 [A]. From these, 38 (70.4%) of the papers focused on the segmented approach to sustainable manufacturing while 16 (29.6%) incorporated the three sustainability dimensions in their approach. Of the 38 segmented approaches, 35 (92.1%) included environmental, 14 (36.8%) included economic, and 8 (21.1%) included social aspects with at least one of the other sustainability dimensions in their assessments. These are denoted by “plus environmental”, “plus economic”, and “plus social” dimensions respectively in Figure 2-5 [B]. The result indicates a higher focus (92.1%) on environmental issues as compared to other sustainability challenges. The segmented approaches were deemed partial approaches to sustainable manufacturing due to the lack of a holistic approach that simultaneously considered the three sustainability dimensions.

Furthermore, the analysis showed that all of the 35 (100%) papers of the segmented approaches that included environmental dimension concentrated on the energy aspect and only 5 (14.3%) included materials and other aspects that related to the environmental dimension; see Figure 2-5 [C]. The result revealed the imbalance of the approaches towards the three sustainability dimensions, with greater neglect of the importance of the social dimension and its interconnection with the other dimensions. It also showed the fact that the current sustainable manufacturing approaches tend to focus more on competitive manufacturing that integrates environmental protection elements such as energy consumption. There are also limited papers in Sustainability Performance Assessment techniques (33.3%) when compared to those techniques that foster the continuous improvement and development of sustainable products (66.7%). The insufficient research in the holistic quantitative sustainability assessment techniques such as LCSA, explains the high volume of literature present in the segmented approach to sustainable manufacturing.

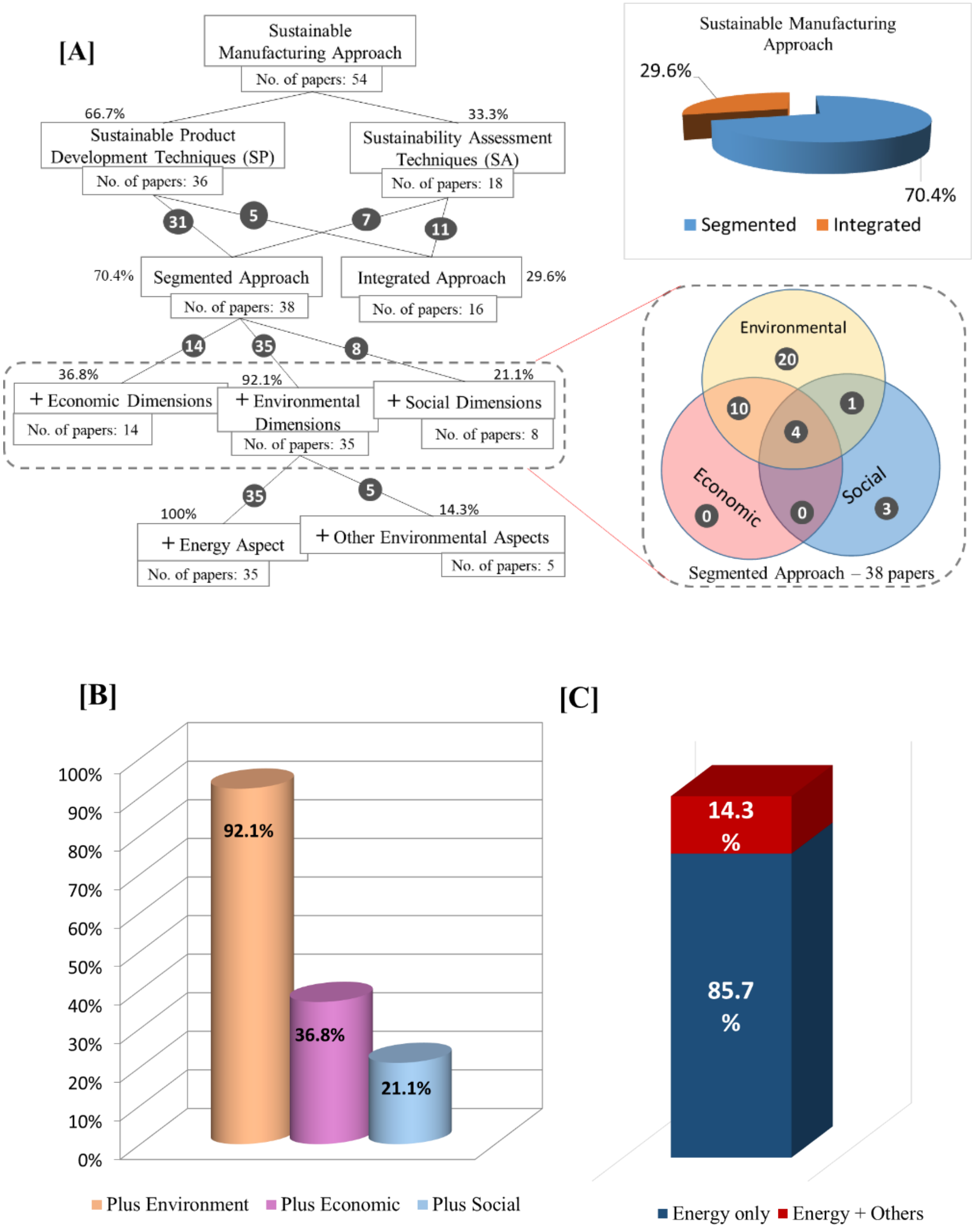


*Figure 2-5 Classification of the focus of sustainable manufacturing approaches*

The data analysis further examined the trend of the approaches to integrated sustainable manufacturing from 2006 to 2015. It was observed that the number of articles in this area increased after the launch of LCSA in 2011 **(United Nations Environmental Program (UNEP), 2011)**, however, there was a fall after the peak in 2013, Figure 2-6. This explains the initial enthusiasm towards the implementation of the holistic approach at the launch of the

LCSA framework and the present fundamental difficulties in integrating the social aspects concurrently with economic and environmental dimensions as indicated in related articles.

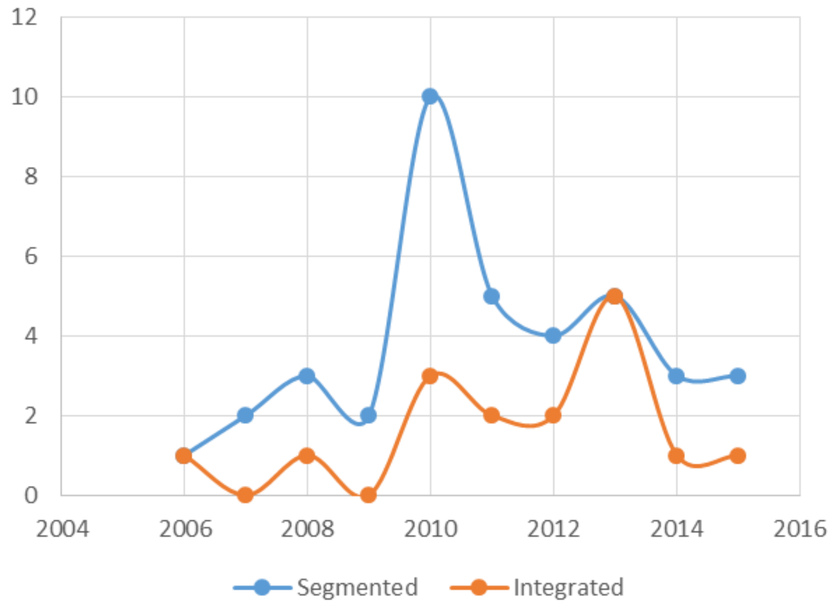


*Figure 2-6 Trend of approach to sustainable manufacturing between 2006 and 2015*

### *2.4.5. Segmented Sustainable Product Development – The Innovative-Approach*

The enormous impacts of manufacturing activities on the environment and the need for resource conservation have attracted a high volume of research focus seen on eco-innovative and eco-design approaches to sustainable product development. Over 90% of the reviewed segmented approaches are environmentally related and energy aspects being embedded in all of these **(Gbededo, Liyanage and Garza-reyes, 2018).** Authors such as **Ijomah *et al.* (2007)*;* Ostlin, Sundin and Bjorkman (2009)** and **Hatcher, Ijomah and Windmill (2011)** have concentrated on approaches that reduce impacts on the environment through design for remanufacturing; **Duflou *et al.* (2008)** focused on ***the*** feasibility of design for disassembly; **Abramovici and Lindner (2011)** product life cycle knowledge discovery methods supported by information technology systems; and **Bakker *et al.* (2014)** the implications of product lifespan extension. Other authors have balanced the environmental aspects with a sound economic approach. For instance, **Yang *et al.* (2011)** incorporated economic and environmental aspects such as lean-green and competitive sustainable manufacturing; **Jovane *et al.* (2008)** discussed the use of a Reference Model for Proactive Action (RMfPA) to enable the development and implementation of Competitive Sustainable Manufacturing (CSM); **Gremyr *et al.* (2014)** presented the application of the Robust Design Methodology for quality management in Sustainable Product development. Other authors deployed a sequential approach to address the three sustainability dimensions. In this line, **(Aguado, Alvarez and Domingo, 2013)** used innovation, lean techniques, and sustainable manufacturing to harmonise efficiency and competitiveness; **Afgan (2010)** used Information Systems to monitor and evaluate energy efficiency; **Kibira and McLean (2008)** employed simulation metrics, software tools, interface standards, and data sets. There are, however, various terms such as eco-innovation, circular economy, design-for-environment, eco-design, design for remanufacturing, design for recycling, and eco-efficient used in a large number of the articles on segmented product development to define design techniques, methods and approaches that aim to reduce environmental impact of products development ***(***e.g**. (Ostlin *et al*. 2009; Oecd 2009; Hatcher *et al.* 2011; Vallet et al. 2015)*)*.** According to **Vallet *et al.* (2015),** some of these terms carry misconceptions and an unclear purpose within the practitioners. Thus, finding a clear understanding and relationships between these terms is of principal importance to the development and application of a practical approach to sustainable production.

### ***2.4.6.*** Sustainable Product Development versus Eco-innovation

The Organisation for Economic Co-operation and Development (OECD) defined eco-innovation as a *"strategic business innovation that aims at improving competitiveness and reducing environmental impact"*. **Oecd (2009)** emphasised that the focus of eco-innovation is on change, redesign or modification of products, processes, and organisational systems such as technology, policy, and services in order to achieve both competitive and sustainable development. For instance, some authors emphasised eco-design such as product modularity and remanufacturing techniques in order to extend the lifespan of a product and conserve resource **(Ijomah *et al.*, 2007; Duflou *et al.*, 2008; Ostlin, Sundin and Bjorkman, 2009; Hatcher, Ijomah and Windmill, 2011; Bakker *et al.*, 2014)**, whereas others have focused on energy modelling and simulation techniques in order to improve the energy efficiency of the production process and the product **(Cannata, Karnouskos and Taisch, 2009; Afgan, 2010; Rahimifard, Seow and Childs, 2010; Rajemi, Mativenga and Aramcharoen, 2010; Ustainability et al., 2010; Seow, Rahimifard and Woolley, 2013; Aramcharoen and Mativenga, 2014).** Similarly, other authors have focused on lean-green and materials substitution techniques in order to improve product materials efficiency and business performance **(Alves *et al.*, 2010; Yang, Hong and Modi, 2011; Aguado, Alvarez and Domingo, 2013; Crabbe *et al.*, 2013)**. Thus, according to the **Oecd (2009)**, eco-innovation has a three-dimensional approach to competitive, sustainable manufacturing and can best be understood and analysed according to these dimensions. As stated by **Oecd (2009)**, the first dimension is TARGETS such as products, processes or technology to be changed, enhanced or renovated due to its negative impacts on the environment; then the MECHANISMS to be adopted to implement the change required in the "target", e.g. modification, redesign, remanufacturing, creation or the use of alternative products, process, marketing methods or information systems. The third dimension is IMPACTS which identifies the effect that the changes will have on the environment, e.g. energy consumption, solid waste, and air emission. Thus, eco-innovation is a methodology of a complete system that combines different methods and approaches to manufacture a competitive environmental friendly product. Figure 2-7 depicts the relationship between eco-innovation and other terms reviewed in this article. The emphasis on competitiveness and environmental friendliness distinct eco-innovation from other methods and terms discussed hereafter.

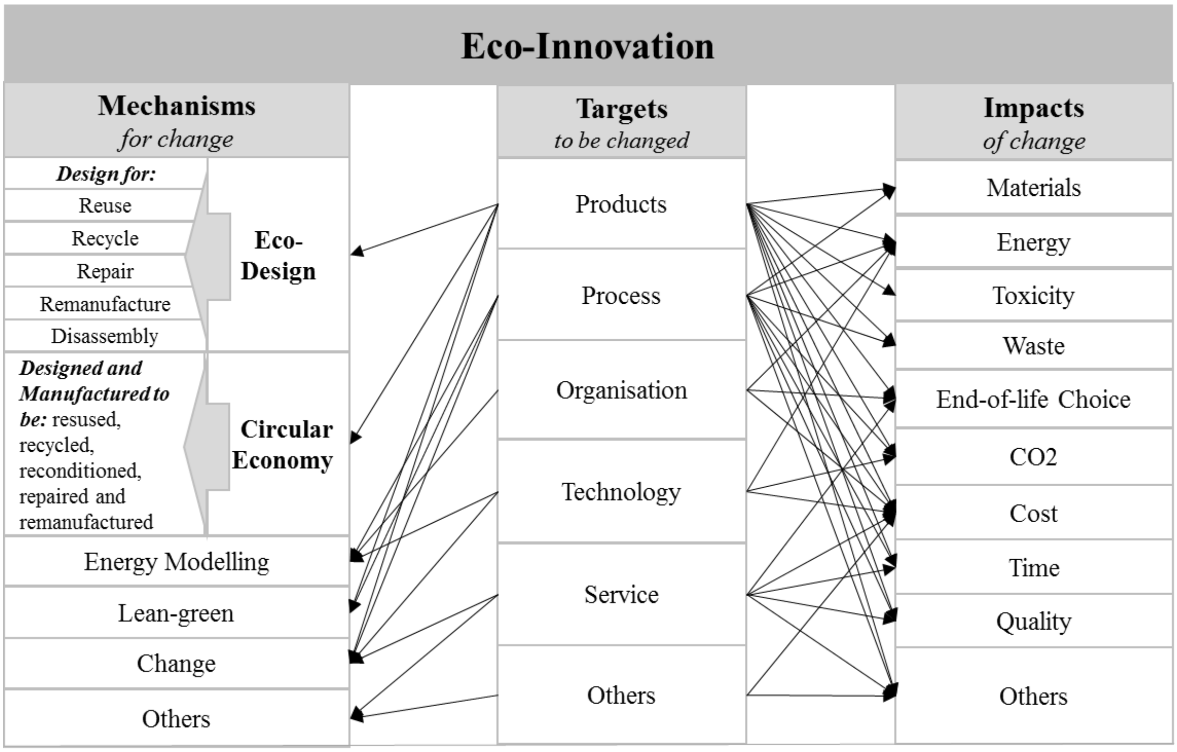


*Figure 2-7 Design for eco-efficiency of production system: an eco-innovation approach*

Table 2-1 shows a summary of various segmented and eco-innovative approaches adopted by researchers for sustainable product development within the reviewed literature. The primary challenge with these methods is the lack of consideration for the three sustainability dimensions and interdependent assessments of the impact of one dimension on the others. The assessments methods are either segmented or performed in a sequential order, which does not support effective decision-making for sustainable development.

*Table 2-1 Summary of research based on segmented approaches to sustainable manufacturing*

| **Targets** | **Mechanism For Change** | **Description** | **Impacts** | | | **Authors** |
|---|---|---|---|---|---|---|
| | | | ***Env*** | ***Eco*** | ***Soc*** | |
| **Product** | Eco-Design | Design for remanufacture | √ | - | - | Ostlin et al. (2009)<br>Hatcher et al. (2014) |
| | | Knowledge Discovery Methods Supported by an IT Prototype Of A Design Assistant System | √ | - | - | Abramovici and Lindner (2011) |
| | | Implications of product lifespan extension | √ | - | - | Bakker et al. (2014) |
| | | Feasibility of design for disassembly | √ | - | - | Duflou et al. (2008) |
| | | Guidelines to Facilitate Remanufacturing | √ | - | - | Ijomah et al. (2007) |
| | | Environmental Impact and Economic Cost | √ | | | Lim et al. (2013) |
| | Lean-green | Effect of Lean & Environmental Manufacturing on Business performance | √ | √ | - | Yang et al. (2011) |
| | Reference Model for Proactive Action (RMfPA) | To enable the development and implementation of Competitive Sustainable Manufacturing (CSM) | √ | √ | - | Jovane et al. (2008) |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| **Product & Process** | EMERGY | Use of Emergy Accounting for material and process selection | √ | √ | - | Almeida et al. (2010) |
|  | Robust Design Methodology (RDM) | Application of RDM quality management in Sustainable Product Development | √ | √ | - | Gremyr et al. (2014) |
| **Production Process Energy Efficiency** | Simulation, Energy Modelling, Monitoring & Evaluation | Use of Simulation & Virtual Reality for production management | √ | √ | - | Abidi et al. (2016) |
|  |  | Analysis of different Machine parameters | √ | - | - | Bhanot et al. (2015) |
|  |  | Modelling present and future state VSM+LCA+DES | √ | √ | - | Paju, et al. (2010) |
|  |  | Sustainability of Unconventional Machining (UCM) | √ | - | - | Gamage and DeSilva (2015) |
|  |  | Simulation metrics, software tools, interface standards, and data sets. | √ | √ | √ | Kibira and McLean (2006) |
|  |  | Simulation and Event-log analysis for data collection | √ | - | - | Rai and Daniels (2015) |
|  |  | Use of Information System to monitor and evaluate energy efficiency | √ | √ | √ | Afgan (2010) |
|  |  | Energy prediction for materials and process selection | √ | - | - | Aramcharoena and Mativenga (2014) |
|  |  | Energy monitoring, analysis, and management | √ | - | - | Cannata et al. (2009) |
|  |  | Simulation-based energy monitoring | √ | - | - | Seow et al. (2013) |
|  |  | Simulation-based energy usage analysis | √ | - | - | Solding et al. (2009) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Energy Efficiency | Simulation and modelling of environmental aspects of sustainability. | √ | - | - | Thiede et al. (2013) |
| | | SIMIO DES to optimise and evaluate energy consumption | √ | - | - | Cataldo et al. (2013) |
| | | An energy-oriented simulation model for production planning and control | √ | - | - | Herrmann et al. (2011) |
| | | Energy consumption prediction during product design and process planning stages. | √ | - | - | Kara and Li (2011) |
| | | Modifying cutting condition / by developing advanced machine conditions | √ | - | - | Mori et al. (2011) |
| | | A detailed breakdown of energy required for production (EPE) to support energy efficiency | √ | - | - | Rahimifard et al. (2010) |
| | | Optimisation of Energy footprint for machine product | √ | - | - | Rajemi et al. (2010) |
| | | Use of Information System for gathering, evaluating and improving environmental responsibility | √ | - | - | Melville and Ross (2010) |
| **Product Materials** | Materials Substitution & Composite Materials | Innovation, integrating lean and sustainable manufacturing to harmonise efficiency and competitiveness | √ | √ | √ | Aguado et al. (2013) |
| | | Environmental improvements related to use of alternative materials | √ | - | - | Alves et al. (2010) |
| | | Use of material innovation to improve the sustainability of products and processes with respect to people, planet, and profit | √ | √ | √ | Crabbé, et al. (2013) |
| | | Procedure for measuring Corporate Social Performance (CSP) | - | - | √ | Valiente et al., (2012) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Organisation**<br>**(Society)** | CSR | Guidelines for social life cycle assessment of products | - | - | √ | Benoît et al. (2010) |
| | | Rigor for effective data collection | - | - | √ | Grubert (2015) |
| | | Societal LCA methodology and its connection with employment | √ | - | √ | Hunkeler (2006) |

Although the methods adopted in the segmented approaches shows weaknesses in the context of sustainability, the analysis and summary in Table 2-2 present a notable degree of strength. According to **Bucherta *et al.* (2014),** combining the advantages of the approaches will facilitate continuous effective decision-making.

*Table 2-2 Summary of techniques adopted in segmented approaches to sustainable manufacturing*

| **Targets** | **Sustainable Product Development (SPD)**<br>**(Mechanism)** | **Sustainability Performance Assessment (SPA)** | **Strengths** | **Weaknesses** |
|---|---|---|---|---|
| **Product** | •Eco-design<br>•Circular Economy<br>•Design for Environment | •Guidelines<br>•Checklists<br>•Materials Energy Toxicity (MET) Matrix<br>•Regulations & directives<br>•LCA<br>•LCC<br>•S-LCA | •Covers every stage of the product lifecycle<br>•Customer's use/ operations' focus<br>•Considered the three sustainability dimensions<br>•Eco-efficient and environmental friendly | •Partial / Sequential assessment of the three sustainability dimensions<br>•Not focus on process sustainability<br>•Environment centric |

|  |  |  |  |  |
|---|---|---|---|---|
| **Process** | •Lean-green<br>•Energy Modelling<br>•Optimisation<br>•Change<br>•EMS<br>•CSR | •Throughput<br>•Energy efficiency<br>•Resources' efficiency<br>•CO2 emission<br>•Water & other wastes<br>•Regulations & directives<br>•Employees' turnover | •Covers the processing stage<br>•Clean production<br>•Energy efficient<br>•Green process<br>•Waste reduction<br>•Competitiveness<br>•Employees' motivation | •Does not consider the dynamic environment<br>•Partial/ sequential assessment<br>•Lacks analysis of the interdependencies of the three sustainability dimensions<br>•Does not cover operations to disposal stage |

### *2.4.7. Integrated Sustainable Product development: Challenges and Consolidated Approach*

In today's industries, sustainable product designers are charged with the responsibility to design products that are competitive, agile, social and environmentally friendly. According to **J.K. Simpson and K. Radford (2014),** in addition to functional and emotional criteria for the basis for which consumer choose among brands, a third dimension is now added based on the firm's social responsibility performance. Customers' demand patterns and product value perceptions have therefore changed. The legislative regulations are also placing greater demand on the manufacturing industry, but most especially on its production system and evaluation of associated energy consumption. Practically, there are many products in the market with "eco-signature" **(ISO 14001:2004, no date)** implying compliance to environmental or energy efficiency specification for the product use region (*Choosing the best eco-design technique*, no date)**.** However, most of the eco-designed products are in sustainability sense, not sustainable without holistic assessment of the entire production system of the product including full consideration of the three sustainability dimensions **(Parent, Cucuzzella and Revéret, 2013; Valdivia *et al.*, 2013)**.  Most researchers have posited that strategic, and life cycle thinking is currently the way forward for designing eco-efficient products **(Halog and Manik, 2011; Parent, Cucuzzella and Revéret, 2013; Zamagni, Pesonen and Swarr, 2013)**.  Thus, an integrated sustainable product is a product that is cost efficient, produced in an eco-efficient system, eco-efficient at the use phase, safe and socially acceptable. The result of this research indicates that only 5 out of 36 articles that have adopted Sustainable Product Development (SPD) techniques considered the three sustainability dimensions in their approaches see Figure 2-5.

### ***2.4.8.*** *Segmented Sustainability Performance Assessment*

The manufacturing industry remains the focal point for measuring economic, social and environmental sustainability; this is due, in part, to the volume of natural resources consumed and the amount of wastes and environmental pollution generated by this sector **(Brundtland, 1987; Kibira and McLean, 2008; Esmaeilian, Behdad and Wang, 2016)**. The effective assessments of the three sustainability dimensions underpin the development of un-abridged sustainable products; these are discussed in many of the articles with different views and approaches, ranging from segmented to simultaneous assessments. As shown in Figure 2-5, most of the approaches are segmented, with overlaps in their classifications due to the existence of a sustainability factor in one or more than one combination of the partial assessment. However, approaches that devoid of the simultaneous consideration of the three sustainability dimensions lack a holistic view and can neither produce a sustainable product nor support effective sustainability decision-making. Authors such as **Hermann, Kroeze and Jawjit (2007); Portha *et al.* (2010); Luz, Caldeira-Pires and Ferrão (2010)** and **Arena, Azzone and Conte (2013)** concentrate only on the assessment of the environmental performance while **Page and Wohlgemuth (2010)** and **Chang, Lee and Chen (2014)** incorporate the assessments of the environmental and economic performance in their strategies, and **Benoît *et al.* (2010)** concentrate on the guidelines for social performance assessment. In **Hermann, Kroeze and Jawjit (2007)** approach, the authors combined environmental performance indicators, lifecycle approach and multi-criteria analysis to assess the overall environmental impact of a business. **Portha *et al.* (2010)** applied LCA to assess the sustainability of a catalytic reforming process using Eco-Indicator99 as a lifecycle impact assessment method to identify environmental impacts on different process parameters. **Luz, Caldeira-Pires and Ferrão (2010)** applied a comparative LCA approach to material substitution by comparing two alternatives for polypropylene composites materials. **Arena, Azzone and Conte (2013)** applied a streamlined LCA to consider each lifecycle stages of a car lifecycle in a more analytical way rather than viewing it as a set of or summary of indicators. **Page and Wohlgemuth (2010)** applied discrete event simulation to model eco-efficient systems such as complex production systems with a focus on process impacts on economic and environmental dimensions.

#### **2.4.8.1.** *The Environmental Life Cycle Assessment (eLCA)*

The International Organisation for Standardisation (ISO) has also developed a series of international standards **(ISO 14000 series, no date)** that demand continuous improvement in industries' Environmental Management System (EMS) (http://www.iso.org/iso/iso14000). This framework is a segmented approach used by many product designers for assessing the environmental impacts of a product from the cradle to the grave **(Krozer and Vis, 1998; Consultants, 2000; Pryshlakivsky and Searcy, 2013).** It consists of four phases: Goals and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation **(ISO 14000 series, no date)** as depicted in Figure 2-8. The framework provides guidelines for gathering information for product lifecycle assessment and support decision-making. Other standards provide guidelines for the use of the framework. "ISO14040: 2006 & 2010 for example; defines the principles and framework for Life Cycle Assessment (LCA); ISO14001: 1996 & 2015 supports Environmental Auditing; ISO14031:2013 provides guidelines for Environmental Performance Evaluation (EPE); ISO14020:2000 states the guidelines for environmental labels and declarations. The ISO14004:2004 defines the EMS general guidelines on principles, systems, and support techniques. ISO14001:2004 is for EMS and the only ISO14000 standard against which it is possible to be certified by an external certification body**"** **(ISO 14001:2004, no date).** There are other methodologies such as Life Cycle Costing (LCC) **(ISO 15686-5:2017, no date)** and Social Life Cycle Assessment (S-LCA) **(ISO 26000:2010, no date)** that are based on LCA principles **(UNEP Setac Life Cycle Initiative, 2009; Leckner and Zmeureanu, 2011)**. Economic Input-Output (EIO) LCA models such as Physical Input Monetary Output (PIMO) and Materials Flow Analysis (MFA) models support the assessment of environmental impact of materials flow within an ecological-economic system **(Halog and Manik, 2011).**

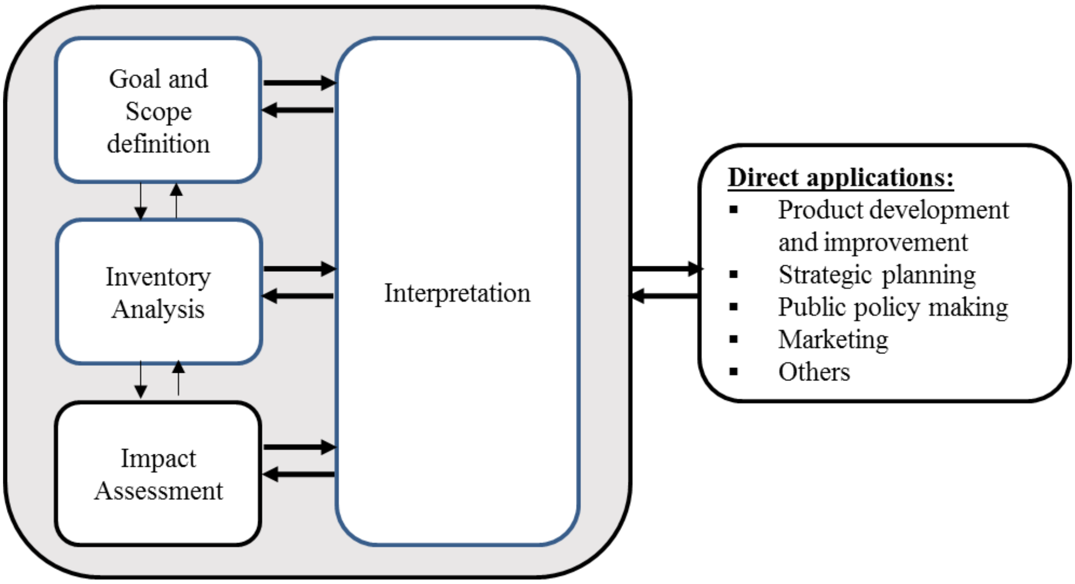


*Figure 2-8 Phases of life cycle assessment framework with direct application*

### **2.4.8.2.** *Life Cycle Assessment (LCA) and Life Cycle Sustainability Assessment (LCSA)*

Many researchers widely discuss the concept of a life-cycle approach to products design and its relevance towards achieving sustainable production and consumption. There are currently many frameworks, methodologies, methods, models, and tools that are now available and supported by various policies and regulations for sustainability assessment **(Zamagni, Pesonen and Swarr, 2013).** The three sustainability dimensions (Economic, Social and Environmental) are, however, being addressed separately under three main subject areas: Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA) and Environmental Life Cycle Assessment (eLCA) **(UNEP Setac Life Cycle Initiative, 2009; Leckner and Zmeureanu, 2011).** The latter which is hereafter referred to as LCA is the most widely discussed **(Valdivia *et al.*, 2013)** with the perspective of some authors that it also incorporates analysis that addresses economic and social sustainability. Some other researchers argued that there is a need to develop a separately integrated life cycle assessment system in order to confront sustainability issues **(Heijungs, Huppes and Guinée, 2010; Halog and Manik, 2011; Leslie JACQUEMIN, Pierre-Yves PONTALIER, 2012; Sala, Farioli and Zamagni, 2013; Valdivia *et al.*, 2013).**

LCA provides the elements to assess the environmental impacts of a product throughout its life-span. The ISO 14000 is a process-based LCA, and ISO 14001 of 2004 defined its environmental feature as elements and activities that are capable of interacting with the environment **(ISO 14001 Environmental management, no date; Aguado, Alvarez and Domingo, 2013).** According to **Halog and Manik (2011),** there are other LCA methods for example, *"ecologically based LCA (Eco-LCA) for assessments of the ecosystems such as water, minerals, and carbon sequestration, Economic Input-Output LCA model is used to assess and understand environmental impact of materials flow within eco-economic systems such as Physical Input Monetary Output, and Materials Flow Analysis models*". In addition to LCA methodology objective to assess environmental indicators, it is also possible to use LCA to capture life cycle inventory and import the result into a model for process optimisation **(Leslie JACQUEMIN, Pierre-Yves PONTALIER, 2012).** Conversely, in addition to the environmental centric of LCA, the challenge includes the difficulty in capturing and measuring the environmental aspects across a product lifecycle, unavailability of life cycle data of a product under design, and lack of standardized weighting methods **(Almeida *et al.*, 2010; Aguado, Alvarez and Domingo, 2013; Zamagni, Pesonen and Swarr, 2013)**. **Groover** (Edition and Groover, no date) viewed this challenge under manufacturing process as a sophisticated supply chain infrastructure consists of various phases and categories of suppliers, processes, and components of which their full existence might not be comprehended by the end consumer. Environmental LCA is therefore streamlined to product lifecycle stages and interpreted to equivalent high-level factors termed Environmental Impact (EI).

The Environmental Impact Assessment (EIA) tools such as Ecotax, Ecovalue08, Eco-Indicator95, Eco-Indicator99, Recipe **(Goedkoop *et al.*, 2013),** LC-Impact, LIME, and Impact 2002+ have been widely discussed and analysed. As in **Cataldo, Taisch and Stahl (2013),** the assessment of economic performances of a manufacturing process is in its matured state; this is due to the application of information technology which provides the necessary support for manufacturers to efficiently collate key performance indicators in order to assess its economic performances. However, assessment of the environmental and social performances is an ongoing challenge. In the past, through the industrial revolution and development, economic performances are in adversarial relationship to both the environment and the society. Thus, by incorporating environmental and social dimensions into product design while maintaining a competitive position with economic growth requires a level of compromises and trade-offs. **Halog and Manik (2011)** identified some indicators for S-LCA to be considered during product sustainability assessment. These include Health and safety, quality of working conditions, impact on employment, education and training, knowledge management, innovative potential, customer acceptance, societal product benefit, and social dialogue.

### *2.4.9. Integrated Sustainability Performance Assessment – Towards Holistic LCSA*

The principles of ISO 14040 LCA have been applied in various articles and by many practitioners **(Morgan, 2005; Luong, Liu and Robey, 2012; Zamagni, Pesonen and Swarr, 2013)**. However, in addition to its environmental centric approach, the complexity of the framework, the challenges and time required to collect an inventory of product's lifecycle make the framework impracticable **(Consultants, 2000; Valdivia *et al.*, 2013; Gbededo, Liyanage and Oraifige, 2015).** Various researchers and practitioners in their proposition to achieve the goal of the LCSA have combined the principles of LCA with other methods for assessment and analysis of products sustainability **(Hermann, Kroeze and Jawjit, 2007; Heijungs, Huppes and Guinée, 2010; Leslie JACQUEMIN, Pierre-Yves PONTALIER, 2012; Parent, Cucuzzella and Revéret, 2013; Valdivia *et al.*, 2013).** However, the challenges of capturing the social aspects in an integrated performance assessment approach have made many researchers to maintain the status-quo. Other researchers such as **Kloepffer (2008)** proposed an outline for LCSA that combines LCA, LCC, and S-LCA, but the author insisted that the system boundaries for the three dimensions' assessments have to be consistent and identical**.** **Finkbeiner *et al.* (2010)** presented the combination of LCSA, Life Cycle Sustainability Dashboard (LCSD) and Life Cycle Sustainability Triangle (LCST) as a communication and decision-making tool for stakeholders. **Parent, Cucuzzella and Revéret (2013)** reviewed the role and development of LCA and S-LCA in the context of Sustainable Production and Consumption pattern with Life Cycle Thinking (LCT) approach. These various approaches used the same methods of setting objectives and actions for product LCA to address LCC and S-LCA as in **Finkbeiner *et al.* (2010).** For instance, setting the goals of product LCA as a reduction of emission and uptake from the environment may follow by dematerialisation or substitution of materials with the focus on cost efficiency and creating values for consumers **(Parent, Cucuzzella and Revéret, 2013; Valdivia *et al.*, 2013; Stefanova *et al.*, 2014)**. In such instance, the S-LCA aspect would have a similar goal or objective to demand all supply chain actors comply with Corporate Social Responsibilities (CSR) ethos through improving the enterprise behaviour throughout the product lifecycle **(Parent, Cucuzzella and Revéret, 2013)**. According to this social approach, the authors emphasised that where the social behaviours of an actor are wrong and cannot be corrected, this could initiate the substitution of the supplier with a focus on creating incentives for consumers. Hence, the social emphasis is on knowing the behaviour of every actor within the supply chain or identifying the "hotspots" and possible options to reduce the potential impacts as in LCA. **Parent, Cucuzzella and Revéret (2013)** associate the economic part to creating price incentives and "eco-labels" for the consumers through technical optimisation of manufacturing process and distribution chain optimisation. Other research based on integrated assessment approaches are listed in Table 2-3. However, in agreement with other authors, this researcher believes that the holistic performance of products and in comparison to alternative products or previous versions have not been well assessed due to the complexity of the methods and the difficulties in integrating all the sustainability aspects of the assessment processes **(Paju *et al.*, 2010; Gbededo, Liyanage and Oraifige, 2015).**

A holistic sustainability performance assessment incorporates the three sustainability dimensions in the assessment processes and aggregates the sustainability performance of all the actors in a product lifecycle to inform the product designers for effective decision-making (Consultants, 2000; Hutchins and Sutherland, 2008b)**.** According to **Hutchins and Sutherland (2008),** sustainability is appreciated when the interdependencies of the three sustainability dimensions are considered and analysed to support effective decision-making **(Arena, Azzone and Conte, 2013; Parent, Cucuzzella and Revéret, 2013; Sala, Farioli and Zamagni, 2013b; Valdivia *et al.*, 2013; Zamagni, Pesonen and Swarr, 2013)**. Hence, it is necessary to characterise the connection and interactions among the three sustainability dimensions before we can achieve holistically sustainable manufacturing.

*Table 2-3 Summary of research based on an integrated approach to sustainable manufacturing*

| | Authors | Environment | Economic | Social | Tool/ Framework | Techniques | Analytical Approach |
|---|---|---|---|---|---|---|---|
| **1** | Kibira and McLean (2006) | √ | √ | √ | Discrete Event Simulation (DES) | SPD | √ |
| **2** | Kloepffer (2008) | √ | √ | √ | LCSA = LCA + LCC + S-LCA | SPA | - |
| **3** | Finkbeiner et al. (2010) | √ | √ | √ | LCSA + LCSD + LCST | SPA | - |
| **4** | Heijungs et al. (2010) | √ | √ | √ | LSCA = LCA + SA | SPA | √ |
| **5** | Afgan (2010) | √ | √ | √ | Energy Technology System | SPD | - |
| **6** | Klöpffer and Ciroth (2011) | √ | √ | √ | LCSA= LCA+LCC+S-LCA | SPA | - |
| **7** | Swarr et al. (2011) | √ | √ | √ | SETAC LCSA | SPA | - |
| **8** | Schau et al. (2012) | √ | √ | √ | LCSA= LCA+LCC+S-LCA | SPA | - |
| **9** | Traverso et al. (2012) | √ | √ | √ | L-C-S-DASHBOARD | SPA | - |
| **10** | Sala et al. (2013a) | √ | √ | √ | SS and SA for development of a holistic LCA | SPA | √ |
| **11** | Parent et al. (2013) | √ | √ | √ | LCSA (Assessment) + SPC | SPA | - |
| **12** | Valdivia et al. (2013) | √ | √ | √ | LCSA= LCA+LCC+S-LCA | SPA | - |
| **13** | Aguado et al. (2013) | √ | √ | √ | Transformation of environmental innovation into Lean System | SPD | - |
| **14** | Crabbé, et al. (2013) | √ | √ | √ | 3P evaluation grids to analyse a study cases | SPD | - |
| **15** | Stefanova et al. (2014) | √ | √ | √ | LSCA | SPA | - |
| **16** | Bhanot et al. (2015) | √ | √ | √ | Network Analysis using graph theory | SPD | √ |

Keys: SPD-Sustainable Product Development; SPA-Sustainability Performance Assessment; LCSA-Life Cycle Sustainability Analysis/Assessment; LCA- Life Cycle Assessment; S-LCA-Social Life Cycle Assessment; LCC-Life Cycle Costing; LCSD-Life Cycle Sustainability Dashboard; LCST- Life Cycle Sustainability Triangle; SA-Sustainability Analysis; SS-Sustainability Science.

### *2.4.10. Consolidating Sustainability Performance Assessment (SPA) and Sustainable Product Development (SPD) Approaches*

The importance of energy efficiency in manufacturing production processes is underscored in all the reviewed articles. The result shows that 100% of the approaches concentrate on the energy aspect. Methods such as energy modelling, eco-design, lean-green, and Energy Management Systems **(Cannata, Karnouskos and Taisch, 2009; Ustainability *et al.*, 2010; Leckner and Zmeureanu, 2011; Aramcharoen and Mativenga, 2014)** are examples of strategies adopted in an eco-efficient production system that aims at reducing environmental impacts and cost of production **(Rahimifard, Seow and Childs, 2010; Matthies, Selge and**

**Klöckner, 2012; Cataldo, Taisch and Stahl, 2013; Parent, Cucuzzella and Revéret, 2013; Zamagni, Pesonen and Swarr, 2013)**. Circular Economy (CE) has also emerged to describe an approach that combines various design techniques under eco-design mechanisms with the aim of reducing the rate of consumption of natural resources through product lifespan extension and feasible economic case **(Hu *et al.*, 2011; Tukker, 2015; Esmaeilian, Behdad and Wang, 2016).** The primary research question, however, is;

> *How sustainable are the production processes involved in manufacturing eco-innovative products? Alternatively, how do we assess their impacts on the economy, environment, and society in order to drive effective sustainability decisions?*

Although there is a significant positive relationship between eco-innovative products and sustainable **(Brundtland, 1987; Luong, Liu and Robey, 2012; Aramcharoen and Mativenga, 2014)**, there is a need to align the manufacturing process of products with a holistic view of sustainable product development **(Brundtland, 1987)**. This research, therefore, proposes an integrated methodology for impact analysis of production processes that enable the assessment of the three sustainability dimensions (i.e. economic, social and environmental) in a dynamic production environment.

### *2.5. Chapter Summary*

In this chapter, the researcher presented the review of the current research approaches, challenges, understanding, and future direction in the creation of manufactured products that are truly sustainable. The systematic review of the literature identified two distinct categories of the current research approach to sustainable manufacturing:

1. Sustainable Product Development (SPD) - This approach supports the goals of continuous improvement process of sustainable product development; these include eco-innovation, energy efficiency, circular economy, lean-green and eco-design.
2. Sustainability Performance Assessment (SPA) – These are the approaches that use quantitative assessment to support sustainable manufacturing decisions such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA). Their weaknesses and strengths were evaluated regarding goals, scope and analytical ability to support decision making that meets sustainable manufacturing objectives.

The study shows that less than 30% of the current approach to sustainable manufacturing considered a holistic approach to sustainable development. Most importantly, the study explores the strengths and weaknesses of the two distinct approaches to sustainable manufacturing with the aim of aggregating their strengths into a robust framework that will support a holistic approach to sustainability decision-making.

In conclusion, the section systematically identified and assessed the existing sustainability methodologies and frameworks, evaluate their decision supporting strengths and weaknesses in accordance with the first objective of this research (section 1.2). The outcome of this chapter underpins both the development of the research question and a strategy for the development of a holistic conceptual framework presented in chapter 5.

# CHAPTER 3

# 3. RESEARCH PROGRAMME DEVELOPMENT

## *3.1.* The research context

### ***3.1.1.*** *Sustainability Dimensions and Sustainable Development Goals*

The three objectives of Sustainable Development (SD): environmental protection, economic development and social development represent the three dimensions of sustainability which have to be achieved in order to secure "our common future" as stated in the Brundtland report **(Brundtland, 1987)**. The Brundtland report defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" **(Brundtland, 1987).** The US Department of Commerce *(US EPA, OA, no date)* also defines sustainable manufacturing as "the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound". The 193 member states of the United Nations and global civil society in 2015, agreed upon 17 SD goals (SDGs) and 169 targets as a universal agenda towards sustainable development **(United Nations, 2015)**. The global agenda tagged **"transforming our world**" which was initiated in 2015 represents a plan of action for the three sustainability dimensions. This action plan replaced the initial Millennium Development Goals (MDGs) which focus was only on the developed countries **(UN RIO+20, 2014; United Nations, 2015)**. The SDGs covers a wide range of targets such as climate change, energy and water consumption, urbanisation, sanitation, education, hunger, poverty, health, gender equality, the environment and social justice **(United Nations, 2015)**. This global interest in sustainable development has resulted in regulations and legislation which are changing the way companies, and organisations perceive and drive their competitive goals **(Gu *et al.*, 2015).** There are also increasing consumers' preferences for ethical and environmentally friendly products, thus creating the need for assessing and reporting the impacts of the manufactured products on the environment and society.

As this research would be developing a framework for evaluating the impacts of the manufactured product on the three sustainability dimensions, it is necessary to clarify the terms "impact assessment" and "impact analysis" which are used to describe the evaluation of the manufacturing impact on the three sustainability dimensions. In this thesis, the term "impact assessment" is used to denote the evaluation of the impact of the manufactured product on the environment, society or economy. It also refers to an independent or segmented approach to assessment as in the environmental assessment and social assessment. The term "impact analysis" is used to denote the simultaneous and interdependent evaluation of the impacts on the three sustainability dimensions.

### *3.1.2. Towards effective sustainability decision-making*

There are contemporary impact assessment frameworks such as ISO 14040 LCA, LCC and S-LCA that are capable of assessing the combination of one or two of the three dimensions **(ISO 14040:2006, no date; ISO 15686-5:2017, no date; ISO 26000:2010, no date; UNEP Setac Life Cycle Initiative, 2009; Guinée *et al.*, 2011; Leckner and Zmeureanu, 2011).** However, the frameworks have neither adequately integrated all the three dimensions nor considered the effects of their interdependencies, and the dynamism involved in the manufacturing production processes. There are other proposed tools such as combining the LCA in parallel with the lean manufacturing, value stream mapping, simulation, Activity Based Costing (ABC), and Decision Making Trial and Evaluation Laboratory (DEMATEL) **(Sumrit and Anuntavoranich, 2012; Deng, Liu and Liao, 2015).** This research asserts that "impact assessment" does not support effective decision-making for sustainable manufacturing because it is not holistic and does not integrate the three sustainability dimensions for interdependent analysis.

Recently, in consideration of possible unintended consequences of the effects of sustainable manufacturing decisions, the joint organisation of UNEP and SETAC launched a holistic and integrated Life Cycle Sustainability Analysis (LCSA) framework. The framework is to enable researchers from different disciplinary fields of study, to discuss and develop methods that integrate life cycle thinking and sustainability analysis in manufacturing design **(United Nations Environmental Program (UNEP), 2011; Valdivia *et al.*, 2013; Zamagni, Pesonen and Swarr, 2013)**. Many authors have emphasised on the analytical requirement of LCSA as against the independent assessment of each of the three dimensions and summing the results **(Heijungs, Settanni and Guinée, 2013; Sala, Farioli and Zamagni, 2013a; Valdivia *et al.*, 2013)**. Various approach and analytical methods have also been posited by many researchers in support of the LCSA framework; these include Data Envelopment Analysis, Mathematical modelling, and other sustainability methodologies that incorporate Simulation model **(Seow, Rahimifard and Woolley, 2013; Tsai *et al.*, 2013; Cortes, 2017)**. The challenge with the existing analytical methods is that the approach is either static or void of consideration for manufacturing dynamic environment or does not simultaneously consider the three sustainability dimensions. The analytical requirement is to enable interdependent analysis, but it has to integrate the aspects of the three sustainability dimensions in order to provide adequate support for sustainable manufacturing decision.

### *3.1.3. Research Question*

Generally, in the parlance of sustainability, environmental protection has gained more attention compared to the economic and social development. This is evidence in many articles and the vast eco-efficient and eco-products in the market. The systematic literature review presented in chapter 2 also indicates that all approaches to sustainable manufacturing include energy consumption. There are lifecycle impact assessments' tools such as eco-design checklists and guidelines used in conjunction with CSR to support the decisions for the manufacture of eco-innovation products. However, the fundamental question of this research is **"*How sustainable are the production processes involved in manufacturing eco-innovative products.*"**

To be able to answer this fundamental research question, the research is interested in examining:

1. *How to determine the best possible sustainable process model for producing an optimum designed sustainable product*
2. *How to analyse the impacts of the processes on the economic, social and environmental aspects interdependently to support effective sustainability decision*
3. *How to make the decision for the best combination and trade-off amongst the three sustainability dimensions in a dynamic manufacturing production environment*

## *3.2.* The development of research aim and objectives

In section 2.2, the impact of manufacturing activities is identified as a major contributor to global warming and other sustainability issues. The main challenge of adopting effective, sustainable manufacturing is highlighted in section 3.1.1 as the need for a holistic analytical tool to support sustainability decisions. The scope of a product lifecycle (sections 2. and 3.4) which may span a combination of geographical locations, different time zones and actors across a supply chain suggests the inadequacy in the lifecycle data collection typically adopts in sustainable manufacturing. In section 2.3 and 3.3.1, the “gate-to-gate” approach is identified as appropriate for limiting the scope of a product lifecycle assessment. The result of the review of the approaches to sustainable manufacturing (section 2.), indicates that research has not been able to simultaneously integrate the aspects of the three sustainability dimensions in an analytical model. Some of the reasons identified include the challenge of integrating the qualitative nature of social aspects with other sustainability aspects and the dynamism involved in the manufacturing environment. The simulation approach to sustainable manufacturing is currently gaining preference due to the inherent analytical functions and ability to support effective decision-making in a dynamic manufacturing environment. Also, simulation has been used to model and improve manufacturing systems’ behaviour, drive competitive advantage and predict production performance **(Robinson, 2013)**. However, the case study and review of existing simulation applications to sustainable manufacturing shows the approach still lacks integration of the three sustainability dimensions **(Paju *et al.*, 2010; Thiede *et al.*, 2013)**. In addition, the current simulation software in the market, as reviewed by **Thiede *et al.* (2013)** do not have environmental or social functions by default.

Based on these findings, this research had the option to develop a holistic product lifecycle assessment tool that integrates the aspects of the three sustainability dimensions or seek to develop a generic sustainability impact analysis tool for a product lifecycle stage. The first option is holistic and details the sustainability impacts of a product from cradle to end-of-life choice, but it lacks applicability regarding data integrity, time and simulation modelling. On the contrary, the second option is detailed and can be applied to support sustainability decision at any stage of a product lifecycle. There is presently moderate research in the field of Life Cycle Sustainability Analysis (LCSA), the second option provides the analytical environment to support effective decision-making and will enable aggregation of the outcome of each of the stages. Hence, the aim of this research is:

> **To develop a holistic integrated simulation-based impact analysis framework that supports decision-making for sustainable manufacturing design and management.**

The study has set the following objectives in order to realise this aim:

- Assess the existing sustainability methodologies and frameworks, evaluate their decision supporting strengths and weaknesses, and develop an effective strategy for the proposed framework.
- Determine an appropriate approach to capture the aspects of the three sustainability dimensions for an analytical model.
- Develop a descriptive framework that allows companies to build an integrated computer simulation model of a real system which is capable of assessing both production and sustainability performance of a dynamic manufacturing system.
- Verify the descriptive framework by the Delphi method, and validate the applicability by modelling a prototype of a real manufacturing environment.

The outcome of the research will enable sustainability practitioners to build a holistic simulation model that support effective decision making at the design phase of sustainable product development. The model will enable the capture of the aspects of the three sustainability dimensions and impact analysis of their interdependencies.

## *3.3.* The development of the scope of research

### ***3.3.1.*** *Introduction*

The scope and boundary of this research are defined in respect to the research question in chapter-2, that is; "*How sustainable are the production processes involved in manufacturing eco-innovative products? Alternatively, how do we assess their impacts on the economy, environment, and society in order to drive effective sustainability decisions?"*

Defining the goal and scope is critical to conducting an effective assessment or a simulation-based sustainability analysis; it provides the necessary guide for collection and collation of modelling data. Another interesting subject of the scope of sustainable development as discussed by **Sala, Farioli and Zamagni (2013b)** is: "what is to be sustained?", "what is to be developed?" and the relationship between both. The level of scale or scope is a function of the defined assessment boundaries since the perception of sustainability varies by geopolitical scale, time frame and relevant manufacturing level. Part of the challenge of the conflict in the performance evaluation of the sustainability factors is anchored on different perspectives of what the scope of the assessment is. According to **Sala, Farioli and Zamagni (2013b),** these differences in ideology are reflected in the various adopted weighting schemes in sustainability evaluation **(Jayal *et al.*, 2010)**. **Sala, Farioli and Zamagni (2013b)** gave further examples of what to be sustained or protected as nature, life and communities, and what to be developed as people, economy and society **(Sala, Farioli and Zamagni, 2013b)**. Thus we can refer to the objective of sustainable manufacturing as environmental protection, economic development and social development. In the business parlance, the three dimensions are often referred to as the triple-bottom-line **(Gmelin and Seuring, 2014)**.

### *3.3.2. The Lifecycle of a Manufactured Product*

The scope of a product lifecycle may sometimes span a combination of geographical coverage, time frames, activities, connecting mechanisms, and stakeholders or participating actors thus, making it complex to capture the required data. As in **Zamagni, Pesonen and Swarr (2013),** the geographical scope of LCA can range from global to continental, country, regional, and up to the local scale as illustrated in Figure 3-1. This complex network of materials' and products' movement made it almost impossible to effectively collect lifecycle data for assessment purpose. Thus streamlining the scope of assessment becomes inevitable for effective analysis of the impacts of the manufacturing processes on the three sustainability dimensions.

*Figure 3-1 The description of a typical product life cycle that spans the borders of continents*

The complexity of this challenge is partly addressed by the well-accepted boundary classification such as "cradle to grave", "cradle to gate", "gate to gate", and "gate to grave"

**(Puettmann and Wilson, 2005)**. These strategic boundaries' definitions address and limit the extent of time coverage, activities involved and actors to be considered to a considerable and practicable scope for assessment. Another challenge that associates with lack of data during sustainability assessment is the inability to influence top players in the supply chain **(Cataldo, Taisch and Stahl, 2013).**

The "gate-to-gate" approach was mostly used when there was no factual or literature information to study **(Jiménez-González, Kim and Overcash, 2000),** however, it has been repeatedly used recently in manufacturing process such as to study environmental impact of temperature change **(Portha *et al.*, 2010; Leslie JACQUEMIN, Pierre-Yves PONTALIER, 2012). Puettmann and Wilson (2005)** also used the gate-to-gate approach to conduct a study of life-cycle inventory for the production of glued-laminated timbers. **Leslie JACQUEMIN, Pierre-Yves PONTALIER (2012)** in their review of application fields dealing with LCA, identified four researchers who used the gate-to-gate approach in the last decade. Base on the research question, this research adopts the gate-to-gate approach as depicted in Figure 3-2. The gate-to-gate boundary definition limits the scope of a decision and minimises the issues of LCA data collection. It is a progressive approach to achieve the holistic life cycle sustainability analysis of a product.

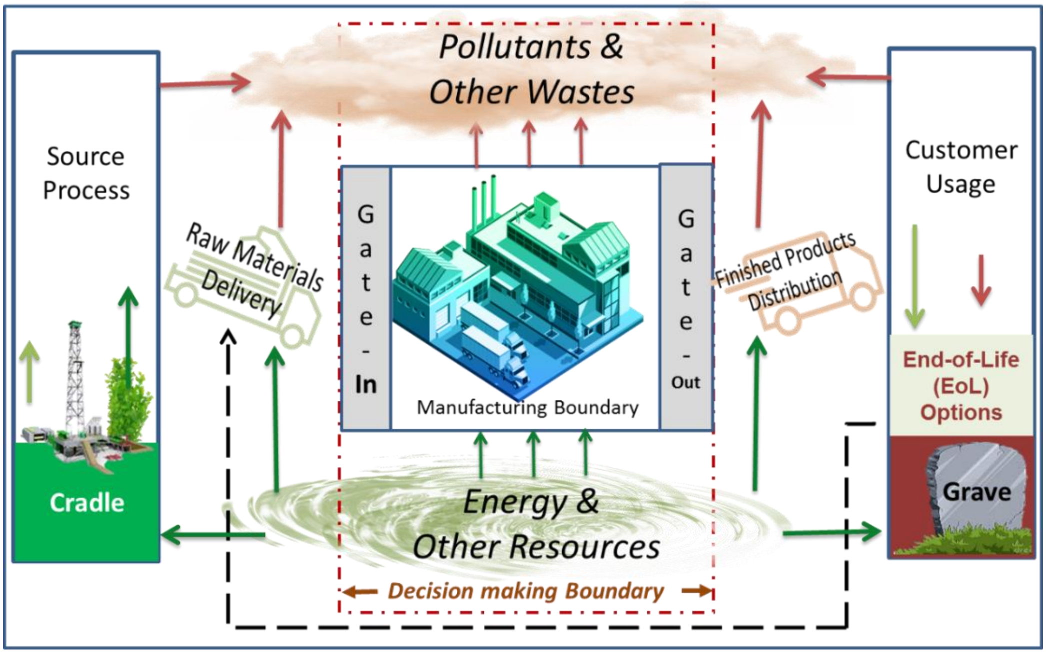


*Figure 3-2 Manufacturing systems gate-to-gate boundary for sustainability decision-making*

The impacts of the activities that occur within the manufacturing system boundary are demonstrated in the Figure 3-2. Manufacturing production processes consume resources such as energy, materials, water, natural gases, finance, and human resources and at the same time produces wastes and harmful pollutants into the atmosphere, water and land/soil **(unfccc, 1992; Nasa, 2015)**. The six common air pollutants are carbon monoxide, nitrogen dioxide, lead, sulphur dioxide, ground-level ozone, and particulate matter **(US EPA, no date)**. These pollutants are known to be very harmful and dangerous to the human health and the environment. They can also cause great damage to properties; hence, they are referred to as “criteria pollutants”. Generally, the governmental bodies regulate the limits of criteria pollutants generated by industries. Other toxic wastes released during manufacturing include benzene, perchloroethylene, methylene chloride, mercury, chromium, and cadmium **(US EPA, no date)**. These toxic air pollutants are hazardous and could cause serious health effects including cancer and birth effect **(US EPA, no date)**. Each organisation is responsible for conducting Environmental Impact Assessment (EIA) of their products and are reported to appropriate organisations as required **(Disclosures, 2016)**. Other assessments performed at the organisational level include Cost Impact Assessment (CIA) and Social Impact Assessment (SIA).

### *3.3.3. Assessment level definition*

Other methods have been adopted by researchers in sustainable manufacturing to define the assessment scope of a manufactured product. For example; the appropriate assessment levels of manufacturing have been used by some authors to streamline the assessment boundary for data collection **(Jayal *et al.*, 2010; Gamage and De Silva, 2015).** These levels include:

- *The product level assessment*
- *The process level assessment*
- *The system level assessment*

The product level assessment is the holistic assessment of the entire product lifecycle from the cradle to the grave or end of life choice. The assessment includes all the stages and processes that are involved in the creation and use of the manufactured product. Methodologies such as LCA, LCC and S-LCA are developed with the focus of product level assessments. The process level assessment concentrates on the assessment of a processing stage of a product lifecycle such as the manufacturing production processing stage or transportation stage **(Jayal *et al.*, 2010; Parent, Cucuzzella and Revéret, 2013)**. However, the system level assessment includes the assessment of an entire supply chain or organisation's enterprise or an entire manufacturing site. The system level assessment may fall within a manufacturing boundary as defined by the gate-to-gate approach in Chapter-2, but the process level assessment is always performed within the gates of a manufacturing facility boundary (Chang, Lee and Chen, 2014; Gbededo, Liyanage and Oraifige, 2015). Figure 3-3 depicts the scope of an impact assessment at the process level compared to other types of assessments.

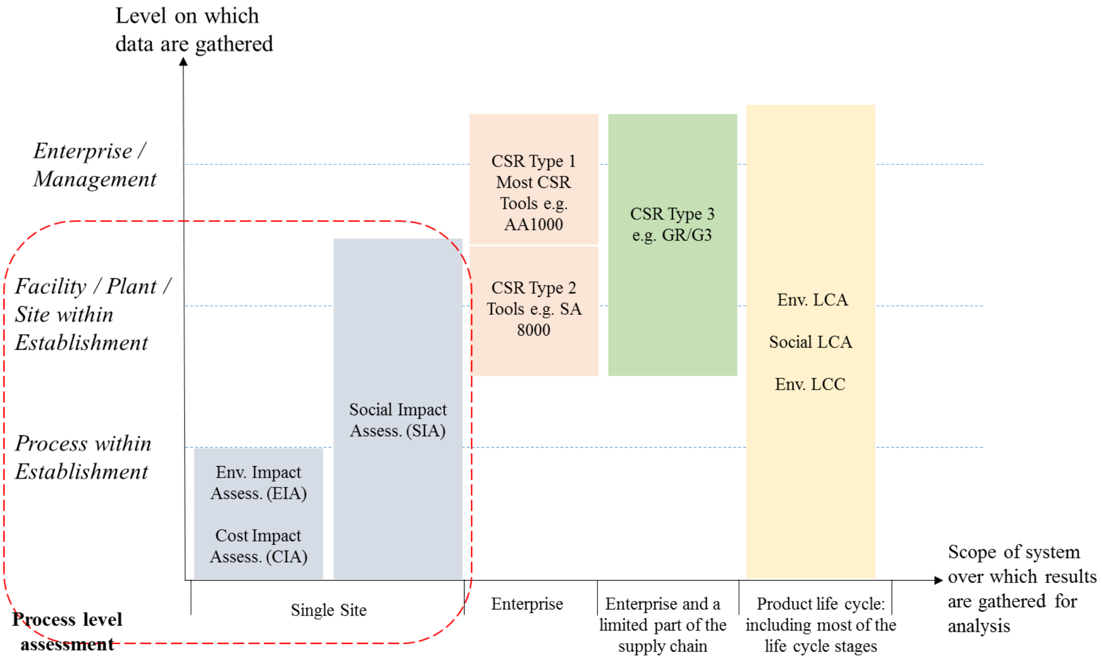


*Figure 3-3 Scope of impact assessment compared to other assessment techniques (adapted from UNEP/SETAC 2009, Benoit et al. 2010)*

In general, the term, "holistic" or "holistic assessment" is used as relating to the totality of a sustainable manufacturing system or the whole product lifecycle as opposed to just a particular stage of the product lifecycle **(Finkbeiner *et al.*, 2010)**. It has also been used to refer to the concepts of the LCSA as the integration of the three sustainability dimensions as opposed to the segmented approach **(Kloepffer, 2008; Afgan, 2010; Stefanova *et al.*, 2014)**.

The "object of study" is also used to streamline the focus and objectives of an assessment, for example; eLCA, LCC and S-LCA would be performed for the assessment of the entire product lifecycle. Hence, the product level assessment represents the object of study for an eLCA, LCC and S-LCA **(UNEP Setac Life Cycle Initiative, 2009; Benoît *et al.*, 2010)**. Whereas, when the object of study is a process level assessment, then, EIA, CIA and SIA are performed.

However, because of the aim of this research, the focus is on the process level assessment within a gate-to-gate manufacturing facility (Chang, Lee and Chen, 2014; Gbededo, Liyanage and Oraifige, 2015). The objective is to analyse the impacts of the production and management processes on the environment, economic and social dimensions within the manufacturing production domain. In respect of this, the object of study is the manufacturing stage of a product lifecycle, and the focus is the impacts on resources which include energy, materials, costs and workers' stakeholders' category. Figure 3.4 depicts the impact types, impact categories and sub-category indicators of a manufacturing process level assessment (chapter 4 presents the full breakdown of sustainability indicators).

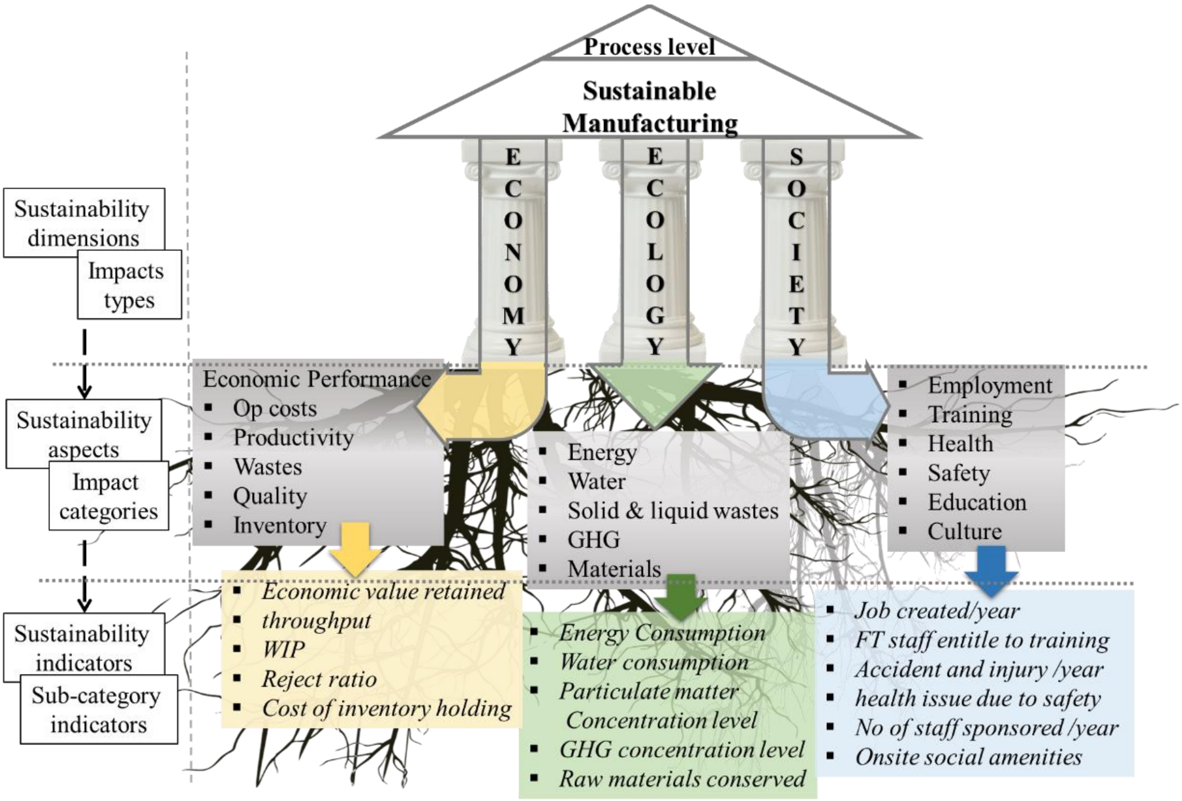


*Figure 3-4 Impact types, impact categories and sub-impact indicators of a process level*

## *3.4.* The Development of Research Methodology

### ***3.4.1.*** *Research Philosophy*

Research has to do with the constructive process of investigation for the purpose of accelerating the process of understanding and creating new knowledge **(Easterby-Smith, Thorpe and Jackson, 2008)**; research is an enquiry into an unknown problem with the intention of acquiring the knowledge about the problem. Every research problem has underlining philosophical and political issues that need to be understood before the research can be conducted (**Easterby-Smith *et al*., 2002 pg.3**). The understanding of the philosophical issues that underlie a research helps to clarify the research designs, adopt and adapt a design that is appropriate for the scope and boundary of the study **(Easterby-Smith, Thorpe and Jackson, 2008)**. The research process followed by a researcher is generally influenced by the way the researcher view, understand and interpret the world **(Ates, 2008)**. Hence, the worldview or assumption of a researcher is limited by what the researcher claims to know or knows about the world or the nature of the world (Ontology), how to learn or know about such knowledge (epistemology); and the corresponding procedures or methods for studying such knowledge in light of ontological and epistemological positions (methodology) **(Reich, 1994; Ates, 2008).** This knowledge claims which underpins various philosophical questions are embedded under what is generally referred to as research **philosophy** **(Reich, 1994)**, or **"paradigm"** **(Ates, 2008),** or **"theoretical perspectives**". The methodology is about providing answers to the way research is planned and executed, the creation and testing of theories and the way the tests are interpreted **(Reich, 1994)**.

A mix of Social Science and Operations Research approaches would be deployed in conducting this research. A Social Science research approach given the fact that management and business research deals with social world issues **(Ates, 2008)**, hence, applying these research philosophies in this study will be appropriate. An Operations Research approach in view of the fact that operations research deals with model building **(Prakash, Rolland and Pernici, 1993; Caliri, 2000; Murthy, 2007).** The context of this research describes operational research or system analysis due to the emphasis on sustainability impact analysis and the need to support effective decision-making. Operations Research (OR) involves the use of mathematical and quantitative techniques to provide a rational basis for decision-making, especially in the absence of complete information.

This approach is to articulate sustainability values, to derive environmental, economic and social design criteria **(United Nations Environmental Program (UNEP), 2011)**. Based on these values, a qualitative picture of an effective, sustainable manufacturing design consistent with the three sustainability dimensions will be developed. Then, to construct a quantitative scenario in a modelling system intended to describe the lifecycle of the manufacturing design **(Cabot *et al.*, 2009; United Nations Environmental Program (UNEP), 2011).**

There are two main traditions of research philosophies that are widely applied in social science research: “Positivism” and “Constructionism”. These are also referred to as “Post-positivism” and “Interpretivism” respectively **(Easterby-Smith, Thorpe and Jackson, 2008).** A useful compromise between “positivism” and “constructionism” philosophies is referred to as “Critical realism” or “Relativism” paradigm **(Ates, 2008)**. In Table 3.1 a comparison between positivism and constructionism philosophies are presented. Given the fact that management and business research deals with social world issues **(Ates, 2008)**, applying a combination of these research philosophies in this study will be appropriate. The strengths in the highlighted descriptions will be deployed for this research.

*Table 3-1 Contrasting implications of Positivism and Social Constructionism*

| | **Positivism** | **Constructionism** |
|---|---|---|
| The observer | Independent of what is being observed. | Is part of what is being observed |
| Human interests | Should be irrelevant | Are the main drivers of science |
| Explanations | Must demonstrate causality | Aim to increase general understanding of the situation. |
| Research progresses through | Hypotheses and deductions | Gathering rich data from which ideas are induced. |
| Concepts | Need to be defined, so they are measured | Should incorporate stakeholder perspectives. |
| Units of analysis | Should be reduced to simplest terms | May include the complexity of 'whole' situations |
| Generalisation through | Statistical probability | Theoretical abstraction |
| Sampling requires | Large numbers selected randomly | Small numbers of cases chosen for specific reasons |
| | | |

According to **Harry Perros, (2009)**, Operations research approach to solving problems is characterised by five steps: Problem formulation, Construction of the model, Model validation, Using the model, evaluate various available alternatives (Solution), Implementation and maintenance of the solution. These steps are in agreement with **(Prakash, Rolland and Pernici, 1993)** process modelling phases: 1) Provide process modelling environment. 2) Elicit/ Design/Analyse a generic model. 3) Compile/customise a specific model. 4) Plan and instantiate process (es). 5) Execute and monitor these processes. The above steps would, therefore, be reviewed and deployed at the modelling stage and would enable for effective research project planning.

### *3.4.2. Research Methodology*

The "Methodology" is the researcher's guiding philosophy for selecting a combination of research techniques or methods and shaping the use of such methods for the purpose of enquiring into a specific situation **(Ates, 2008; Easterby-Smith, Thorpe and Jackson, 2008)**

Research methodology can be broadly categorised into three: "Quantitative research methods", Qualitative research methods", and Mixed research methods" **(Swanson and Holton, 2010).** In view of this research question, the researcher is interested in understanding the strengths and weaknesses of the existing approaches to sustainable manufacturing and developing a holistic framework to support effective sustainability decision-making. Thus, the method adopted in this study is a mixed or convergence research method that is consequence oriented, problem-centred, and pluralistic (**Swanson and Holton, 2010**). This method deploys quantitative and qualitative research methods hence; it allows the researcher to have multiple views of the issues and thus, enhances greater accuracy.

This thesis research methodology deploys a combination of four stages of research methods, approaches, tools and techniques in accordance with the stated research objectives (Figure 3-5).

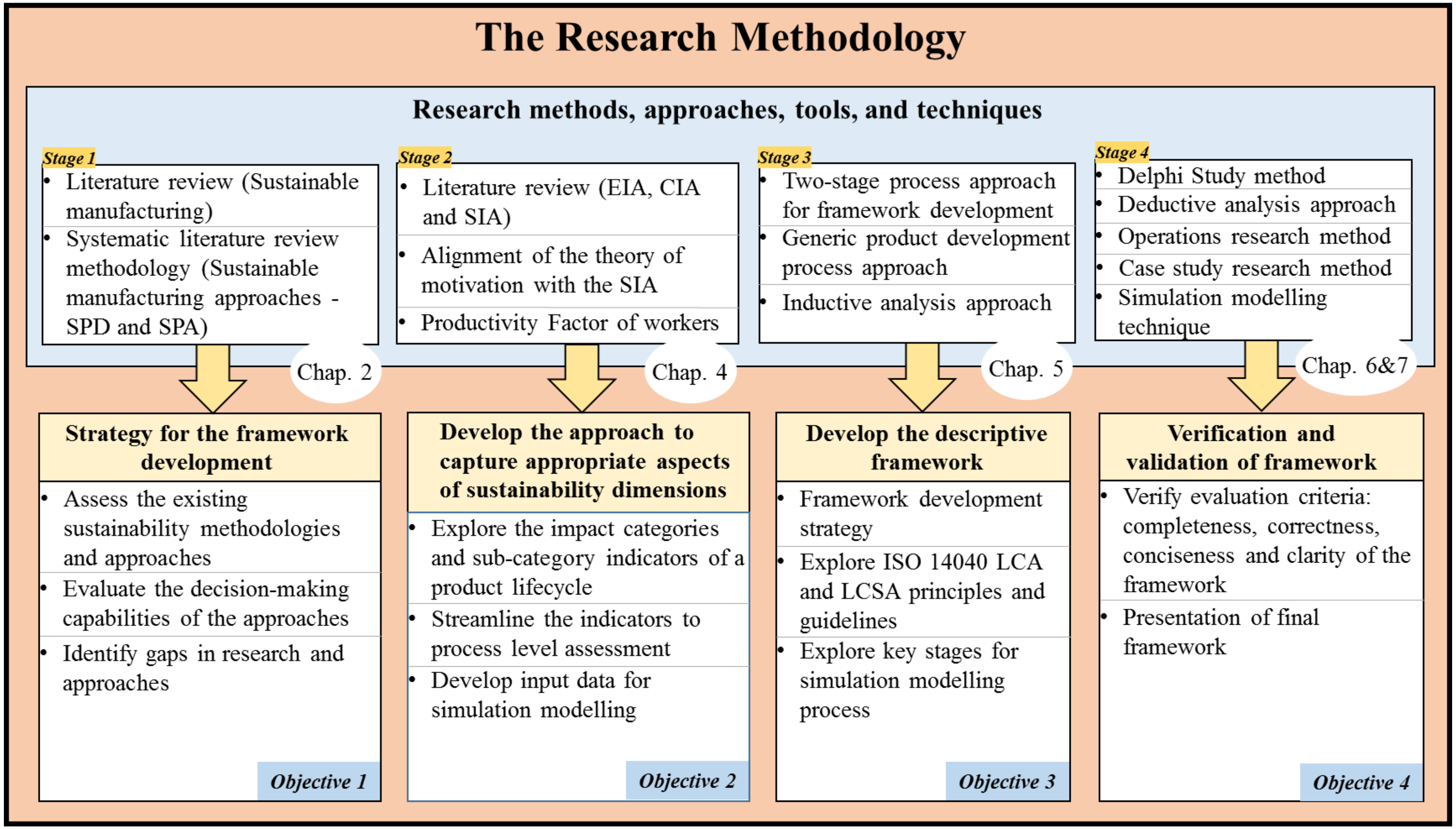


*Figure 3-5 The multi-methodology research approach adopted for this thesis*

**In stage 1,** the objective is to assess the existing sustainability methodologies and frameworks, evaluate their decision supporting strengths and weaknesses, and develop a constructive strategy for the development of the proposed framework. In this stage, the two major sustainable manufacturing approaches identified in the literature review of chapter 2 were further analysed for their strengths and weaknesses in respect of effective decision-making. Hence, the research method applied in this stage is literature review and steps for conceptual framework development. The outcome of the literature review chapter underpins the formulation of the research questions and the development of the holistic sustainability impact analysis framework (covered in chapter 2).

**Stage 2**: In this stage, the output of stage 1 and further literature review in environmental, economic and social sustainability impact categories are enhanced to determine the appropriate approach to capture the aspects of the three sustainability dimensions into an analytical model. The technique enables the streamlining of the sustainability impact categories and sub-category indicators within the process level assessment of manufacturing production domain (covered in chapter 4).

**In stage 3**, the development of a holistic integrated sustainability impact analysis framework deploys a two-stage systematic process for conceptual framework development. The input from the stage 1 and 2 above enabled the inductive analysis method applied in the first stage of this stage 3. The outcome is a "descriptive integrated simulation-based sustainability impact analysis framework" that will provide the guidance for building an integrated computer simulation model of a real or proposed system. The simulation model will enable assessment of both production and sustainability performance of a dynamic manufacturing system and support sustainability decision-making (covered in chapter 5).

**In stage 4**, the second stage of the stage 3 above was deployed in this stage 4 to verify the framework developed in stage 3 above. A Delphi method was used in the verification process to verify the correctness, conciseness, clarity and completeness of the framework. This stage also used a case study of a real manufacturing environment to validate the applicability of the framework by following the framework guidelines to model a prototype of the real manufacturing environment (covered in chapter 6 and 7).

### ***3.5.*** *Summary*

The chapter discussed the background and motivation for this research and concluded the research programme development phase of the thesis. This first section presented the research question followed by the development of the research aim and objectives in the second section. The chapter also presented a third section that discussed the development of the research scope. In this third section, the general scope for sustainability life cycle assessment and the associated challenges were discussed. The use of the terms "holistic" as relating to the totality of a sustainable manufacturing system or the whole product lifecycle and "object of study" to streamline the objectives of the process levels assessment were presented based on the context of this research. The chapter concluded with a section on the research methodology development and the outline of the research objectives and the corresponding stages that made up the multi-methodology.

# CHAPTER 4

## 4. THE SUSTAINABILITY INDICATORS FOR PROCESS LEVEL MANUFACTURING

This chapter focuses on capturing sustainability impact categories and key sub-category indicators that are able to provide input data and enable effective modelling of the process level impact analysis. The Global Reporting Initiative (GRI) classification for impact categories and category indicators **(GRI, 2016)** is adopted and adapted for use due to its wide coverage and versatility for application in the context of this research. In this chapter, the researcher also discussed the alignment of the social aspects of sustainability with the theory of motivation. The method applied the principles of social economy and reciprocity, and the theories of motivation and social exchange to guide the capture and calculation of social indicators. In the study, the Herzberg two-factor theory of motivation is adopted to classify the negative and positive social impacts of the workers' stakeholder category.

### *4.1. Introduction*

The LCC and S-LCA are lifecycle approaches used similarly to eLCA to avoid shifting of burden from one process phase to another in a product lifecycle. Though it is not feasible to use the same life cycle inventory for eLCA, LCC, and S-LCA due to different data access and flows, it is ideal to use the same system boundary and functional unit to quantify the performance of the three sustainability dimensions **(Schau, Traverso and Finkbeiner, 2012)**. There is also the need for some adjustment of the Life Cycle Inventories (LCI) to fit different lifecycle techniques, due to the differences in the data sets, measuring units and misalignment of the lifecycle phases of the three dimension **(Lichtenvort *et al.*, 2008; Hunkeler, David; Lichtenvort, Kerstin; Rebitzer, 2013)**.

It is out of the scope of this study to define new sustainability indicators, which are well covered in other articles and studies **(Consultants, 2000; GRI, 2016; João Fontes, 2016),** but rather, the study reflects some of the key performance indicators (KPIs) for the impact analysis within a manufacturing domain. The purpose is to select a combination of product and process that is environmentally friendly, socially beneficial and economically advantageous over those that are less profitable for both the investors and users.

The interconnection between environmentally friendly manufactured product and economic development has been studied and established in many research. However, the economic studies of the benefits of social development to economic growth and manufacturing sustainability have not been adequately captured or itemised in the literature. According to **Cropanzano and Mitchell (2005)**, the interdependency of various social aspects on other sustainability dimensions needs to be studied in order to deduce appropriate indicators. Similarly, the UNEP/SETAC guidelines for Social Life Cycle Assessment (S-LCA) framework **(UNEP Setac Life Cycle Initiative, 2009)**, advised the identification of the categories of affected stakeholders and their associated impacts subcategories across a product lifecycle. The Global Reporting Initiatives framework **(GRI -400 Series, 2016)** also stated in the background of most of the employees' related social disclosures, the importance of the social initiatives in boosting employee morale and productivity. Hence, social impact assessment of a product/process needs to reflect both the intrinsic and extrinsic social aspects in order to support effective assessment and improvement decisions **(GRI -400 Series, 2016; João Fontes, 2016)**.

### *4.1.1. The impact of Manufacturing Process on Sustainability*

Manufacturing may be defined technologically and economically as the application of physical and chemical processes to transform a given starting material into an item of greater value **(Groover, 2010)**. The process of transformation includes the use of combinations of machinery, power, labour and tools to alter the shape or properties of a given material **(Groover, 2010)**. Manufacturing processes consume resources (tangible and intangible), create value, and impact the environment, economy and society. The US Department of Commerce, defined Sustainable manufacturing 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" *(US EPA, OA, no date).* Manufacturing process creates new products by adding value to an initial starting material or part through a series of value-adding processes such as tooling, cutting and machining. These processes consume resources such as cost, labour and energy based on the processing materials and the quality of the desired products, and produce wastes and harmful substances. Hence, the goal of sustainable manufacturing assessment is to evaluate alternative process and products with minimal negative impact on the three sustainability dimension. Figure 4-1 depicts how value is distributed (consumed), created and negatively impacted by resource flow in a manufacturing process.

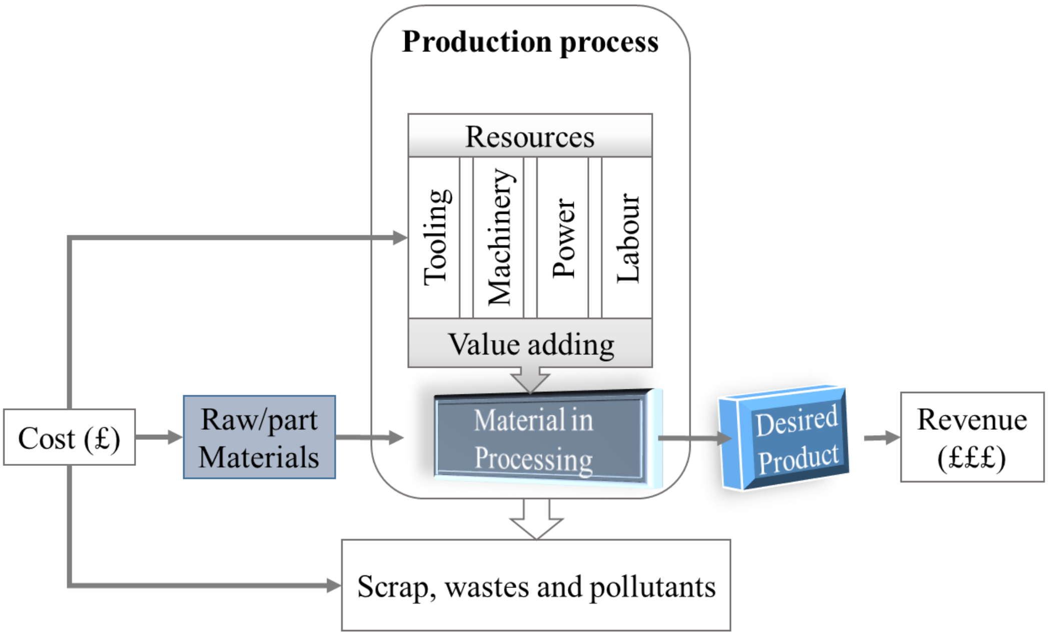


*Figure 4-1 A conceptual framework of a value-adding manufacturing process*

In an economic term, the Value (££) created is the Revenue (£££) generated less the Cost (£). In an environmental term, the energy consumed by a unit product can be calculated from the embodied product energy (direct energy required + indirect energy required). Socially,  values are created for users when a material is transformed into a useable item. However, the impact of the manufacturing process on human health and the environment cannot be easily calculated without a useful tool to support the decision for alternative product or process. It is important to note that some alternatives may seem contradictory in a short-term assessment but aligns economically, socially and environmentally in the long-term and vice versa. Hence as emphasised by **Wood and Hertwich (2013)**, the full degree of economic benefits only becomes apparent when the assessment of alternatives are stretched beyond the focus of the single stage of a product lifecycle. The unification of all the sustainability impacts of the product lifecycle stages, therefore, accounts for the total impacts exerted by the creation of the manufactured product. This research focuses on the manufacturing production stage of the product lifecycle to examine the interdependencies of the aspects of the three sustainability dimensions.

### ***4.2.*** *The Environmental Life Cycle Assessment (eLCA)*

The application and associated challenges of ISO 14040 LCA principles and framework **(ISO 14040:2006, no date)** have been discussed in the literature review chapter (sections 2.4.8.1 and 2.4.8.2). The methodology for the application is provided by the requirement and guidelines framework **(ISO 14044:2006)** which describes the four phases of study for the environmental assessment of a product lifecycle. The requirements and guidelines provide the methodology for the LCA study:

1. ***The goal and scope definition phase*** enables the sustainability analysts to define the aim and intended use of the assessment clearly. This, in turn, helps to define the level of details and system boundary or cut-off point for the assessment. The Functional Unit (FU) as a reference point and the data quality requirements are also defined in this phase.
2. ***The Life Cycle Inventory (LCI) Analysis phase*** is involved in the gathering/collection and modelling of input data appropriate to support a decision or meet for the purpose of the study. Hence this phase is driven by the “goal and scope phase.”
3. ***The Life Cycle Impact Assessment (LCIA) phase*** provides the platform for the analysis of the input data collected in the LCI phase. This phase provides information and can support decision-making or implementation of the defined goal of the study.
4. ***The fourth phase is the interpretation phase*** which is an iterative process, summarises each of the stages in a way to provide recommendations, conclusion and support decision-making according to the goal and scope definition.

The guidelines for the LCA does not enforce the application of the four phases in an assessment, for example; the goal of a study may be satisfied by conducting only the LCI and interpretation phases without the LCIA phase **(ISO 14044:2006)**. Though the LCA framework does not address the social and economic dimensions of sustainability, the approach, principles and methodology can be applied to the three sustainability dimensions **(ISO 14044:2006)**. The challenge, however, is integrating the three dimensions in a study due to the differences in the data types and sources during the data collection phase. There are vast categories of elements that contribute to the environmental impact of a product lifecycle. Many classifications of the data source and impact assessment methods have been prescribed in the literature to be used in accordance with the LCA. The Environmental Impact Assessment (EIA) tools such as Ecotax, Ecovalue08, Eco-Indicator95, Eco-Indicator99, Recipe, LC-Impact, LIME, and Impact 2002+

have also been widely discussed and analysed **(Consultants, 2000; Goedkoop *et al.*, 2013)**. The Global Sustainability Standard Board (GSSB) provides flexible Global Reporting Initiative (GRI) standards that can be used by organisations of any size, type, and operating within any geographical location to capture and report the impacts related to an aspect of a sustainability dimension **(Foundation, 2016)**. The GRI standards enable organisations that want to report the environmental, economic and social impacts to capture the impact categories and sub-category indicators based on the goal and scope of the report. The standard is adopted in this study due to its flexibility and capability to capture key performance indicators of the three sustainability dimensions. Table 4-1 shows the major eLCA impact categories and the corresponding category indicators of a product life cycle. The listed impact categories may not be applicable for the Environmental Impact Analysis (EIA) of a single organisation. Hence, the goal and scope definition phase helps in the streamlining of the impact categories and the required indicators.

*Table 4-1 Significant eLCA Impact Categories and Indicators by GRI*

| Impact Categories (Env. Aspects) | Sub-category Indicators |
|---|---|
| **Energy (GRI 302, 2016)** | Energy consumed within and outside the organisation, energy intensity, reduction in energy requirement or consumed for the production or use of the product. |
| **Materials (GRI 301, 2016)** | Input and package materials used by weight or volume, recyclable, and reclaimable products and package materials |
| **Water (GRI 303, 2016)** | Water withdrawal by source, water source significantly affected by withdrawal, water recycled and reused |
| **Biodiversity (GRI 304, 2016)** | "Closeness of operational sites to protected areas and areas of high biodiversity value, Significant impacts of activities, products, and services on biodiversity, Habitats protected or restored, IUCN Red List species and national conservation list species with habitats in areas affected by operations" |
| **Emissions (GRI 305, 2016)** | GHG emissions: Energy indirect (Scope 1, 2 and 3), intensity, reduction, "Emissions of ozone-depleting substances (ODS)" and "Nitrogen oxides |

| | |
|---|---|
| | (NOX), sulfur oxides (SOX), and other significant air emissions” (GRI, 2016) |
| **Effluents and Waste (GRI 306, 2016)** | “Water discharge by quality and destination, waste by type and disposal method, significant spills, transport of hazardous waste, water bodies affected by water discharges and/or runoff.” |
| **Environmental Compliance (GRI 307, 2016)** | “Non-compliance with environmental laws and/or regulations.” |
| **Supplier Environmental Assessment (GRI 308, 2016)** | “New suppliers that were screened using environmental criteria, negative environmental impacts in the supply chain and actions taken.” |

### ***4.2.1.*** *Environmental Impact Assessment (EIA) At the Manufacturing Stage*

The type and level of machinery, tools, power and labour required during a manufacturing process depend on the starting materials, quality and the quality of the desired end product. There are various manufacturing processes which include: Solidification Process such as metal casting and glass working, Metal Forming which include metal deformation and sheet-metal working, Plastic Shaping such as melting and extrusion, and Metal Removal such as machining, tooling and cutting **(Groover, 2010)**. The processes consume natural resources such as raw materials, water and energy, and pollute the environment through the emission and wastes discharged during the creation of the desired products. According to **Groover (2010),** there are three building blocks in a manufacturing plant:

1. *Materials to be transformed into a finished product*
2. *Processes for transforming the material*
3. *Systems that constitute the processes including people and other resources*

#### **4.2.1.1.** *Energy Required for Processing a Unit Product and Assumptions*

The systematic literature review conducted in chapter 2 identified energy consumption as a leading impact category that contributes to the environmental impact of the manufacturing production processes. Most of the non-renewable energy sources are powered by coal, fossil fuel and gases which contribute to the most substantial world greenhouse gas emissions. Various studies have also confirmed the consistent correlation between energy consumption and the greenhouse gas (GHG) emission (Wang, Huang and Zou, 2016; Elkadhi, Kalai and Ben Hamida, 2017) This energy is a function of the power generated in watts by the mechanical or electrical machines and the length of time in hours the power was generated.

Research has established that most of the energy consumption occurs during manufacturing by powering the plant infrastructure, storage and production processes **(Rahimifard, Seow and Childs, 2010)**. Hence, to reduce the total energy consumed by a unit product, various authors have suggested the framework for modelling the Embodied Product Energy (EPE) which integrates energy consumed both at plant level and production process level as shown in Figure 4-2 **(Rahimifard, Seow and Childs, 2010; Branker, Jeswiet and Kim, 2011; Feng *et al.*, 2014).** This is calculated as shown below:

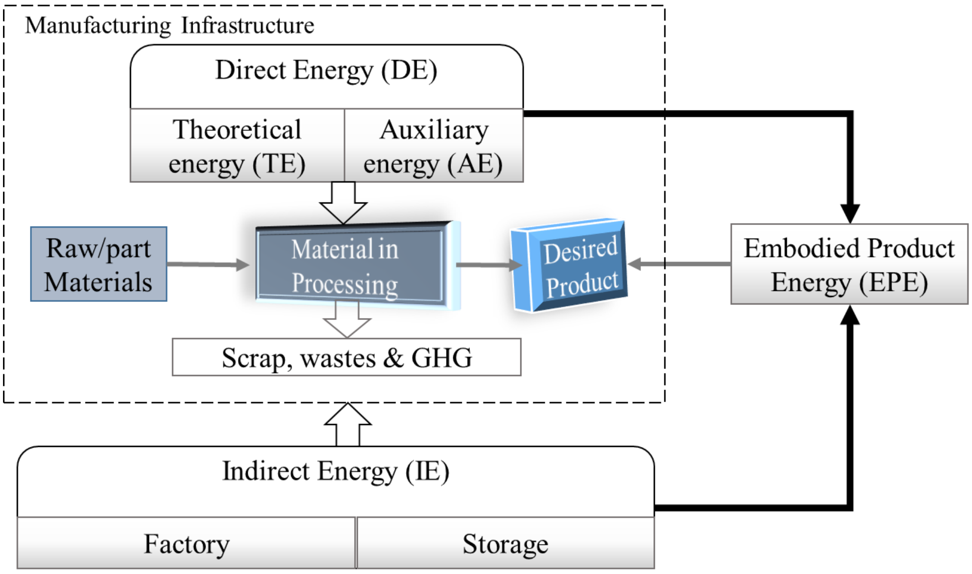


*Figure 4-2 A conceptual framework of embodied product energy of a manufacturing process*

*Total energy (Embodied) for a unit product (EPE) = Direct energy + Indirect energy*

*Where Direct Energy (DE) = Theoretical Energy (TE) +Auxilliary Energy (AE)*

The Direct Energy (DE) is at the process level while the indirect energy is at the plant level. The DE represents the aggregate of the energy required directly by the machinery to process the material, and the energy required by the supporting activities (auxiliary process) such as the lubricants, control systems and coolants **(Rahimifard, Seow and Childs, 2010; Branker, Jeswiet and Kim, 2011; Feng *et al.*, 2014)**. The Indirect Energy (IE) is the share of the overhead energy required by the manufacturing site where the process is being carried out. The IE includes the energy required for lighting, heating and air conditioning the factory and storage facilities. However, while the IE is static and could be calculated or estimated from the overhead energy consumed by the manufacturing plant (that is; the value will not change during a simulation run), the DE is dynamic and dependent on the type of materials being processed and the quality of the desired product. This research focus on the DE consumed for analysing the impact of alternative product or process on the environment. This research also assumes that the energy consumption of the auxiliary processes (AE) is continuous and not discrete as in the theoretical energy consumption (TE). Hence, the modelling of energy is this study focuses on the TE consumed which is the energy consumed by the machinery in processing a particular raw material or part.

#### **4.2.1.2.** *Choice of Materials for Sustainable Product Design*

Choosing and grading the best material that satisfies the quality of the desired product is one of the crucial stages of product development. The choice of a material influences the required production process, product lifecycle, product function, environment, cost and society in a multiple and complex ways **(Jahan *et al.*, 2010; Prendeville, O'Connor and Palmer, 2014)**. The criticality of some materials to a product design makes the selection and choice of alternative a tough task.

It is the responsibility of the sustainable product designers and analysts to reduce or find alternative material with minimal environmental impact and which satisfy the same quality of the desired products. There are three major types of materials in "hardware manufacturing", these are Metal, Ceramic, and Polymer. The forth is Composite Materials. Another category is Alloys which are a composition of one or two elements of which one is metallic. There are existing tools which include materials databases, physical materials libraries and software that are available to assist the designer in making alternative choices. Also, eco-design tools such as eco checklist and guidelines, eco Audit tool, MET matrix, regulations and directives, LCA, LCC and S-LCA methods are available to assist eco-designers to explore and compare different lifecycle options. Where multi-objective criteria are involved, methods such as multi-criteria decision making (MCDM), fuzzy methods and computational methods are deployed **(Jahan *et al*., 2010; Prendeville, O'Connor and Palmer, 2014)**. However, focusing only on the technical properties of materials at the product design level without consideration for the production system risks over-rationalising the material selection for sustainable product design **(Prendeville, O'Connor and Palmer, 2014)**. The energy and resources required for processing each category of materials vary and the environmental, economic and social impacts differ based on many other factors including the required capacity and planning. Hence, materials selection needs a broader view of the material system which reflects the processing behaviour, stakeholders' impact and technological requirements.

In accordance with the aim of this research that is; ***to develop a holistic integrated simulation-based impact analysis framework that supports decision-making for sustainable manufacturing design and management,*** the capabilities of both Sustainability Science (SS) and LCSA (section 2.3) are deployed in this study with the view of systemic and analytic approach to sustainability. This approach to sustainability is a Life Cycle Thinking (LCT)-based (section 2.3) that incorporates various sustainability assessment methodologies, methods and tools to analyse the interactions of the aspects of sustainability dimensions and to evaluate their sustainability within a defined domain. Figure 4-3 shows a high-level conceptual diagram of the proposed analytical model. The proposed framework is to interdependently analyse in a simulation model the changes in specific properties of the sustainability aspects to support effective sustainability decision.

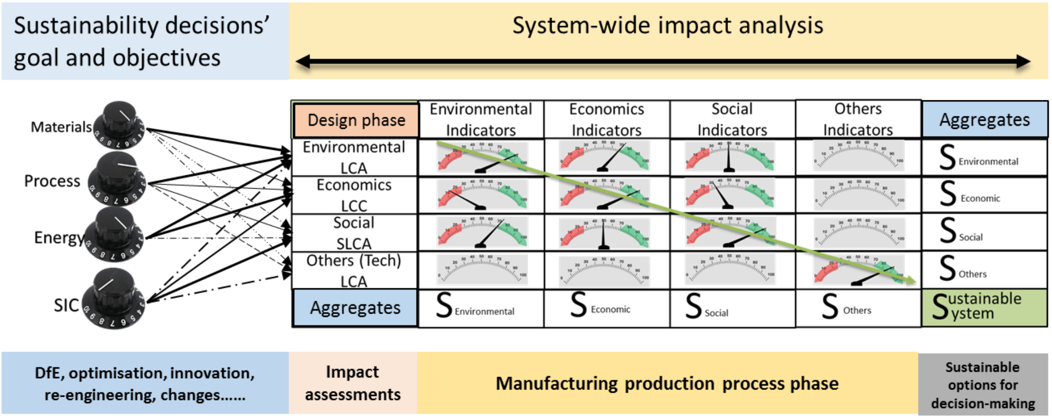


*Figure 4-3 Simulation-based conceptual model for life cycle sustainability analysis (LCSA)*

The appropriate environmental sub-category indicators and the corresponding description of indicators within the “process level” of a manufacturing system are listed in Table 4-2. The indicators are extracted from the GRI **(Foundation, 2016)** and can be applied based on the defined goal and scope of sustainability study.

*Table 4-2 Environmental sustainability indicators for manufacturing production process*

| **Sub-category Indicators** | **Description of Indicators** |
|---|---|
| • **Energy**<br>Reduced energy consumption or requirement | Direct energy consumed per functional unit, embodied the energy of a product |
| • **Material**<br>Effective alternative or redesign of product and packaging materials | Biodegradable, extendable life-span, recoverable, remanufacturable, reduced weight and volume, recyclable |
| • **Water**<br>Reduced water usage | Water recycled, water used per functional unit, discharged |
| • **Emission**<br>Reduced emissions | GHG related to direct energy consumed |

| Sustainability Dimensions | Impact Category | Experimental factors (Population) | Sub-factors (Focuses) |
|---|---|---|---|
| **Environmental** | • Materials | ▪ Alternative materials | ○ Environmentally friendly<br>○ Recyclable<br>○ Reusable |
| | | ▪ Alternative designs | ○ Remanufacturable<br>○ Repairable<br>○ Recoverable |
| | • Energy | ▪ Alternative energy / Technology | ○ Non-renewable<br>○ Renewable |
| | | ▪ Power Consumption | ○ Processing rate<br>○ Idle time<br>○ Blockage |
| **Economics** | • Process | ▪ Productivity | ○ Circle time<br>○ Throughput |
| | | ▪ Lean | ○ Flow<br>○ Wastes |

| | | | |
|---|---|---|---|
| | | | ○ Inventory<br>○ WIP |
| | • Cost | ▪ Assets (cost per use) | ○ Machines |
| | | ▪ Consumables | ○ Auxiliaries |
| | | ▪ Capital (costs) | ○ Materials<br>○ Labour<br>○ Machining |
| | | ▪ Alternative technology | ○ Robots<br>○ IoT<br>○ CNC |
| **Social** | • Social Impact Coefficient (SIC) | ▪ Negative social impacts | ○ Personnel health<br>○ Operational safety |
| | | ▪ Positive social impacts | ○ Training<br>○ Job creation<br>○ Onsite amenities |
| | | ▪ Technology | ○ Automation |

### ***4.3.*** *The Environmental Life Cycle Costing (eLCC)*

In the past, through the industrial revolution and development, economic performances were in adversarial relationship to both the environment and the society. The current global awareness and preference for environmentally friendly and ethical products have not however compromised the desires of industries to engage in optimising profits but strategically seek a balance of the three sustainability dimensions.  It has also been posited that the assessment of economic performance or Cost Impact Assessment (CIA) of manufacturing processes is in its matured state **(Cataldo, Taisch and Stahl, 2013)**. This is due to the availability of information technology systems which provide the necessary support for manufacturers to collate key performance indicators easily, assess and predict the economic impacts **(Cataldo, Taisch and Stahl, 2013)**. However, while the traditional cost evaluation tools such as the net present value, total cost of ownership, LCC, total supply chain management cost are still useful indicators for financial performance, they have not been aligned with the current environmental protection and social development demands. According to **Wood and Hertwich (2013),** LCC is a useful indicator in conventional economic assessment but does not capture full economic sustainability for a product life cycle due to a potential contradiction in system boundary to an eLCA.

The code of practice for environmental Life Cycle Costing (eLCC) published by the SETAC **(Lichtenvort *et al.*, 2008; Swarr *et al.*, 2011)**, thus, provides a new framework for evaluating the economic impacts of a manufacturing decision. This is consistent, though flexible, with the system boundaries of the ISO 14040 eLCA **(Swarr *et al.*, 2011).** According to SETAC, LCC is classified into three categories: conventional, environmental and societal LCC of which environmental LCC (eLCC) is considered to be most appropriate to combine with eLCA for sustainability assessment **(Lichtenvort *et al.*, 2008; Schau, Traverso and Finkbeiner, 2012).** The SETAC eLCC framework enables a comprehensive modelling of all costs involved in the creation of a product through its lifecycle including those incurred by the consumers and other stakeholders in compliant with the ISO 14040 LCA framework **(Lichtenvort *et al.*, 2008; Hunkeler, David; Lichtenvort, Kerstin; Rebitzer, 2013)**. The SETAC code of practice puts the eLCC into perspective by differentiating it from the conventional LCC which is based on the direct economic evaluation of conventional costs associated with the production of a product **(Hunkeler, David; Lichtenvort, Kerstin; Rebitzer, 2013)**. In addition, eLCC summarises all costs directly covered by one or more of the actors in the life cycle of a product including the costs of end-of-life choice **(Hunkeler, David; Lichtenvort, Kerstin; Rebitzer, 2013).** The application of eLCC enables decisions on source and procurement of materials, production and distribution, use and maintenance, disposal and end-of-life choice to be made in consideration of full cost implications. It is central to the cost management process and provides an input to the assessment of alternative materials, processes, products and distribution channels during product development phases **(NSW Treasury, 2004)**. The GRI provides comprehensive cost impact categories for an eLCC with their components as summarised in Table 4-3. Each stage of a product lifecycle identifies appropriate impact categories and applies various appraisals' techniques such as economic and financial appraisals, risk management, value management, and demand management as a means to evaluate alternatives.

*Table 4-3 Significant eLCC Impact Categories and Indicators by GRI*

| Impact Categories (Aspects) | Sub-category Indicators |
|---|---|
| Economic Performance (Global Reporting Initiative, 2016a) | The direct economic value generated and distributed, Financial implications and other risks and opportunities due to climate change, Define benefits plan obligations and other retirement plans, Financial assistance received from the government |
| Market Presence (Global Reporting Initiative, 2016b) | Ratios of standard entry level wage by gender compared to local minimum wage, Proportion of senior management hired from the local community |
| Indirect Economic Impacts (Global Reporting Initiative, 2016c) | Infrastructure investments development, services supported and significant economic impacts. |
| Procurement Practices (GRI 204, 2016) | Percentage of products and services purchased locally |
| Anti-corruption (GRI 205, 2016) | Risks assessed related to corruptions and disguised donations |
| Anti-competitive Behaviour (GRI 206, 2016) | Evidence of anti-competitive behaviour, anti-trust and monopoly practices |

### *4.3.1. Cost Impact Assessment (CIA) At the Manufacturing Stage*

The goal of every organisation is to increase economic performance by maximising the revenue generated and reducing the operating cost or other value distribution costs. Operating costs include materials costs, power generation costs, product components costs, facilities costs, personal protective equipment (PPE) costs, license fees, and service purchased costs such as contract workers and agencies costs. The basic indication of how well an organisation creates wealth for its stakeholders is a function of the economic value created and distributed by the organisation **(Global Reporting Initiative, 2016a)**. An organisation creates value when revenue is generated from the sales of the products or assets and it distributes values on operation costs, capital investment costs, wages and benefits, community developments, taxes, and government legal fees. The economic value retained after all payments is an indication of economic soundness of the organisation. The impact category “Economic Performance” and its sub-category indicators as shown in Table 4-4 is appropriate for the economic impact analysis within the scope of this research.

*Table 4-4 Economic Performance indicators for Manufacturing Production Process*

| **Sub-category Indicators** | **Description of Indicators** |
|---|---|
| The direct economic value generated (EVG) | Revenues: Productivity, throughput, reject ratio, Takt time, machine rate |
| The direct economic value distributed (EVD) | Operating costs, labour wages and benefits, capital provider’s costs, tax, community investments |
| The ceonomic value retained (EVR) | “Direct economic value generated” less “economic value distributed” |

### **4.3.1.1.** *Cost Distribution Methodology*

In determining the cost efficiency in a dynamic environment, cost of resources and time of usage are critical factors hence identifying high-level cost resources and reducing the number or time of usage becomes paramount in effective decision making. The maximisation of resources in order to increase the throughput plays a second-best rule in generating economic value for the organisation. One approach to distributing the cost to operating activities is the Activity-Based Costing (ABC). The concept of ABC has its origin in the manufacturing industry where the proportion of indirect or overhead cost increases whereas the proportion of direct labour and materials cost reduces due to advance technological developments and productivity improvements **(Edwards and Technical Information Service, 2008)**. ABC is a costing methodology that helps to reveal hidden sources of profitability and embedded cost **(Turney, 2010; Tsai *et al.*, 2012).** It is a tool used in cost accounting to analyse profit and improve competitive position; it supports decision-making for resource and capacity planning, improved profitability and predictive modelling. Some authors have used ABC in costing of sustainable manufacturing, for example; **Tsai et al. (2012)** used ABC “to track a product environmental costs and estimate the environmental costs of different pollutants per unit”. The authors also deployed ABC to support decision-making about product-mix in green manufacturing **(Tsai *et al.*, 2013)**. ABC methodology overcomes the inappropriate allocation of accumulative cost to products or services by distributing relative costs to operation resources and enhance effective decision making. Hence, ABC aligns with the value distribution techniques of the GRI. In addition, the simulation modelling software such as SIMIO which is deployed in this research is built on the platform of ABC for activities' costing.

The GRI disclosure 201 **(Global Reporting Initiative, 2016a)** provides explicit guidelines on the definition of each of the items in the sub-category indicators. The interest of this research is to streamline the items to suit the goal and scope of the production domain of the manufacturing process. The components of direct economic value generation include throughput, resource utilisation and reject ratio. The direct economic distribution includes operating costs, labour wages and benefits. These are functions of the time an item spent in the system, work in progress and energy consumption. Hence to increase economic value retained, the process has to maximise the economic value generating components while minimising the economic value distribution components.

## *4.4. The Social Life Cycle Assessment (S-LCA)*

### *4.4.1. Introduction*

In this study, the researcher examined some theories and principles such as the social economy principles, social exchange theory, and motivational theory that are related to management and organisational psychology in order to establish a viewpoint then, combined motivational and commitment models into an integrated framework. First, the study used Herzberg motivational theory to explain the motivational model and sustainability of social aspects to explain the commitment model before aligning the models into a single framework. The Herzberg's two-factor theory of motivation is most relevant to this study because it establishes the study of motivation in the workplace and provides a framework to understand the mutual relationships between employer and employee, and the implications of social initiatives on work-force **(Herzberg, 1959)**. This study establishes the fact that organisational social development can lead to employees' commitment to work and improve productivity without the "KITA" **(Kick In The A**)** approach to employees' motivation **(Herzberg, 1959; Yusoff, Kian and Idris, 2013)**. Thus, social development is driven by the ethical duties and moral obligations of corporate organisations to ensure the social well-being of their employees.

The next two sections of this study cover the importance of social impacts assessment and identify the stakeholders' categories and subcategories in a product lifecycle. This is followed by section 4.4.4 which covers the relationships between social impacts and motivations at the workplace. Section 4.4.5 describes the theory of reciprocity as related to employees' productivity. Section 4.4.2.6 and section 4.4.2.7 detailed the alignment of social impacts assessment with Herzberg two-factor theory and the process of calculating the social impacts coefficient. Section 4.4.8 demonstrates the procedure for calculating the social impact coefficient, and section 4.4.9 summarises the study and conclude.

## *4.4.2. Impact Assessment of a Product Life Cycle*

### **4.4.2.1.** *The Importance of Social Impacts Assessment in a Product Lifecycle*

The manufacturing production processes have been identified as social hotspots which are associated with both high risks of negative social impacts and high opportunities for positive social impacts. Depending on the stakeholders' category in the product lifecycle, the assessment and remedial actions of the impacts are critical to sustainable product development. Research on Social Life Cycle Assessment (S-LCA) are prevalent, however, the translation and effects of the negative and positive social impacts on economic and environmental dimensions are yet to be harnessed in the research. Similarly, there are acknowledged challenges associated with the development and application of social and socio-economic life cycle assessment **(Benoît *et al.*, 2010; João Fontes, 2016)**. In the early development stages and research of environmental Life Cycle Assessment (eLCA), social aspects were included in the methodology **(Benoît *et al.*, 2010)**. This was due to various environmental impacts identified to directly or indirectly give rise to social impacts and many social activities that resulted in environmental impacts **(Benoît *et al.*, 2010)**. The difficulty of capturing and integrating the qualitative social aspects into the quantitative environmental aspects, however, increased the complexity of the LCA framework **(Benoît *et al.*, 2010; João Fontes, 2016)**. Amongst the three sustainability dimensions, the social indicators are often classified as positive indicators due to their positive contribution **(Vinyes *et al.*, 2015)**. The S-LCA guidelines, however, grouped the social impacts into positive and negative impacts. The positive social impacts are defined as the "social performances that go beyond compliance"; hence, any social aspect or benefits that are provided and protected by appropriate laws may not be seen as a positive social impact **(Petti, Ugaya and Di Cesare, 2014)**. Other challenges with this classification are the effects and response provoked by social impacts as soon as there are changes in the social conditions of certain stakeholders **(Slootweg,**

**Vanclay and van Schooten, 2001)**. The function of S-LCA is, however, to allow identification and assessment of key social issues and detail their impacts on the production, use and through the product end of life choices **(Benoît *et al.*, 2010; João Fontes, 2016)**. **João Fontes (2016)** defines S-LCA as the evaluation of the potential social impacts of a product or a service throughout its lifecycle stages. According to **João Fontes (2016)**, an aligned social impact can improve the economic performance of an organisation. Figure 4-4 depicts an example of product lifecycle stages covered by S-LCA. At each of the stages, the Social Impact Assessment (SIA) is conducted to assess the social performance of the stage. The aggregation of the SIA of a product lifecycle stages, therefore, represents the S-LCA.

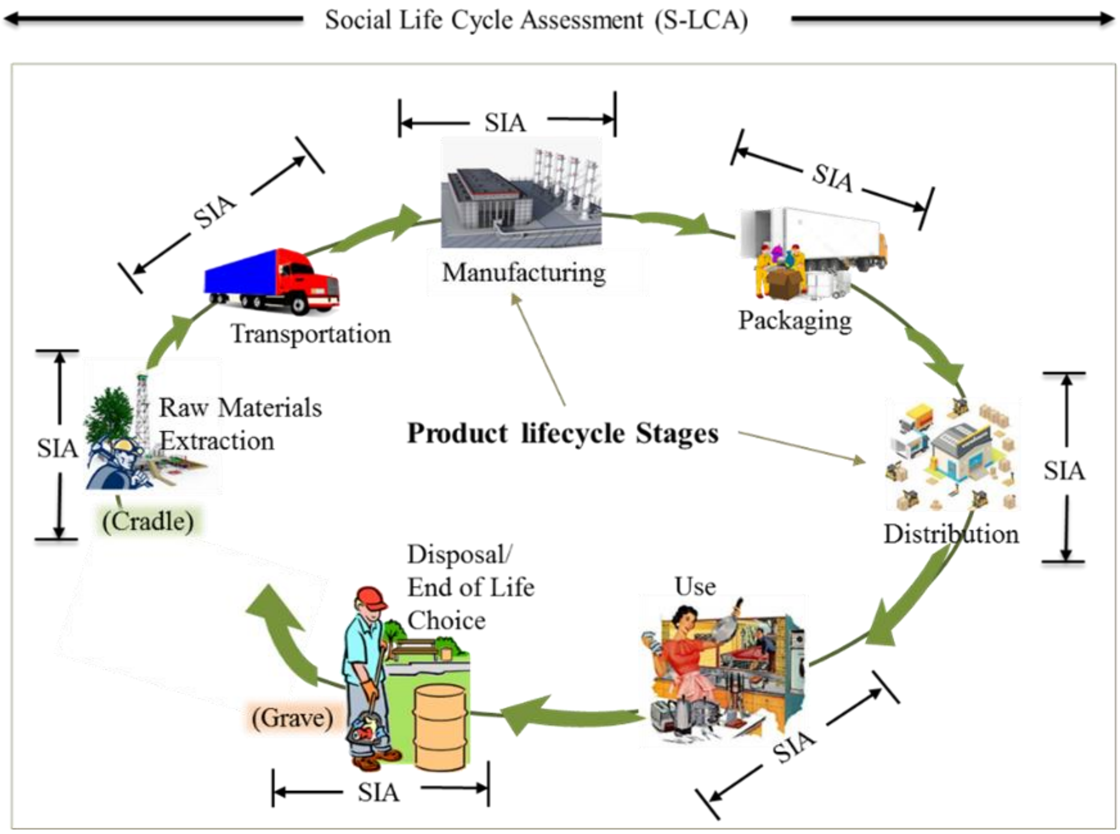


*Figure 4-4 Product lifecycle stages and social impact assessment (SIA)*

### **4.4.2.2.** *Social Life Cycle Assessment*

In consensus with the international group of experts leading research in the field of social, economic and environmental impacts of a product lifecycle, the UNEP/SETAC in 2009 published the guidelines to clarify the impact of a product S-LCA, and compliment the guidelines for eLCA and Life Cycle Costing (LCC). The ISO 14040 LCA framework **(ISO**

**14040:2006, no date)** has been standardised and is used by various practitioners to assess the environmental impacts of their processes throughout a product lifecycle **(Chang, Lee and Chen, 2014)**. Though the approach has been criticised by many authors for its overwhelming data collection process, time-consuming and environmental centric, the principles and procedures remain indubitable. According to **Benoît *et al.* (2010)**, a different level of assessments is often applied along the supply chain due to political and cultural differences across the chain. For instance, a developed country may have legislation and laws in place to cover workers right whereas this might not be so in a developing country. The functions of Social Life Cycle Assessment (S-LCA) are, therefore, to identify and assess the key social issues at every stage of the product lifecycle and detail their impacts through to the use and product end of life stages. S-LCA spans internal and external stakeholders across a product lifecycle **(Benoît *et al.*, 2010)**.

There are five major stakeholders' categories: the workers, local communities, customers, suppliers, and national and global societies as listed in Table 4-5. These are related to the geographical locations such as factories, roads, mines, shops, recycling firms, disposal sites and warehouses where processes are carried out **(Benoît *et al.*, 2010; Nabavi-Pelesaraei *et al.*, 2014)**. The government and non-government agencies, future generations and the businesses are other stakeholders' categories relevant to S-LCA **(Benoît *et al.*, 2010)**.

*Table 4-5 Social impacts stakeholders' categories-Adapted from (Hunkeler, 2006; UNEP Setac Life Cycle Initiative, 2009; Benoît et al., 2010; GRI -400 Series, 2016)*

| Stakeholder Categories | Impacts Subcategories |
|---|---|
| **Workers (Employees)** | • Investment on HR, freedom of association and collective bargaining, child and forced labour, fair salary, working hours, equal opportunities/discrimination, health & safety, social initiatives, social benefits/ security, training |
| **Consumers–(supply chain and end users)** | • Health and safety, feedback mechanism, consumer privacy, transparency, end of life responsibility |
| **Local community** | • Access to material resources, access to immaterial resources, delocalization and migration, cultural heritage, safe and healthy living |

| | |
|---|---|
| | conditions, respect for indigenous rights, community engagement, local employment, secure living conditions |
| **Society–(national and global)** | • Public commitments to sustainability issues, contribution to economic development, prevention and mitigation of armed conflicts, technology development, Corruption |
| **Value chain actors-suppliers (not including end-consumers)** | • Fair competition, promoting social responsibility, supplier relationships, respect for intellectual property rights |

### *4.4.3. Social Impacts Assessment and Social Impact Subcategories*

The Social Impact Assessment (SIA) is an approach for assessing the social impacts occurring at a single process and or facility level **(UNEP Setac Life Cycle Initiative, 2009; Benoît *et al.*, 2010; João Fontes, 2016)**. For example; the social impact assessment of a project site, product lifecycle stage, jobbing or batch process. **João Fontes (2016)** suggested that since social impact assessment is consistent with the principles of environmental and economic assessments, it should be integrated into the entire sustainability assessment of a product (see Figure 4-5). However, the author encouraged the documentation of social issues and benefits associated with a product at every identified social hotspot in order to drive programmes for performance improvements **(Benoît *et al.*, 2010; João Fontes, 2016)**. Social hotspots as defined by **Benoît *et al.* (2010)**, is the *"unit processes that are within a sector and region that has high risks of negative impact or high opportunities for positive impact*". Table 4-6 shows an example of impact subcategories of workers' stakeholder category with the corresponding positive and negative impacts types. The positive social impacts present high opportunities for workers wellbeing and performance improvement, while the negative social impacts present high risks both to the worker's' well-being and the business economic growth. The government regulations and legislation provide instruments to enforce Corporate Social Responsibility (CSR), and its compliance is a starting point for an organisation's social sustainability. However, while CSR uses management information to address social impacts mostly at the enterprise level **(Benoît *et al.*, 2010)**, SIA concentrates on the social impacts occurring at a specific phase of the organisation. Figure 4-5 represents the process of breaking down a product lifecycle into social impact assessment stages and impact subcategories.

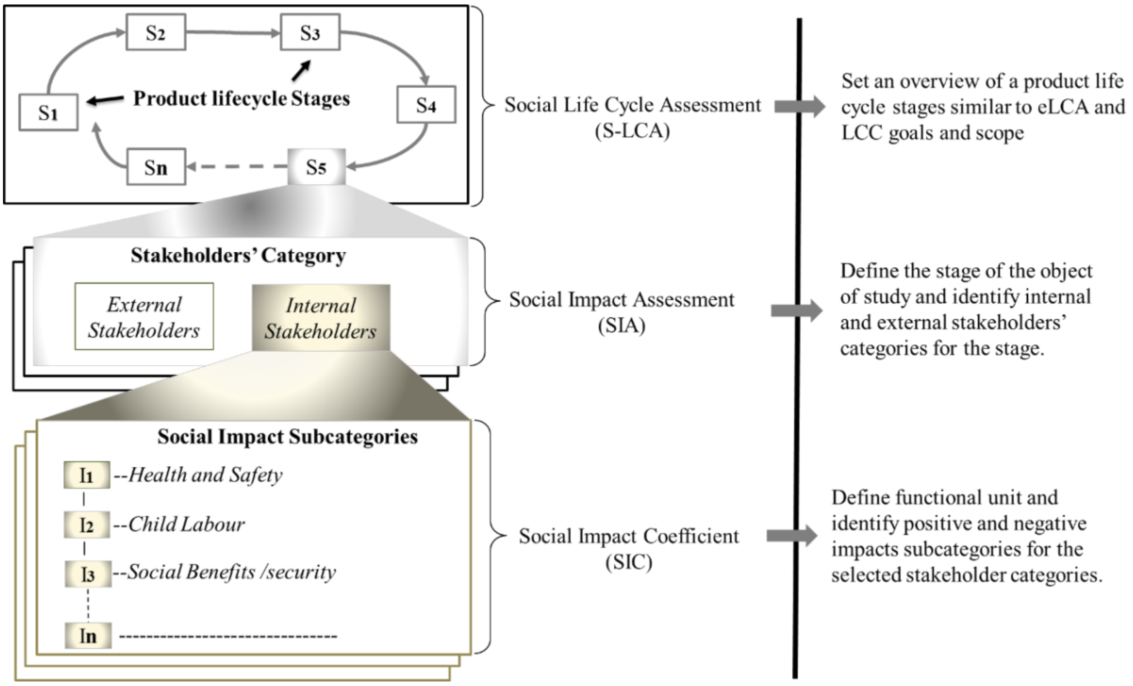


*Figure 4-5 Decomposition process of a product lifecycle stage into impact subcategories*

*Table 4-6 Impacts subcategories of workers' stakeholder categories-Adapted from (UNEP Setac Life Cycle Initiative, 2009; Benoît et al., 2010; GRI -400 Series, 2016).*

| Impact Subcategories | Descriptions of Indicators | Impact Types |
|---|---|---|
| • **Risks of the right to Freedom of Association and collective bargaining** | i. Violation of workers' rights to exercise freedom of association or collective bargaining<br>ii. Right of Association Policy in place | Negative (Regulated) |
| • **Risk of incidents of Child labour** | a. Operations and suppliers considered having significant risk for incidents of:<br>i. Child labour;<br>ii. Young workers exposed to hazardous work. | Negative (Regulated) |

|  |  |  |
|---|---|---|
|  | b. Measures taken by the organization to contribute to the effective abolition of child labour (e.g., policies against child labour) |  |
| • **Elimination of forced and compulsory labour** | a. Operations and suppliers considered having significant risk for incidents of forced or compulsory labour either in terms of i. Type of operation (such as manufacturing plant) and supplier; ii. Countries or geographic areas with operations and suppliers considered at risk.<br>b. Measures were taken by the organization to the elimination of all forms of forced or compulsory labour (e.g., Policies against forced labour) | Negative (Regulated) |
| • **Job Creation** | i. Work hour created per year<br>ii. Fair salary compare to similar industries | Positive (Unregulated) |
| • **Equal opportunities/non-discrimination** | i. The diversity of governance bodies and employees<br>ii. Non-gender bias and equal opportunity<br>iii. Ratio of basic salary of men to women<br>iii. Availability of equality policy and training of staff on relevant codes and guidelines related to discrimination and equality | Negative (Regulated) |
| • **Occupational Health & Safety Management** | i. Respect for workers right; ii. Injury and Absentee rates; iii. High-risk work or work environment;<br>iv. Formal Health and safety agreement with trade union v. RIDDOR | Negative (Regulated) |
| • **Social Initiatives** | i. Provision of social amenities onsite for workers<br>ii. Onsite social events and outing<br>iii. Recognition and Award events | Positive (Unregulated) |
| • **Investment in Human Resources (Social** | The number of full-time staff entitle to: | Positive (Regulated) |

| | | |
|---|---|---|
| **benefits/social security)** | I. Life insurance; ii. Healthcare; iii. Disability and invalidity coverage; iv. Parental leave; v. Retirement provision; vi. Stock ownership | |
| • **Labour & Management Relations (Effective Communication)** | i. Minimum notice period provided to employees and their representatives prior to the implementation of significant operational changes.<br>ii. Notice period and provisions for consultation and negotiation are specified in collective agreements | Negative (Regulated) |
| • **Training** | i. Average hours of training available to the employees per year<br>ii. Programmes for skills upgrade and development<br>iii. Regular Performance Review/Appraisal of employees | Positive (Regulated) |

The objective is to assess the social impacts and its influence on the productivity within the manufacturing production domain. Hence, the object of study, in this case, is the manufacturing stage of a product lifecycle and the focus are the workers' stakeholders' category.

### *4.4.4. Social Impacts and Motivations at Workplace*

Research on workers' behaviour has posited that negative social impacts can lead to high employees' turnover rate, social instability and downturn in productivity **(Afful-Broni, 2012)**. However, identification of positive social impacts can be enhanced to promote improvement programmes that would lead to employees commitments and increase in performances **(Meyer *et al.*, 2004; Benoît *et al.*, 2010; Afful-Broni, 2012; João Fontes, 2016)**.

The relationships between employees' motivation and commitment have long been an interesting field of study for organisations and manufacturing practitioners. This is due to the notion that motivation influences workers' commitments or behaviour to work and, leads to increase in productivity **(Meyer *et al.*, 2004; Afful-Broni, 2012; Yusoff, Kian and Idris, 2013)**. According to **Afful-Broni (2012)**, motivation is the driving force that makes persons stay focus and determined to achieve their set goals irrespective of any opposing challenge.

However, while motivational theories have to do with the organisational strategy or goal-setting for increasing task performance **(Yusoff, Kian and Idris, 2013)**, commitment according to research, has to do with sociology and social psychology and a potential tool to predict employee turnover. According to **Meyer *et al.* (2004)**, commitments can take the form of "effective attachment to the organisation, the obligation to remain, and the perceived cost of leaving". Commitment can also be directed towards a target such as an organisation to the employee. Motivation, in the other hand, which has to do with the organisation goal-setting, may lead to job and work avoidance, protest, vengeance, and defiance depending on whether the employees are satisfied or dissatisfied.

### *4.4.5. The Theory of Reciprocity and Employees' Productivity*

Relating social development and its benefits to other sustainability dimensions especially, economic growth is an on-going study. Currently, there is a shift from the economic theory that considers principles of cooperation as something obscure or marginal **(Magzan, 2014)**. According to the author, "human beings are not to be considered as self-centred individuals but 'gift exchanging animals', naturally, capable of cooperating for mutual benefits". According to **Ryan and Deci (2000)**, "Human beings can be proactive and engaged or, alternatively, passive and alienated, largely as a function of the social conditions in which they develop and function". These statements expressly explain the strong links between an individual performance and his social wellbeing or environments. The recent result of an American research firm, Gallup, shows that "only 29% of US employees are practically engaged in their work, while others are just marking time or actively undermining their companies" **(Abercrombie, 2005)**. It is certain that having a great number of workers for a task is not tantamount to higher productivity, human workers are cognitive and social beings: they are sensitive, respond to their environmental stimuli, undergo stress and depression, have expectations and responsibilities. Thus, neglecting the investment in the social wellbeing of the workers does not only hamper their productivity but the goal of sustainable development.

#### **4.4.5.1.** *Social Economy and Social Exchange Theory*

The adoption of principles such as the social economy and Social Exchange Theory (SET), which are based on reciprocity and mutual cooperation establishes the connection between the society and economy and tends to meet the social needs often neglected by the public and private economy. Social economy emphasises on the animate behaviour of human beings, establishes the links between society and economy, and promotes the needs for collective mutual benefits and cooperation **(Magzan, 2014)**. According to the author, it inserts social goals such as welfare for workers and consumers, introduces reciprocity and environmental protection into economic thinking and decision-making. **OCED (2013)** asserts it is paramount for social economy to seek to capture all elements related to the social and economic dimensions.

The Social Exchange Theory (SET) is mostly used by researchers to explain the reciprocity and relationship between perceived organisational investment in employee development and the employees' commitments to work **(Thibaut and Kelley, 1986; Konovsky and Pugh, 1994; Cropanzano and Mitchell, 2005; Kuvaas and Dysvik, 2009)**. SET involves a series of interactions that lead to employees' citizenship behaviour thus; it explains the rule of reciprocity that results in a mutual and complementary transaction between two parties. According to **Konovsky and Pugh (1994)**, Citizenship behaviour is an employee behaviour that exceeds the call of duty, and this is driven by the organisation's development of the employee's trust. **Thibaut and Kelley (1986)** refer to this behaviour as a comparison level or threshold at which an employee perceives an offer to be attractive and results in motivation to work. Various organisations such as cooperatives, credit unions, religious organisations, not-for-profit organisations and recreational groups are examples of social enterprises that adopt these principles for building healthy and sustainable communities through cooperation, solidarity and reciprocity **(OCED, 2013; Magzan, 2014)**. According to **Magzan (2014)**, "social economy would enable the market economy to become socially accountable, and self-reliant while remaining competitive, productive and profitable". Corporate Social Responsibility (CSR) is an example of this concept which has gained considerable attention of market economy. It has become a useful tool to promote ethics and moral obligations of the organisations towards their workers, local communities and global society **(Brønn and Vidaver-Cohen, 2009)**. Organisations that promote social wellbeing make its employees feel a sense of belonging and inclusive, more healthy, focus and effective at work.

#### **4.4.5.2.** *Job Satisfaction and Productivity*

Studies in the field of human behaviour believe that a dissatisfied employee will negatively affect productivity and a motivated worker would be dedicated to his work and thus improve productivity **(Paper, 2014)**. Job satisfaction is linked to motivation to work and it is the measure of an individual attitude or response in relation to his work. The response can be measured by the increase in productivity of that worker, devotion to his tasks, less absent from work or workers turnover rate **(Paper, 2014)**. It is, therefore; imperative to understand the factors which lead to jobs satisfaction in order to drive productivity and competitiveness. This is, however, a complex subject as job satisfaction could be subjective and varied based on situation and circumstances **(Paper, 2014)**. For example; while salaries are most important to job satisfaction to some people, it is not a motivating factor to others. According to **Kuvaas and Dysvik (2009)**, employee dedication to work and good organisational citizenship behaviour is driven by a high level of intrinsic motivation. Theories such as Locke's theory of value, for example, described job satisfaction as the extent to which a worker is satisfied with the outcome of the job itself. Further, the theory suggests that job satisfaction is a function of organisational factors such as reward system, pleasant working environment, and organisational structure, and personal factors such as the balance between personal interest and work, status, training and overall life satisfaction **(Paper, 2014)**. Herzberg two-factor theory of motivation described job satisfaction within actions beyond the factors that brings dissatisfaction.

#### **4.4.5.3.** *Herzberg Two-Factor Motivational Theory and the Social Aspects*

Prior to the declaration of the Brundtland report in 1987, the subject of social responsibility of employers to provide a workplace that is safe, conducive, and enables self-actualisation of employees has been discussed as anchored on the theory of motivation **(Maslow, 1970; Thibaut and Kelley, 1986; Dartey-Baah and Amoako, 2011)**. In this context, employees are considered as one of the most critical resources of an organisation, and their motivation and commitments are critical determinants of any business success **(Yusoff, Kian and Idris, 2013)**. Motivation influences human behaviour and organisational performance, explicitly; the level of workers commitment to work is driven by their level of motivation. In 1940–1950's, Abraham Maslow developed the five-stage Hierarchy of Needs Model to understand and explain human motivation, promote management training, and personal development (full description of the model is out of the scope of this study but can be found in **(Maslow, 1970)**). According to Maslow, "human beings are naturally trustworthy, self-protecting and self-governing, can grow and capable of love". Laziness, selfishness, indolence, cheating, and lack of commitment are not what human nature is thought to be **(Maslow, 1970)**. Maslow postulates that there are four types of needs called deficiency needs; these needs must be met before a person can become unselfish. Maslow stated that the first and most basic drives are physiological needs which include craves for food, water, oxygen, sex, sleep, and freedom of movement. This is followed by the need for safety such as personal protection, security, and religion, then comes the desire for love and belongingness, and then the quest for self-esteem which is the product of a person's competency or mastery of a task. According to **Janis (1998)**, lack of these needs create tensions within a person.

However, in 1959, Frederick Herzberg expounded on Maslow theory to establish a two-factor theory of motivation. Herzberg two-factor theory of motivation is most relevant to this study because it establishes the study of motivation in the workplace and provides the understanding of the mutual relationships between employer and employee, and alignments within the psychological contracts **(Chapman, 2008)**. Herzberg theory indicates that satisfaction and dissatisfaction at work do not arise from the same factors, and are not opposing in reaction to each other. That is; the factors that cause workers dissatisfaction are not the same and simply not the opposite of the factors that give rise to satisfaction. Putting it in a clear statement, **Ryan and Deci (2000)**, explained; supplying the low-level needs (hygiene or extrinsic factors), such that give rise to dissatisfaction does not mean there will be satisfaction but, "no dissatisfaction", and lack of high-level needs (motivational or intrinsic factors) such that give rise to satisfaction does not imply dissatisfaction but, "no satisfaction".

### *4.4.6. Alignment of Social Impacts Assessment (SIA) with Herzberg Two-Factor Theory*

The hygiene or extrinsic factors are considered to have high risks of negative impacts on the employees and the organisation **(Noell, 1976)**. This is because the absence of extrinsic factors gives rise to employees' dissatisfaction and eventual high employees' turnover rate or low productivity **(Yusoff, Kian and Idris, 2013)**. These factors are often called the "maintenance factors", and their existence is paramount to create a safe and favourable working condition. The presence of the factors is also responsible for the removal of unpleasant feelings or reactions that might give rise to the employees' dissatisfaction. Though their supply does not bring any sense of satisfaction for the employees **(Janis, 1998; Chapman, 2008)**, organisations are unable to stimulate any motivational strategy in the absence of these maintenance factors. In parallel with the SIA, the absence of negative social aspects (i.e., factors which absence impacts negatively on the employees' safety and well-being) gives rise to dissatisfaction, social instability, and lack of commitments from the employees. In the absence of the negative social impacts, an organisation is unable to stimulate any social initiative or sustainability strategy that could give rise to job satisfaction and productivity. Figure 4-6 depicts how these two phenomena are aligned in similarities. Organisations with motivational goals will initiate the supplies of intrinsic factors to increase employees' satisfaction and productivity. Similarly, organisations with social sustainability goals will increase the supplies of positive social aspects to drive social sustainability and increase productivity.

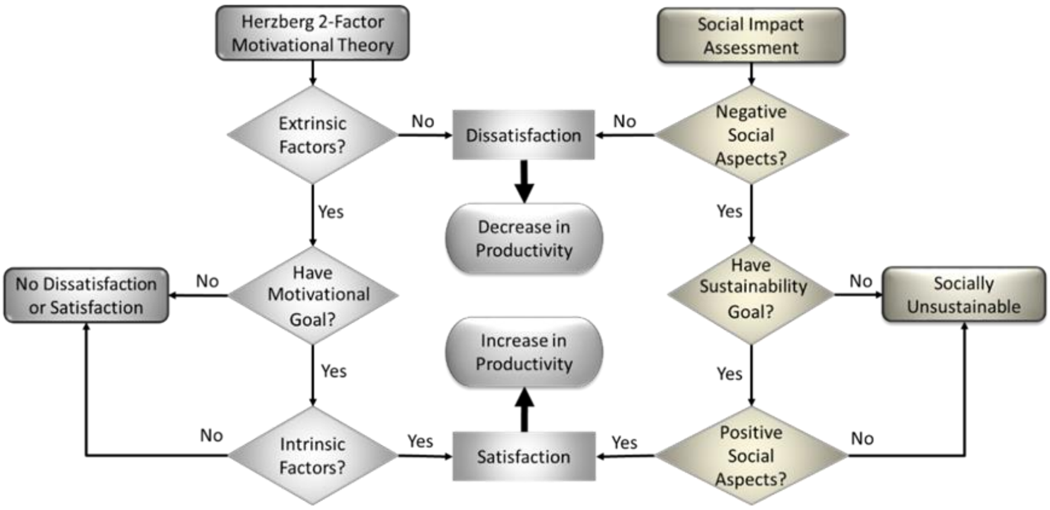


*Figure 4-6 Alignment of social impact assessment (SIA) with the theory of motivation.*

### *4.4.7. The Role of Legislation and Regulations in the Alignment Process*

In the social sustainability development parlance, regulations and legislation are enforced on businesses to comply with the supply of the factors which have high risks of negative social impacts such as health and safety, and child labour. The organisation that fails to comply with these regulated factors are considered socially unsustainable and are liable to be penalised, hence; organisations are mostly driven by the compliance obligations **(Brønn and Vidaver-Cohen, 2009)**, however, this helps in the removal of factors that may give rise to employees' dissatisfaction.

In Figure 4-7, the role of regulations and legislation is demonstrated in the diagram: There is direct enforcement of government regulations and statutory laws on negative social aspects, though these may vary by geographical locations and markets of interest. The organisations' compliance with these laws and regulations removes employees' dissatisfaction and provides the opportunity to initiate motivational or social sustainability strategies that can give rise to economic growth. Some positive social aspects such as "training and study at work" are also under regulations as denoted by the dotted iterative arrows in the diagram. In such cases, the regulations will help in smoothening the identified opportunities in the positive social aspects. One major difference between organisational social development and motivation theories is that while social development focuses on policies and procedures that promote employees development and well-being, the motivation theories focus on the tasks and approaches that induce stimuli in employees for growth and performance. However, the two approaches create a platform for the development of employees' satisfaction which has a correlation with organisational performance **(Herzberg, 1959; GRI -400 Series, 2016)**. As discussed in the previous sections, social economy principles are linked to the promotion of workers and customers' well-being in an economic market **(OCED, 2013; Magzan, 2014).** Thus, organisations that pay attention to the satisfaction or motivation of their employees through a variety of social initiatives will increase workers commitment to work, productivity, and the company profit level **(Brønn and Vidaver-Cohen, 2009)**. The American global workplace survey company (Great Place to Work) in collaboration with Fortune magazine published the top best 100 companies to work for in 2017 with Google on the top list for the 11th time **(Fortune, no date).**

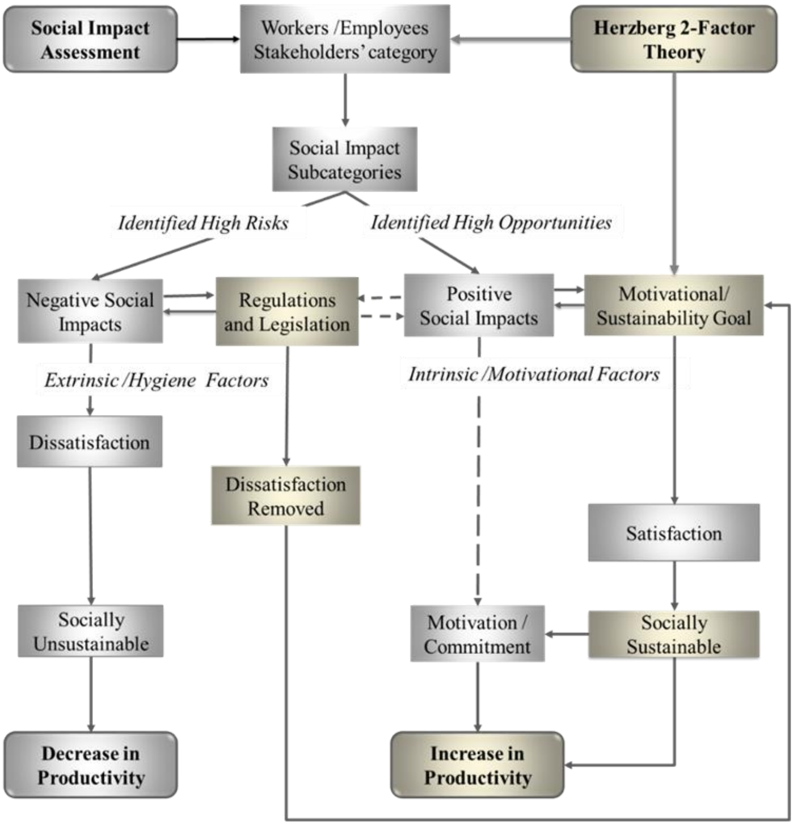


*Figure 4-7 The role of regulations and legislation in the alignment, and employees' motivation.*

#### **4.4.7.1.** *Social Initiatives and Economic Growth*

Social initiative in the business context is defined as any program, practice, or policy undertaken by a business firm to benefit society **(Brønn and Vidaver-Cohen, 2009).** Corporate philanthropy, onsite well-being amenities, corporate support for training and educating youths and adults in local communities, helping job seekers and welfare recipients get jobs across the nations, and providing charity aids to developing countries across the globe are examples of social initiatives relevant to various stakeholder categories **(Brønn and Vidaver-Cohen, 2009)**. Google is famous for social initiatives which include onsite amenities such as free gourmet food, gym, laundry, and haircut services. Wegmans Food Markets Inc., which is the second on the list of the "Top Best 100 Companies to Work For" provides onsite free beverages and snacks, birthday cake, health screening services, blood pressure machine, ATM/banking, discount fitness classes, ticket sales, and gym membership. RW Baird & Co Inc., the fourth on the list provides onsite free hair salon, dry cleaning, coffee shop, shower and locker rooms **(Fortune, no date).** Other social initiatives seen in these best in class businesses include onsite full service restaurant/catering, health screenings for breast cancer, glucose, cholesterol, and high blood pressure, smoking cessation programme, personal concierge services, subsidised weight watchers, weekly contests for tickets to concerts, plays, sporting events, and musicals **(Fortune, no date).** While these social initiatives are not enforced by any regulation or legislation and could be aligned with the motivational or intrinsic factors to drive productivity, businesses ought to be driven by ethical duty and moral obligation to give back to their society **(Brønn and Vidaver-Cohen, 2009)**. Training of employees and investment in human resources such as social benefits and social securities are other social aspects that are not fully enforced under regulations, organisations that are driven by ethics and moral obligations would invest in their employees and increase their morals and satisfaction level.

*The question, however, is how do we measure the level of a corporate commitment to social values, or the employees' productivity level as related to social sustainability?*

#### **4.4.7.2.** *Productivity Factor and Social Impact Coefficient (β)*

The productivity of a manufacturing process is a function of many inputs and how efficient the inputs are utilised in the production process. Resources such as technology, capital assets, and human labour are examples of key inputs to any manufacturing process. Productivity is the measure of the quantity of an output in relation to the inputs (Equation (1)); hence, the quality or efficiency of the inputs determines the level of productivity. For example, in theory, an employee could be seen to be very productive but in an actual sense, producing below capability or creating horrible outputs. Employee level of productivity, therefore, has a huge impact on the economic growth **(Esposito, 2015).** Productivity factors such as Partial Factor Productivity (PFP), Multi-Factor Productivity (MFP) and Total Factor Productivity (TFP) have been discussed and recognised by both researchers and practitioners as important tools for explaining and improving efficiency and productivity of manufacturing inputs, economic growth, and improvement of income and welfare **(The World Bank, 2000; Comin, 2008; Adak, 2009; D'Auria *et al.*, 2010)**. According to **Comin (2008)**, TFP is "the part of the production output that is not explained by the amount of inputs used during the production process". Hence, the efficiency and intensity of the utilisation of the inputs are major determinants of economic growth **(Comin, 2008; Adak, 2009; Esposito, 2015)**. Measuring human labour factor of productivity is one of the important requirements in driving improvement. The Social Impact Coefficient (β) represents the labour factor productivity for a socio-economic development. The use of Cobb-Douglas production function has helped in defining the coefficients for PFP, MFP and TFP in a linear equation **(The World Bank, 2000)**.

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}}, \qquad (1)$$

The Social Impact Coefficient (SIC), β, is that factor which determines the intensity of the utilisation of an employee. In an ideal situation, a fully utilised employee will work at 100% of his capability when all the necessary tools and skills are available. For example, suppose the Output (Y) of a process is produced using two factors of human labour: (1) Machine Setup and Teardown Time ($M_t$); and (2) Manual Operation Time ($N_t$).

Using Cobb-Douglas production function:

$$\text{Y} = \beta(\text{Mt}, \text{Nt})\,, \qquad (2)$$

Where Y is the output of the production, $M_t$ and $N_t$ are the inputs/capabilities of the human resources, and β is the Social Impact Coefficient. The coefficient β is the multiplier of employee's capability and determinant of the efficiency or degree of utilisation of the employee's capability. The factor β is a calculated weighting factor of the organisations' social impacts, and a function of an organisation aggregated social performances (Equation (3)).

Where α is the aggregated negative social impacts, and γ is the aggregated positive social impacts.

$$\beta = f(\alpha, \gamma)\,, \tag{3}$$

In reference to the employee productivity, the β has the highest value of "1" which implies 100% level of motivation and commitment state of an employee, and the lowest value of "0" implying the lowest state of an employee. The higher the value of β, the higher the employee's productivity, and organisations' economic growth: For example, if in an ideal situation (when β = 1), 200 working hours of an employee is required to produce £5000 worth of product, but the actual number of working time for the employee is 250 working hours. Then the employee productivity can be calculated as follows:

$$\text{When } \beta = 1\text{: Employee Productivity} = \frac{£5000}{200\text{ h}} = £25 \text{ per hour of work}$$

$$\text{Using the above information to calculate } \beta\text{: } \beta = \frac{200}{250} = 0.8$$

$$\text{When } \beta = 0.8\text{: Employee Productivity } = \beta\,(£25) = £20 \text{ per hour of work}$$

In this case, the ideal situation represents a benchmark for which employee productivity can be compared against, and to obtain the β. The closer the β to "1", the more the organisation becomes socially-sustainable. However, the employees' social aspects which negatively or positively influence workers' productivity need to be identified, assessed and managed in order to drive economic growth. Figure 4-8 is a description of the components and process for calculating the β of an organisation from social aspects. The process requires setting a base index based on the organisation best-ranked social performance of each social aspect or the use of social performance indexes of the Best-In-Class (BIC) industry within the understudying industrial sector. A scaled based approach can be used to calculate the weighting value or the use of multi-criteria decision analysis to capture the qualitative aspects of the social aspects **(Haapala, *et al*., 2011; Halog and Manik, 2011)**. For example, the safety of an organisation is measured by groups of indicators such as the number of months without accident, near-miss and recorded incidents or by following the procedures of Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR). The job creation measured by variables such as the employees' turnover and retention rates. This research proposed the use of weighted-scale based approach, and the Global Reporting Initiatives **(GRI -400 Series, 2016)** formulas to model social aspects data for the workers' stakeholder category.

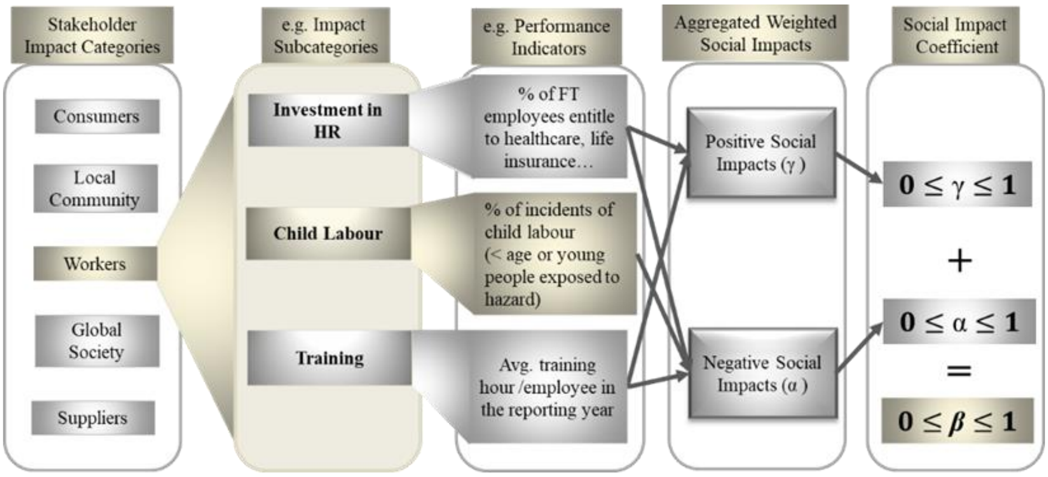


*Figure 4-8 Key components and a process for calculating the social impact coefficient (β).*

Among the vast social indicators, the decisions to choose and use certain social aspects (impact subcategories) are based on the business' sustainability goal and the context in which the assessing organisation operates **(Petti, Ugaya and Di Cesare, 2014; João Fontes, 2016)**. Hence the social aspects are not necessarily applicable in all context or company. According to **Hunkeler (2006)**, social indicators are huge ranging over 200 indicators which are related to regulated and unregulated factors. Hence, the selection of the social aspects to be analysed is based on the company's sustainability goal. However, compliance with the government regulatory and legislative controlled social aspects, takes priority in initiating any sustainability or motivational goal.

### *4.4.8. Procedure for Applying the Aligned Framework to Calculate Social Impact Coefficient*

The successful application of LCA framework strongly depends on the goal and scope phase of the four-components based framework **(Chang, Lee and Chen, 2014)**. However, adopting its principles for Life Cycle Sustainability Analysis (LCSA) broadens the requirements to the extent of defining the sustainability questions and structural representation of the systems or process to be analysed **(Stefanova *et al.*, 2014)**. According to **Stefanova *et al.* (2014)**, the requirements are to enable a clear link with the subsequent modelling phase and the representation of different stakeholders' view. However, this could be complex and daunting at the product development phase where there are not enough data and specific information to support the new product or process development **(Chang, Lee and Chen, 2014)**. Figure 4-9 shows the step-by-step process for SIC (β) calculation project. The starting point is the goal and scope definition which should be in line with the ISO 14040 LCA framework ***(ISO 14040:2006* - no date)** as well as the object of study, and the functional unit should be the same with which the economic and environmental impacts are being assessed.

The complexity of analytical models increases with data, and it is impossible to account for all the sustainability aspects of a single assessment. It is, therefore, necessary to scope which aspects of the three sustainability dimensions are to be included, not included and reference in the data collection stage. As discussed in the previous sections, social impact assessment is conducted at a specific site or stage of a product lifecycle. This is covered when defining the boundary or object of the study; in this case, a gate-to-gate approach is adopted to define the boundary of the object of study. The scope and identification of the social impact subcategories that need to be included in the analysis are also very important especially in streamlining the data collection process. Though the procedure for data collection is covered in chapter 5, it is important to note here that the data analyst needs to comply with privacy protection laws and respect freedom of information during the data collecting phase.

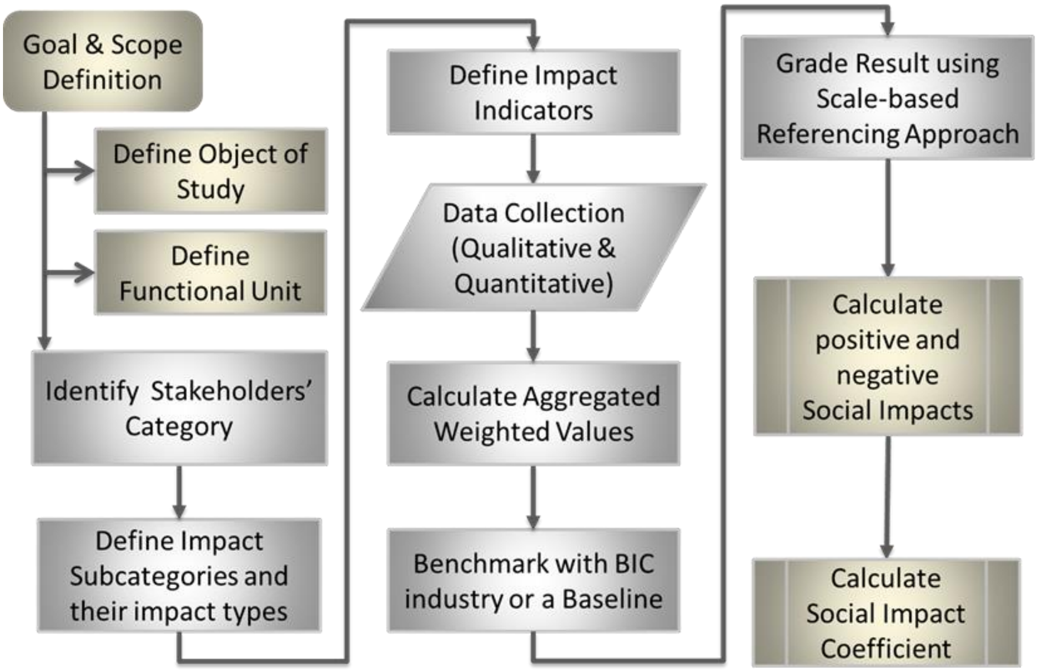


*Figure 4-9 SIC calculation process-Adapted from (UNEP, 2009; Benoît et al., 2010)*

The Functional Unit (FU) enables comparison of processes, products, and systems depending on the sustainability level at which the study is being conducted. According to **Chang, Lee and Chen (2014)**, FU is “a measure of performance of the functional outputs of the studied process, and it relates to specific inputs and outputs, the time range and the impact categories”.

### ***4.4.9.*** *Summary*

This chapter presented the groups of sustainability impact categories and sub-category indicators deployed in this research for the modelling and conducting the sustainability impact analysis at the process level. The chapter detailed the types of sustainability aspects or sub-categories appropriate for conducting the environmental impact analysis (EIA), economic or cost impact analysis (CIA), and social impact analysis (SIA) based on the context of the research. The discussion in the chapter enables the identification of sustainability impact analysis objectives and the setting of key performance indicators (KPI). The chapter also discussed the application of the principles of social economy and reciprocity, and the theories of motivation and social exchange to guide the alignment of the social aspects of sustainability with the Herzberg two-factor theory of motivation.

# CHAPTER 5

## 5. CONCEPTUAL FRAMEWORK DEVELOPMENT

### *5.1. Introduction*

The discussion and process in this chapter begin with the outcome of the systematic literature review in Chapter 2 This chapter presents a step-by-step approach to the development of the initial descriptive framework for the construction of a holistic simulation-based sustainability impact analysis. The chapter concentrates on an inductive-approach based on the grounded theory to explore the new phenomena **(Lacey and Luff, 2007; Rose, Spinks and Canhoto, 2015)**.

### *5.2. The Framework Development Background*

In chapter 2, the systematic review of approaches to sustainable manufacturing design identified two primary techniques:

1. Sustainable Product Development (SPD) and
2. Sustainability Performance Assessment (SPA) techniques.

These techniques are either segmented or integrated in their specific approaches as summarised in Table 2-2. Some of the authors discussed the Life Cycle Sustainability Analysis (LCSA) and suggested the approaches which integrate the three sustainability dimensions. For example; **Heijungs, Huppes and Guinée (2010)** proposed a three-component framework that combines the LCA principles and Sustainability Analysis (SA). According to the authors, SA is broader and covers more aspects than LCA, which includes economic and social dimensions. Further, the authors stated that this does not necessarily mean more Sustainability Indicators (SI) but an integrated result that addresses the three dimensions. **Sala, Farioli and Zamagni (2013a)** discussed the incorporation of Life Cycle Thinking (LCT) and Sustainability Science (SS) in assessment processes as a holistic approach to achieving sustainability. According to **Heijungs, Huppes and Guinée (2009),** LCT is often applied in product design to ensure all qualitative and quantitative life cycle aspects are covered. Other authors proposed the integration of LCA, LCC and S-LCA in a summative framework, but insist the system boundaries for the three assessments have to be consistent and identical **(Kloepffer, 2008; Klöpffer and Ciroth, 2011; Schau, Traverso and Finkbeiner, 2012; Traverso *et al.*, 2012).** Most articles on sustainable product development deploy techniques such as eco-design guidelines, checklists, Materials, Energy and Toxic (MET) matrix, with lifecycle assessment tools **(Ostlin, Sundin and Bjorkman, 2009; Abramovici and Lindner, 2011; Hatcher, Ijomah and Windmill, 2011; Bakker *et al.*, 2014)**. Simulation, energy modelling, monitoring, and evaluation has also been discussed by many authors to analyse sustainability impacts and improve process efficiency **(Cannata, Karnouskos and Taisch, 2009; Paju *et al.*, 2010; Seow, Rahimifard and Woolley, 2013; Abidi *et al.*, 2015; Bhanot, Rao and Deshmukh, 2015; Gamage and De Silva, 2015).** An approach such as Embodied Product Energy (EPE) attempted to address environmental impacts of the entire system of an organisation **(Rahimifard, Seow and Childs, 2010; Seow, Rahimifard and Woolley, 2013)**.

### ***5.2.1.*** *The Scope of the Descriptive Framework*

An evaluation of the approaches and techniques has revealed there is a lack of a holistic approach that integrates and considers the interdependencies of the three sustainability dimensions especially, in a dynamic manufacturing environment. Thus, suggests the need for a generic framework that not only combines and assesses the impacts of the three sustainability dimensions but also identifies and analyses their interdependencies in a dynamic environment. In this regard, the focus is on the impact analysis at a product lifecycle stage rather than the entire product lifecycle. The lifecycle stages are defined by the gate-to-gate boundaries, and the focus is on the operations' processes within the boundary rather than the whole system that made-up the organisation. The framework can be applied to different processes within a stage and any stage of a product lifecycle to drive effective sustainability decision-making.

## ***5.3. Methodology***

A two-stage process to framework development as in **Bacon and Fitzgerald (2001)** and **Holsapple and Joshi (2002)** was adopted in this research (Figure 5-1): The first stage deploys an inductive approach for the development of the initial descriptive framework of simulation-based impact analysis **(Crabbé *et al.*, 2013)**. This involves the synthesis and matching of theories, concepts, principles, approaches, and methodologies, and the evaluation of their strengths and weaknesses in order to explore the new phenomenon **(Fereday and Muir-**

**Cochrane, 2006; Crabbé *et al.*, 2013; Deborah Gabriel, 2013)**. The complete literature review of the approaches, methods and methodologies adopt in sustainable manufacturing is detailed in chapter 2.

The second stage is presented in Chapter 6. This involves a Delphi process used in a deductive approach to evaluate the theories, concepts and principles applied in the development of the new phenomenon **(Deborah Gabriel, 2013; Greener and Martelli, 2015)**. The Delphi study involves repeated iteration process of assessing the theoretical background of the framework concerning a set of selected criteria until a group of the panellist reaches a consensus.

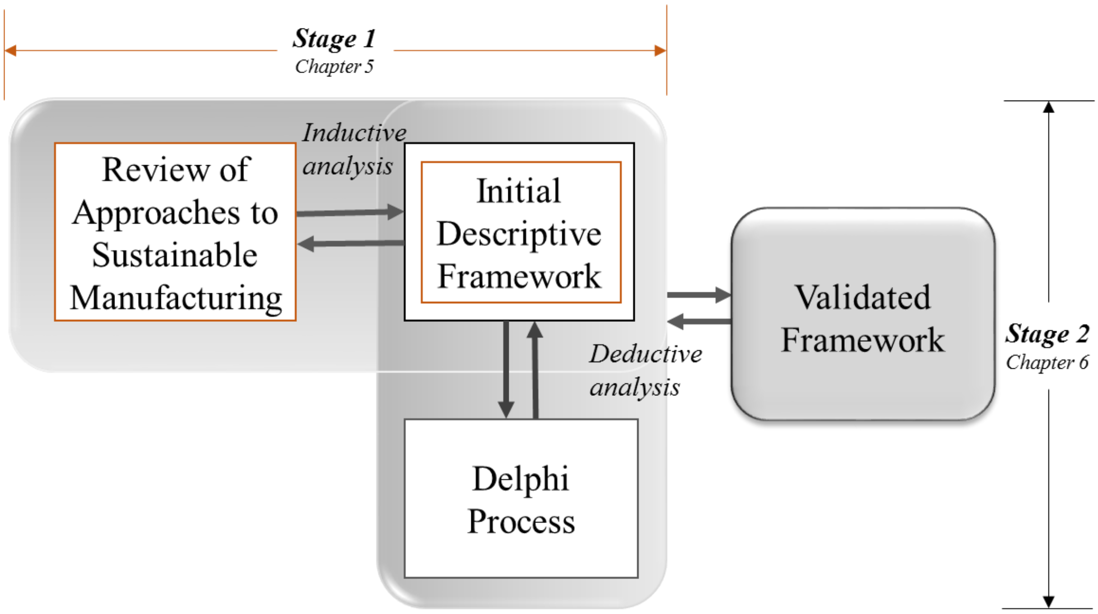


*Figure 5-1 A two-stage approach to framework development*

According to **Bacon and Fitzgerald (2001)** and **Holsapple and Joshi (2002)** methodologies for framework development and validation; the first phase of the two-stage approach is to outline the boundary conditions and evaluation criteria as depicted in Figure 5-2. This phase provides a guide in defining the scope of the study, identifying relevant literature for the study, and data collection process. The boundary conditions also provide a guide for assessing contributions which are within or outside the framework development boundary **(Bacon and Fitzgerald, 2001; Holsapple and Joshi, 2002)**. The second phase of the stages is to outline the criteria for selecting the panel of experts, experts' employment process, the size of the experts' group, the consensus, iterative rounds, mode of communication and the questionnaire for the Delphi study. This is presented in Chapter 5.

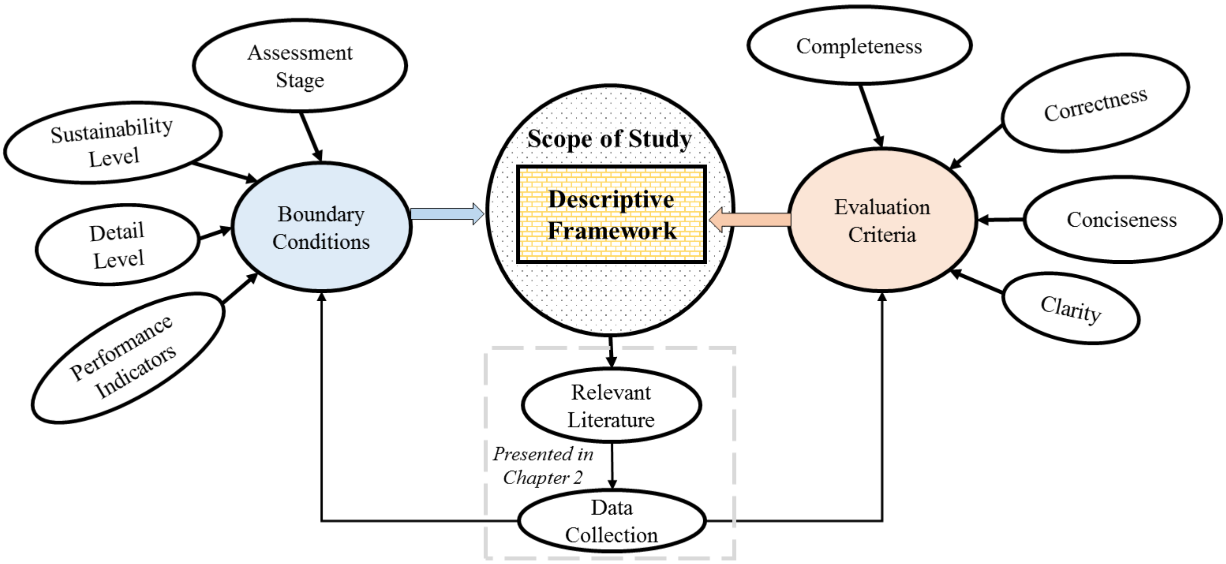


*Figure 5-2 Stage-1 first phase-outline of boundary conditions and evaluation criteria*

### ***5.3.1.*** *Stage 1- The Initial Descriptive Framework Development Process*

The initial descriptive framework developed accounts for the result of the process of matching sustainability approaches, concepts, principles, ideas, methodologies with their inter-relationships as found through the inductive analysis and synthesis of the literature surveyed **(Holsapple and Joshi, 2002)**. This includes the optimisation of the strengths of Sustainable Product Development (SPD) and Sustainability Performance Assessment (SPA) techniques in an analytical environment.

**The Boundary conditions**: The development of the framework identified the following four boundaries: Assessment Boundary, Sustainability Level Boundary, Performance Indicators' Boundary, and Detail Boundary.

1. The assessment boundary of the framework is confined to the manufacturing production stage of a product lifecycle.
2. The sustainability level boundary is delimited to the process level rather than the product or the entire system level of the manufacturing plant.
3. The performance indicators' boundary encompasses the performances of the three sustainability dimensions within the identified boundaries.

4. A top-down approach and two-level detail boundary were used. The first level detailed the fundamental concepts incorporated within the framework and the second level the sub-activities.

**Evaluation Criteria:** The guiding criteria for the development and evaluation of the simulation-based sustainability impact analysis framework are based on the key criteria used in the evaluation of theories **(Davidson, 2002; Holsapple and Joshi, 2002; Fawcett, 2005; Burton, 2011; Sanders and Nafziger, 2011)**. These are:

1. ***Completeness:*** The focus of the completeness criteria is on the context of the theory that guided the development of the framework, the justification for the need of the framework and the exact conceptual origins **(Fawcett, 2005)**. This criterion covers the broadest perspective of sustainability concepts, approaches, discipline and domain, the explicit origins of the descriptive framework and the philosophical claims from which the framework is derived.
2. ***Correctness:*** The Correctness criterion for the framework development and evaluation focuses on context and content of the proposed framework and demands the compatibility of all the elements of the philosophical claims, concepts and propositions. In addition, the clarity, logical and structural consistency of the framework development process is vital in evaluating the correctness of the proposed descriptive framework.
3. ***Conciseness or Parsimony***: According to **(Fawcett, 2005)** the correctness of the content of a "proposed framework should be structured in the most economical way possible without oversimplifying the phenomena of interest". The author emphasised that the fewer, the better, for the concepts and propositions required to explain the new phenomena explicitly. An over complex framework may require additional skills and expertise which may make it almost impracticable.
4. ***Clarity:*** Clarity criterion addresses the feasibility and pragmatic adequacy of the framework for sustainability practitioners. This criterion focuses on whether the effectiveness of the framework can be measured, and if unique skills and training are required before application of the framework in sustainability impact assessment practice **(Fawcett, 2005)**.

The four criteria formed the foundation and guided the development of the initial descriptive framework, and the basis for the Delphi study to assess if the framework satisfies its objective.

According to **Sanders and Nafziger (2011)**, evaluation gives information about the effectiveness and quality of a testing framework, document desire outcomes, identifies strengths and weaknesses, additional resources, and provides opportunities for improvement.

### *5.4. Stage – 1: The Development of Theoretical Framework for a Holistic Approach*

The literature review in chapter 2, presented the existing approaches that support the development of sustainable products ranging from methods that deploy checklists and guidelines for eco-design products to those that use quantitative and analytical tools to assess the sustainability performance of a product lifecycle. Each of the approaches though, presents a notable degree of weaknesses as discussed and highlighted in the previous sections and summarised in Table 5-1, combining the advantages will facilitate continuous effective decision-making **(Bucherta *et al.*, 2014)**. This section, therefore, presents the process of matching the advantages of sustainability approaches, concepts, principles, ideas, and methodologies with their inter-relationships in order to foster the development of a holistic, integrated framework.

*Table 5-1. Summary of techniques adopted in segmented approaches to sustainable manufacturing*

| Targets | Sustainable Product Development (SPD) (Mechanism) | Sustainability Performance Assessment (SPA) | Strengths | Weaknesses |
|---|---|---|---|---|
| Product | • Eco-design<br>• Circular Economy<br>• Design for Environment | • Guidelines<br>• Checklists<br>• MET Matrix<br>• Regulations & directives<br>• LCA<br>• LCC<br>• S-LCA | • Covers every stage of the product lifecycle<br>• Customer's use/ operations' focus<br>• Considered the three sustainability dimensions<br>• Eco-efficient and environmental friendly | • Partial / Sequential assessment of the three sustainability dimensions<br>• Not focus on process sustainability<br>• Environment centric |
| Process | • Lean-green<br>• Energy Modelling<br>• Optimisation<br>• Change<br>• EMS<br>• CSR | • Throughput<br>• Energy efficiency<br>• Resources' efficiency<br>• CO2 emission | • Covers the processing stage<br>• Clean production<br>• Energy efficient<br>• Green process<br>• Waste reduction<br>• Competitiveness | • Does not consider the dynamic environment<br>• Partial/ sequential assessment<br>• Lacks analysis of the interdependencies of |

| | | | | |
|---|---|---|---|---|
| | | • Water & other wastes<br>• Regulations & directives<br>• Employees' turnover | • Employees' motivation | the three sustainability dimensions<br>• Does not cover operations to disposal stage |

### *5.4.1. Optimisation of Sustainable Product Development Approach*

A company's environmental impact is a function of the impacts of its production activities and processes, and the impacts of the main products produced by the company **(Guziana, 2011)**. Thus, a single focus on designing or re-designing a product for environmental performance without considering the effects of the design on the production process may result in an ineffective decision for the design of a sustainable product. A product which design is optimised for environmental friendliness, but failed to consider the impact of the production process and other sustainability aspects of the manufacturing of the product is partially sustainable. Another partial approach exists when there are conflicts of priorities within the aspects of one of the sustainability dimensions.

**Nissen (1995)** discussed a method for unifying “extreme-product-versions” into an “ideal-eco-product version” in a situation where eco-priorities are in conflict. The “extreme-product-versions” represent the uttermost/ best possible product versions of different aspects such as energy efficiency, materials efficiency or recyclability of an eco-product. **Nissen (1995)** emphasised the use of "ideal-eco-product approach” as an input for an eco-design process to achieve an “Ideal-eco-product versions”, which is the unification or best compromise of “Extreme-product versions”. However, this method neither addressed the unification of the product and process design criteria, nor it considered the holistic approach to sustainable product design. Furthermore, sustainable manufacturing is a complex multi-criteria environment where the performance of one sustainability dimension is influenced by the other. Hence, a multi-objective optimisation that models a decision maker's preference based on the relative importance of sustainability objectives’ functions and desired goals becomes paramount in attaining optimal sustainable product **(Marler and Arora, 2004)**. This section, therefore, deploys a multi-objective optimisation process with the view of using an analytical or simulation model to analyse and achieve the best set of compromise of the three sustainability dimensions.

### *5.4.2. Partial-Sustainable-Product/Process*

In reference to the review and the summary presented in Table 4-1, In an eco-innovative environment; when the “target” for change is the product, various “mechanisms” are deployed based on the sustainability goal to design versions of eco-products while their environmental performances are assessed with eco-design tools such as checklists, guidelines, and LCA to achieve an “optimal-eco-product versions”. Also, when the “target” for change is the production process, “mechanisms” such as lean-green and energy modelling are deployed with process performance assessment tools such as throughput and resource efficiency to achieve an “optimal-clean-process models”. Hence through inductive analysis, it can be stated that:

> H1. The combination of SPD techniques and SPA tools in product design may lead to an “optimal-eco-product version.”
>
> H2. The Combination of SPD techniques and SPA tools in a process design may lead to an “optimal-clean-process model.”

However, a sustainable product, according to the findings of this research, is a product that is created using an eco-efficient manufacturing production process, conserves natural resources, is eco-efficient in the use phase, cost-efficient, safe and promotes social values and amenities for the workers and communities.

> H3. Hence the combination of “H1” and “H2” above in a process that is economically efficient and promotes social values may lead to “partial-sustainable-product /process versions” see Figure 5-4.

A "partial-sustainable-product/process version" represents an optimal product/process in respect to a specific sustainability objective such as “optimal for environmental protection” or “optimal for economic development” or “optimal for social development”. The trade-off or optimisation of the “partial-sustainable” versions to an attainable set and a feasible criterion space **(Marler and Arora, 2004)** for each of the dimensions is, therefore, paramount to an “optimal-sustainable-product/process” or “preferred sustainable product and process”.

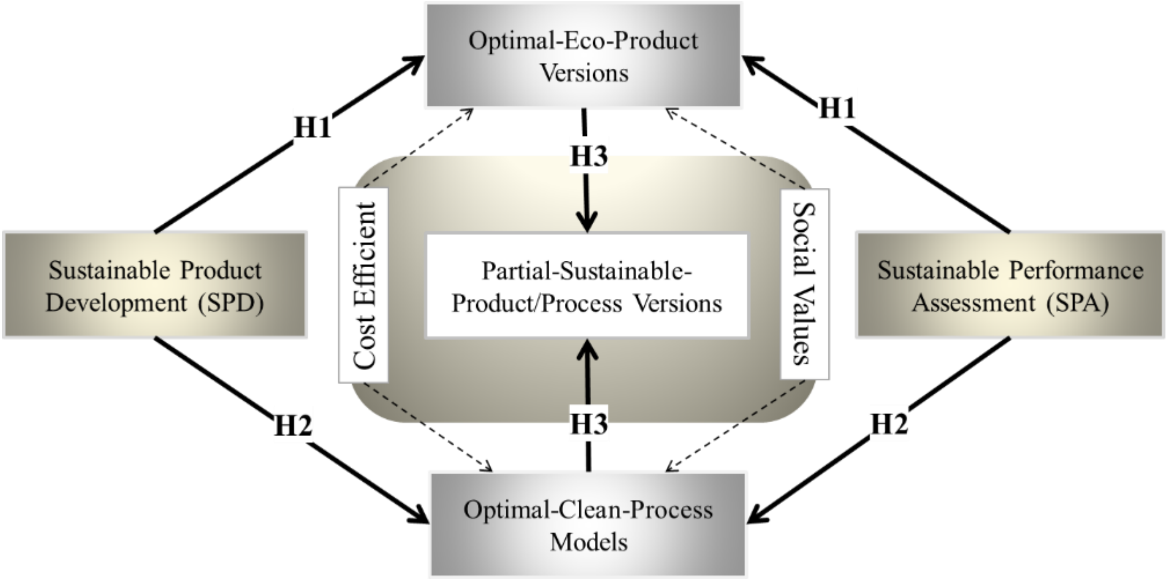


*Figure 5-3 Partial-sustainable-product/process versions derived from SPD and SPA approaches*

### *5.4.3. Optimisation of the Performances of the Three Sustainability Dimensions*

The successful outcome of the optimisation of the "partial-sustainable versions" of the three sustainability dimensions underpins the development of a holistic LCSA and determines the effectiveness of sustainability decision-making. The classical approach to unification of the "partial-sustainable versions" is demonstrated in the sequential integrated approaches as posited by many authors **(Kloepffer, 2008; Afgan, 2010; Swarr *et al.*, 2011; Schau, Traverso and Finkbeiner, 2012)**. A sequential approach assesses the performance of each sustainability dimensions in the design process and sum-up the outcome. According to **Valdivia *et al.* (2013)**, summing the performance outcome does not take into consideration the interconnections and interdependencies of one dimension on the other hence, it is ineffective and does not support effective decision-making **(Sala, Farioli and Zamagni, 2013b)**. The authors posited that the outcome of each of the assessment should not be add-up but the interdependencies of the three dimensions must be analysed and evaluated for effective sustainability decision. The application of the principles of life cycle thinking, strategic thinking, and sustainability analysis thus becomes necessary to support the philosophy of LCSA **(Sala, Farioli and Zamagni, 2013b; Valdivia *et al.*, 2013)**. This research, therefore, proposes the "unification" or optimisation of the "partial-sustainable" versions in an analytical environment as depicted in Figure 5-4.

Authors such as **Bhanot, Rao and Deshmukh (2015)** have used graph theory of network analysis to analyse the interdependencies of the three sustainability dimensions; some authors adopted mathematical modelling to analyse the three dimensions. Discrete-event simulation (DES) has also been used by various authors to analyse and optimise environmental and economic aspects in a dynamic production environment and support trade-off scenario for effective manufacturing decisions **(Kibira and McLean, 2008)**. DES has the potential for process optimisation, energy modelling in a dynamic manufacturing production process and supports effective decision-making in a what-if scenario **(Kibira and McLean, 2008; Gbededo, Liyanage and Oraifige, 2015)** hence, the adoption of a simulation-based "unification" or impact analysis of the "partial-sustainable-process models" to achieve a preferred/optimised sustainable product/process in a manufacturing production domain.

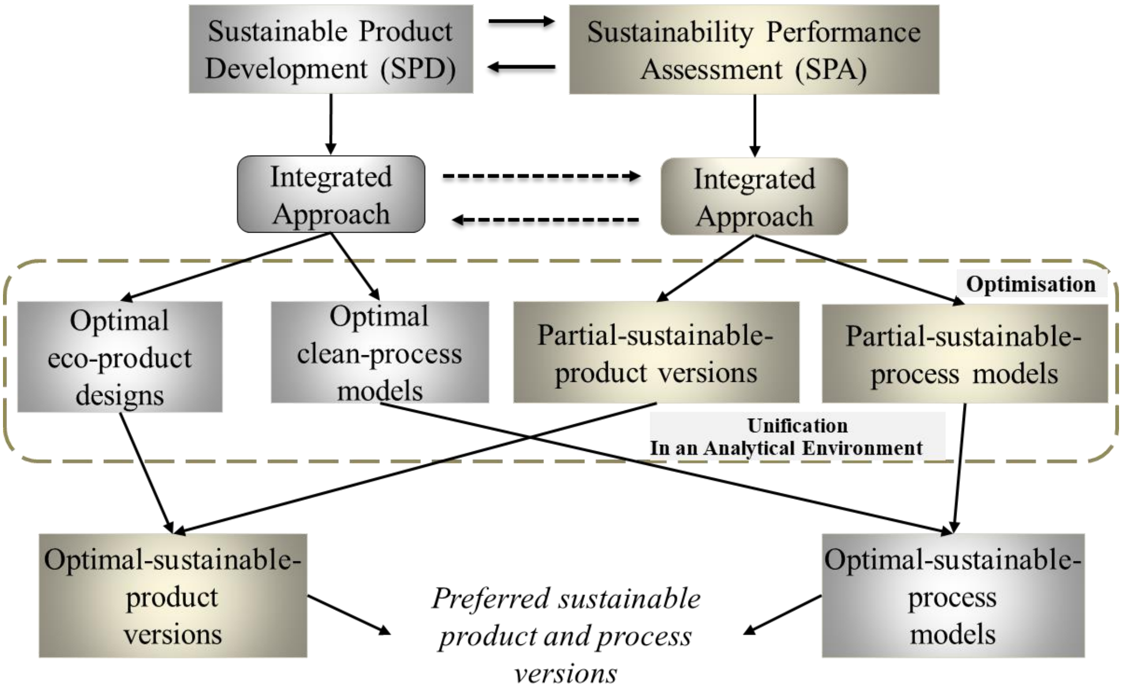


*Figure 5-4 Optimisation of partial-sustainable versions in an analytical environment*

### *5.4.4. Application of the Concepts of ISO 14040 LCA Framework*

The concepts and principles of ISO 14040 LCA framework **(ISO 14040:2006, no date)** is a standardised decision supporting tool for environmental life cycle assessment. In 2009, the UNEP/SETAC published the guidelines for S-LCA based on the same concepts and principles in order to compliment the eLCA **(UNEP Setac Life Cycle Initiative, 2009; João Fontes,**

**2016).** Similarly, the LCC is based on the same concepts and principles enabling a common view-point when conducting an assessment of the three sustainability dimensions. Though, due to the lack of existing inventory database the inventory analysis phase of the framework has not been fully applied to S-LCA and LCC. It is, however, essential to recognise the similarities in the principles and guidelines especially the use of a common goal and scope phase for the frameworks **(Chang, Lee and Chen, 2014; Petti, Ugaya and Di Cesare, 2014; João Fontes, 2016)**. According to **João Fontes (2016)**, since social impact assessment is consistent with the principles of environmental and economic assessments, it should be integrated into the entire sustainability assessment of a product. Figure 5-5 shows how the ISO 14040 LCA framework can be aligned for the assessment of the three sustainability dimensions.

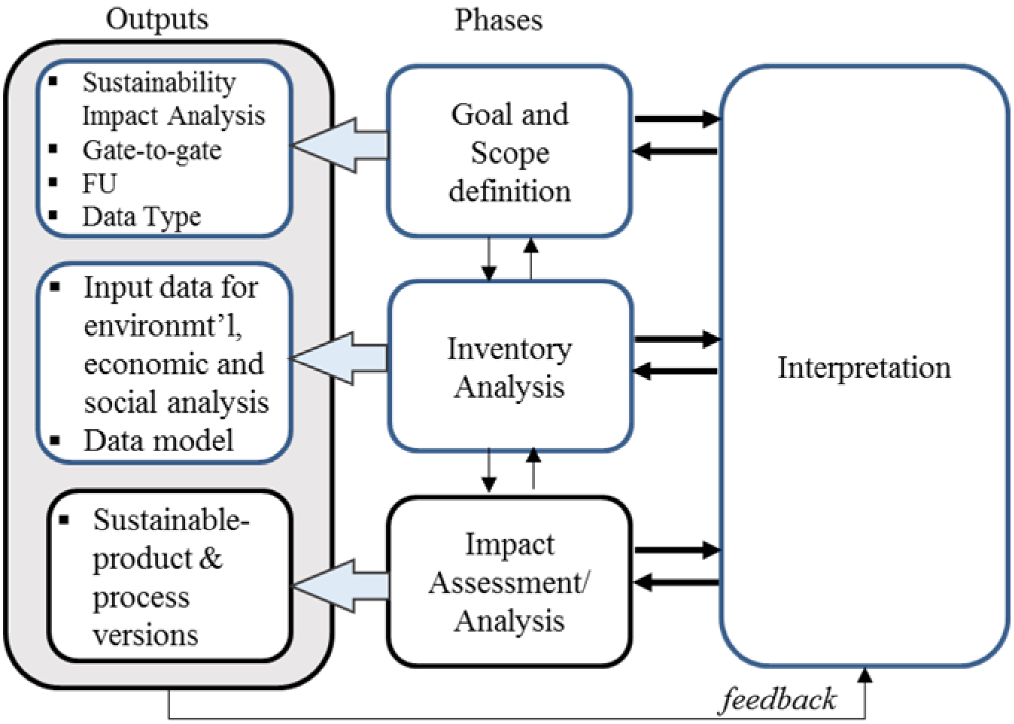


*Figure 5-5 ISO 14040 LCA framework with the output of the phases*

The application of the goal and scope phase of the ISO LCA framework include defining a common system boundary for the three sustainability dimensions, problem statement, input resources and the impacts being studied **(Chang, Lee and Chen, 2014).** This phase enables the identification and documentation of the four boundary conditions as discussed in section 5.3.1. In addition, **Chang, Lee and Chen (2014)** emphasised on stating a clear common Functional Unit (FU) at this phase to enable process, product and system comparison, The authors also warned against double counting of related impacts during an assessment. The FU represents "a measure of performance of the functional outputs such as relates to specific inputs and outputs, time range and the impact categories" **(Chang, Lee and Chen, 2014).**

### *5.4.5. Application of Generic Concept of Product Development Process*

The generic product development process consists of multiple steps from the conception of the product to the delivery of the manufactured product. **Chang, Lee and Chen (2014)** described these steps as the four distinct action phases which include concept design, part design, process design and then decision-making as depicted in Figure 5-6. The concept design phase represents an important stage of the product development process where the product designer engages and learns more about the customer needs, generate solutions, test and get feedback from the user. The Concept Design phase involves five iterative stages which include:

1. ***Empathising,*** learning and gathering information about the customer or technological requirements.
2. ***Defining*** a point of view or an actionable problem statement based on the customer's need. This may include materials, size, shape, and scope of sustainability performance requirements.
3. ***Ideating*** and brainstorming to generate and create possible solutions.
4. ***Prototyping*** by building or modelling representation of one or more ideas which are capable of providing solutions to the customer needs.
5. ***Testing*** the prototype to learn more from the customers.

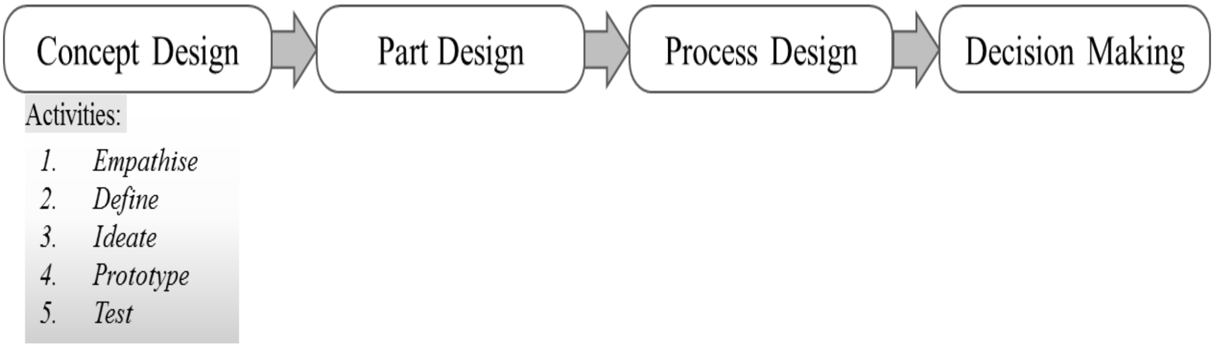


*Figure 5-6 Product development phases – (adapted from Chang, Lee and Chen (2014))*

The next phase following the **Concept Design** phase is the **Part Design** phase which receives the tested prototype of a new product as the input. At this phase, materials are selected and alternative packaging and materials based on the defined goal and objectives are identified. The **Process Design** phase involves selecting appropriate machining, routing and shop floor setup. The **Decision-making** phase provides the opportunity for the decision makers to assess the entire product life cycle in terms of sustainability performance **(Chang, Lee and Chen, 2014)**. The obvious challenges with this process are, however, the sequential approach of the phases to product development and lack of analytical stage to support effective decision-making. For example; the Process Design phase is disintegrated from the Concept Design phase making it ineffective by generating a product solution which does not simultaneously consider the sustainability performance of the production process.

### *5.4.6. Sustainability Approach to Product Development Process*

In this research, the two-stage approach to sustainable product development process is applied to the descriptive framework development Figure 5-7. The stage-1 involves the optimisation of the product design and process design phases through the application of lifecycle thinking and strategic thinking techniques for the generation of “optimal-eco-product-designs” and “optimal-clean-process-models”. This stage of sustainable product development deploys methodologies such as LCA, LCC and S-LCA to evaluate the lifecycle impact of the proposed product. In addition, methods such as eco checklists and guidelines, and MET are deployed to assess the impacts of alternative materials. This stage does not consider the interdependencies of the aspects of the three sustainability dimensions or the dynamism of the manufacturing environment, and inherently subjects to the issues with the LCA framework.

The application of eco-designed products and cleaner production to sustainable product development has been discussed in section 2.4. The approach deploys both life cycle thinking and strategic thinking at the product design and process design stages **(Halog and Manik, 2011; Parent, Cucuzzella and Revéret, 2013; Zamagni, Pesonen and Swarr, 2013)**. The concept of simultaneous approach to product development process involves the generation of possible solutions in an iterative process between the concept design phase and process design phase. In this approach, strategic thinking and life cycle thinking are simultaneously incorporated into the concept design and process design phases as shown in Figure 5-7. This generates optimal-eco-product-designs and optimal-clean-process-models which output data represents the input to the stage-2.

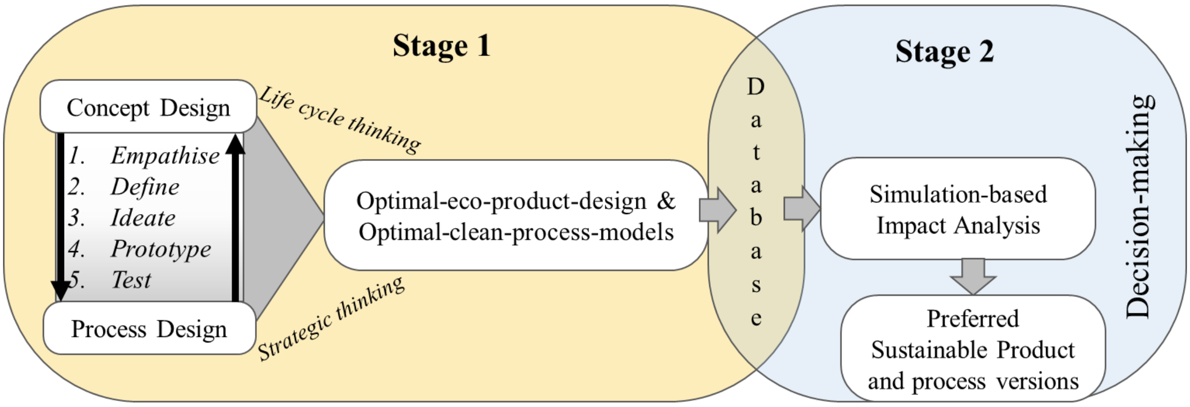


*Figure 5-7 Integration of sustainability approaches into the product development process*

The stage-2 involves further optimisation and analysis of the impacts of the optimised- eco-product and clean-process on the three sustainability dimensions. This stage is designed to support effective decision-making for the creation of the sustainable product through simulation-based analysis. The stage enabled the sustainability analysts to experiment and select optimal-sustainable-product and optimal-sustainable-process. This research concentrates on the development of a conceptual modelling framework that will guide the development of a simulation-based sustainability impact analysis for the stage-2.

### *5.4.7. Integration of Sustainable Manufacturing Approaches into Competitive Product Development Phases*

The combination and matching of the discussed concepts, principles, and approaches into a common theoretical framework represents a road-map to the development of an integrated conceptual modelling framework. A simplified conceptual diagram of the theoretical framework is presented in Figure 5-8. The theoretical framework describes the process of integration of holistic sustainability functions into the “traditional” competitive product and process design phases.

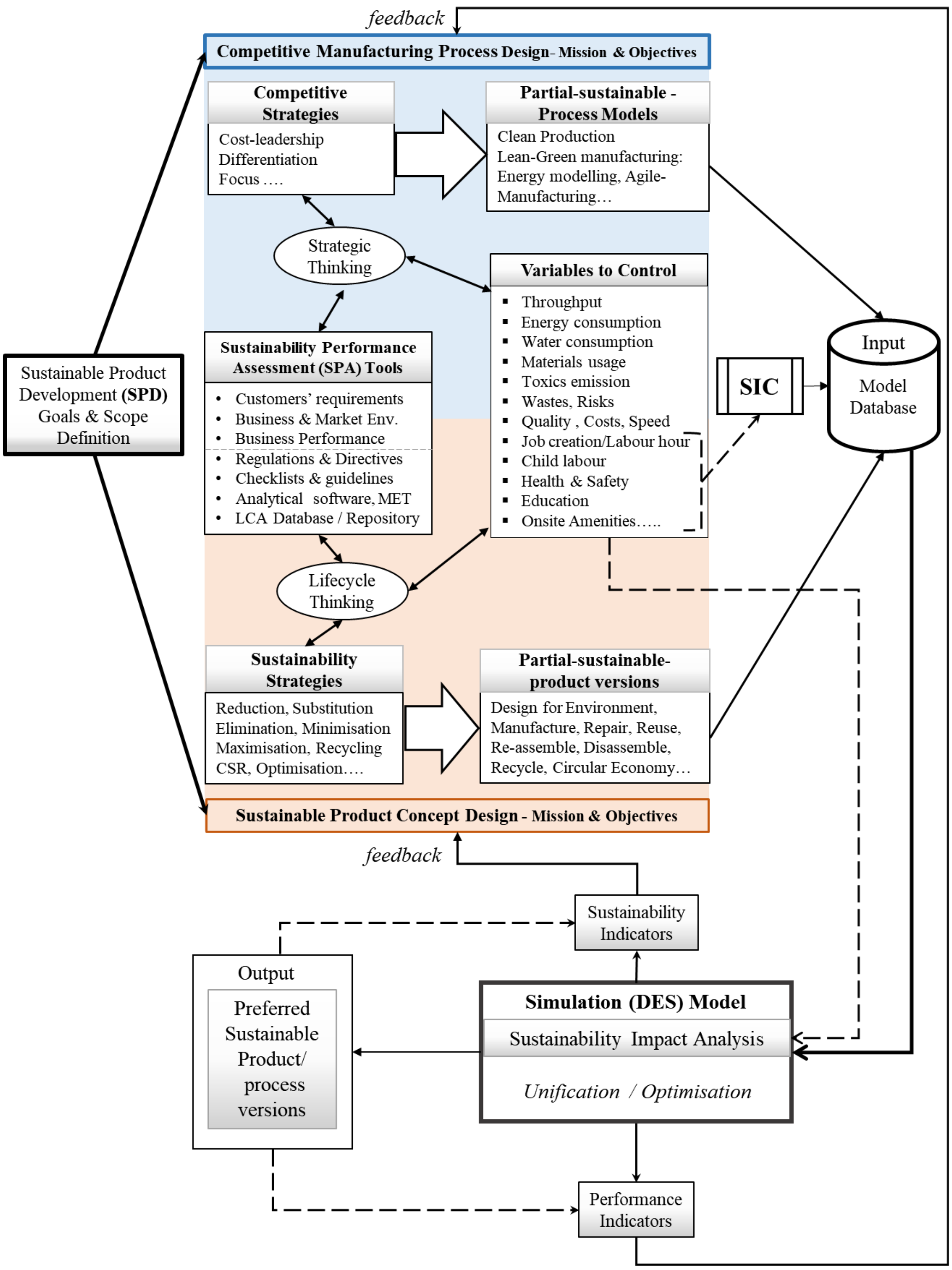


*Figure 5-8 Theoretical framework for holistic simulation-based sustainability impact analysis*

### **5.4.7.1.** *Description of the Theoretical Framework*

The first phase of the framework is the definition of the SPD goals and scope which highlights the aim, objectives, and boundaries for the proposed study **(ISO 14040:2006, no date)**. In the second phase, the problem statements are well crafted based on the sustainability missions and objectives to model the competitive manufacturing process and design the concept for the proposed sustainable product. In the “competitive manufacturing process design” axis, strategic thinking is initiated based on the missions and objectives of the competitive strategies. The double-end arrows represent the iterative processes with continuous analysis with the SPA tools and checking with the combined competitive and sustainability “control elements” to generate new innovative ideas. The lower axis of “sustainable product concept design”, deploys lifecycle thinking and sustainability strategies in an iterative process, with the SPA tools and continuous checking with the combined competitive and sustainability “control elements”. The upper axis of the “competitive manufacturing process design” and the lower axis of “sustainable product concept design” generate “partial-sustainable-process models” and “partial-sustainable-product versions” respectively. The parameters from the two axes which include process configuration, routing information, arrival rates, part-types, processing time, required resources, and CAD data are coded into the input database. The model database provides an input for the DES software and, in an iterative process, the DES experiments with the inputs optimises and generates sustainable product and process options for evaluation. The response which includes sustainability and competitive performance indicators from the DES provides feedback for the experimentation process and evaluation of resulting sustainability options. The process is repeated until a preferred option or sustainable solution is achieved based on the study objectives.

### ***5.4.8.*** *Application of Workers’ Productivity Factor as Social Inputs*

The proposed simulation-based sustainability impact analysis deployed the method of Productivity Factor (PF) and weighted Social Impact Coefficient (SIC) as the social inputs to the simulation parameters (Gbededo and Liyanage, 2018a). The SIC which is determined in a predefined process as shown in the Figure 5-8 is an aggregated weighted value of the social impacts indices (positive and negative) of an organisation, and it corresponds to the labour factor productivity for socio-economic development. Partial Factor Productivity (PFP) and Total Factor Productivity (TFP) are examples of PF used by practitioners to explain and improve efficiency and productivity of manufacturing inputs, economic growth, and improvement of income and welfare **(The World Bank, 2000; Comin, 2008; Adak, 2009).** The SIC represents an organisation’s social performance of defined stakeholder categories and can serve as a multiplier to sustainability analytical equation to determine the influence of social impacts on productivity. The social impact indices will also provide employers with insight into where there are high opportunities for improvement and high risks of threat. The successful calculation of SIC from the social indicators, therefore, enables integration of social aspects in a sustainability analytical equation, and the successful application of the holistic simulation-based sustainability impact analysis.

This holistic approach will enable simulation modelling and sustainability impacts analysis of a partial-sustainable-product version under various sustainable production process controls and resources. The production process will be evaluated and optimised based on holistic sustainability objectives for the best competitive, sustainable process, and product design.

Though some of the contemporary approaches suggest the importance of a holistic approach to sustainability, none presented a pragmatic approach that integrates the three sustainability dimensions in an analytical framework. Translating and converting qualitative social aspects into corresponding weighted values often eliminates social dimensions from the integrated sustainability analytical equations **(Kibira and McLean, 2008; Paju *et al.*, 2010).**

### *5.4.9. The application of Simulation Models in Sustainable Manufacturing*

The integration of Discrete Event Simulation (DES) with other sustainable manufacturing approaches into a common framework is not a new concept in sustainable product development **(Heilala *et al.*, 2008; Kibira and McLean, 2008; Fakhimi, Mustafee and Stergioulas, 2016)**. The approach enables the optimisation of production processes and support decision-making at the operational level **(Robinson, 2013)**. Hence, the combination of DES with SPD techniques and SPA tools has the potential to model a sustainable production process of a proposed or real scenario. The combination will enable investigation of different production and sustainability aspects at different time intervals, and support analysis and optimisation of wastes, energy consumption, circle time, and materials **(Kibira and McLean, 2008; Laroque *et al.*, 2012)**. In addition, modern DES software such as SIMIO software is armoured with functionalities that enable the application of 3D animation, and Lean techniques such as value stream mapping (VSM), just-in-time (JIT), bottleneck analysis, elimination of waste, and continuous flow. Thus, so far, contemporary simulation software can provide the analytical environment required for the optimisation and impact analysis of environmental and economic aspects. The integration of the social aspects into the analytical equation is provided in this research through the calculation of the Social Impact Coefficient (SIC) as discussed in Chapter 4. The approach enables the interdependence analysis of the aspects of the three sustainability dimensions as proposed in the LCSA framework of UNEP and SETAC life cycle initiative **(UNEP, 2011)**.

#### **5.4.9.1.** *Simulation Project Cycle and Conceptual Modelling*

Simulation studies involve a collection of key stages of iterative processes that cover the project lifecycle from the definition of the real world problem situation to the implementation of recommended solutions **(Robinson, 2004)**. Figure 5-8 depicts the outline of the key stages of a simulation project. Each of the stages is very important to the studies and represents key deliverables of the project **(Robinson, 2004)**.

The purpose of a simulation model can be defeated if the model becomes overly complex and the criteria for the project is not well defined and sustained. An over complex model may represent a detailed real-world system but could lack adequate data and consume much time to simulate and run. The real world problem situation stage helps to clearly define the problem statement which includes the goal, aim, and objectives of the simulation project, and in relation to that, the scope of the study are documented in a form that can drive the derivation of the conceptual model development **(Robinson, 2008b)**.

Conceptual modelling is a process of choosing what to be included and not to be included in a simulation model. In another word, it is a process of abstracting a model from the part of a real-world system **(Robinson, 2013).** According to **Robinson (2008a)**, conceptual modelling is *"a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions, and simplifications of the model"*. Hence, while the simulation model is a software-based model, a conceptual model is a non-software-based description of the real world system that forms the foundation for the development of computer codes **(Robinson, 2013)**.

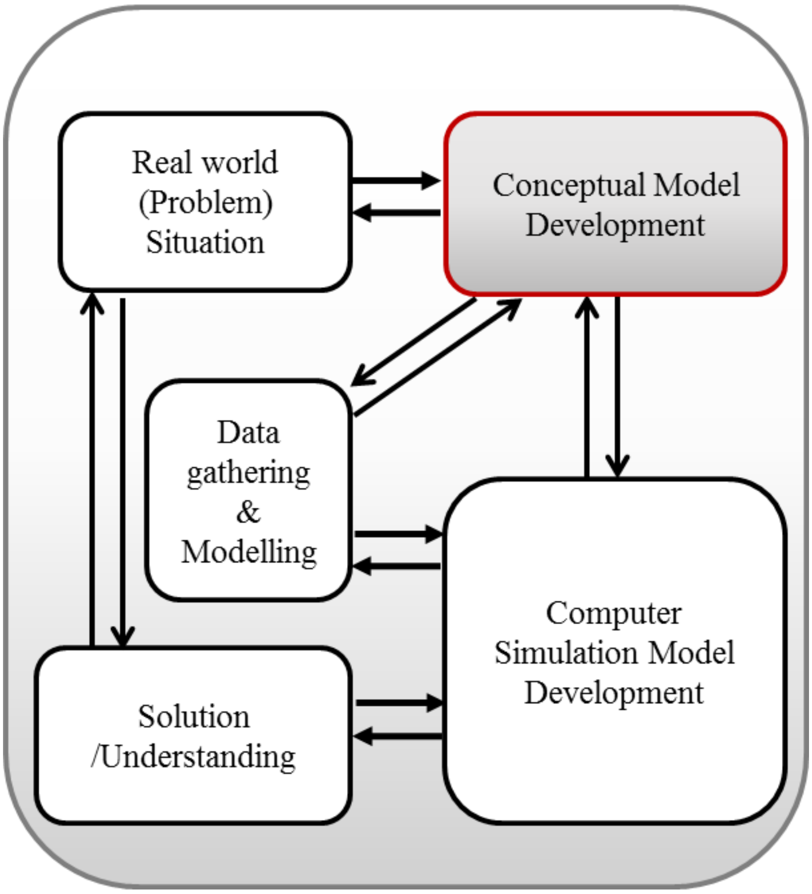


*Figure 5-9 Key stages and processes for simulation project (adapted from Robinson, 2007)*

### ***5.4.10.*** *Aligning the LCA Framework with the Key Stages of Simulation Project*

The key stages of simulation project have a common concept and principles with the ISO 14040 LCA framework. For example; the stages of each of the framework started with goal and scope definition followed by the iterative processes of similar stages. The matching of these two frameworks with other concepts and approaches will underpin the development of the proposed descriptive framework for modelling a holistic simulation-based sustainability impact analysis. The objective of matching and combining the two frameworks as shown in Figure 5-10 is to provide a common guideline for sustainability practitioners who want to build a holistic simulation model for the analysis of the three sustainability aspects.

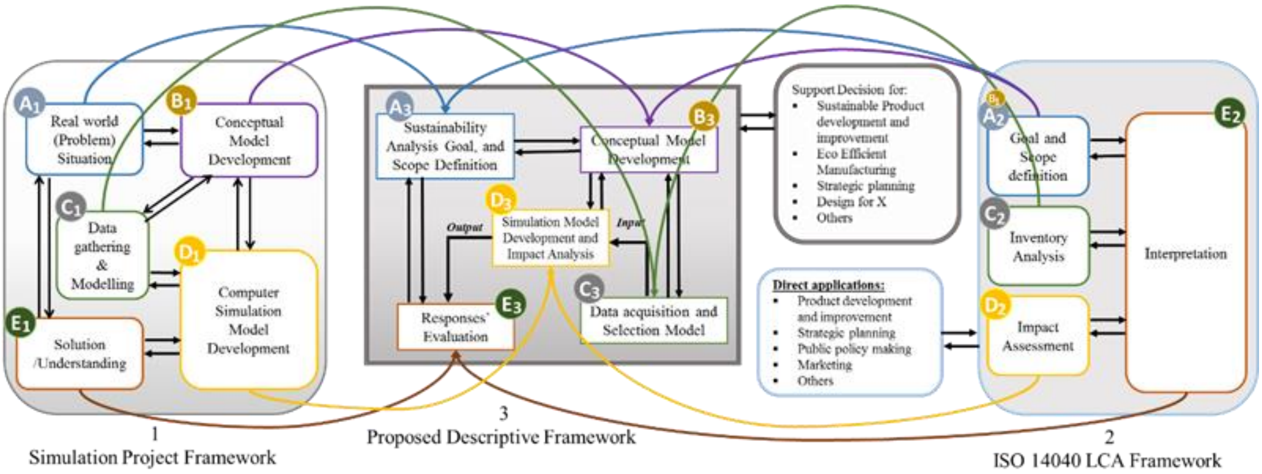


*Figure 5-10 Amalgamation of ISO LCA framework and simulation project modelling stages*

1 U 2 = 3 (U means "union of" e.g. A1 U A2 = A3)

## *5.5. Descriptive Framework for Modelling a Holistic Simulation-based Sustainability Impact Analysis*

The principles of Life Cycle Sustainability Analysis (LCSA) emphasised the evaluation of all environmental, economic, and social impacts of a product lifecycle. The evaluation process addresses the impacts of manufactured products throughout their life cycle, analyses the interdependencies of the three sustainability dimensions and clarifies the trade-off and supports effective decision-making. Research has shown that the existing methodologies, approaches, and tools for sustainable manufacturing have not been able to integrate the three dimensions effectively.

The descriptive simulation-based sustainability impact analysis framework is an amalgamation of sustainability tools and approaches, the principles of LCSA, and simulation conceptual modelling frameworks. The principles of LCSA drive a holistic approach to sustainability assessment and the analysis of the interdependencies of the aspects of three sustainability dimensions. While the simulation conceptual modelling framework guides the building of a computer simulation model and enables integration and optimisation of the aspects of the three sustainability dimensions in an analytical environment. In the proposed simulation-based framework, the four components of ISO 14040 LCA methodology are aligned with the key stages of building a simulation project as described by Robinson **(Robinson, 2008a, 2008b)**.

Studies have shown that contemporary computer simulation models consist of tools and elements that support the application of sustainability approaches such as energy modelling, value stream mapping, Lean-green, and competitive manufacturing.

The descriptive simulation-based framework as depicted in Figure 5-11 identifies major sustainable manufacturing activities such as the study goal, scope and objectives definition, development of a conceptual model, acquisition and selection of sustainability data, development of computer simulation model and impact analysis of sustainability variables to generate a new knowledge-base that supports decision making. The double arrows represent an iterative process between the activities while the single arrows represent a flow of information.

The proposed integrated simulation-based framework is both a decision supporting and management tool that provides the basis for modelling and analysing the sustainability impact of a manufacturing production process. It will provide a structured framework for sustainability analysts and practitioners to gather product data effectively, and simulation modellers to model and experiment with variables and alternative solutions in order to support sustainability decision-making.

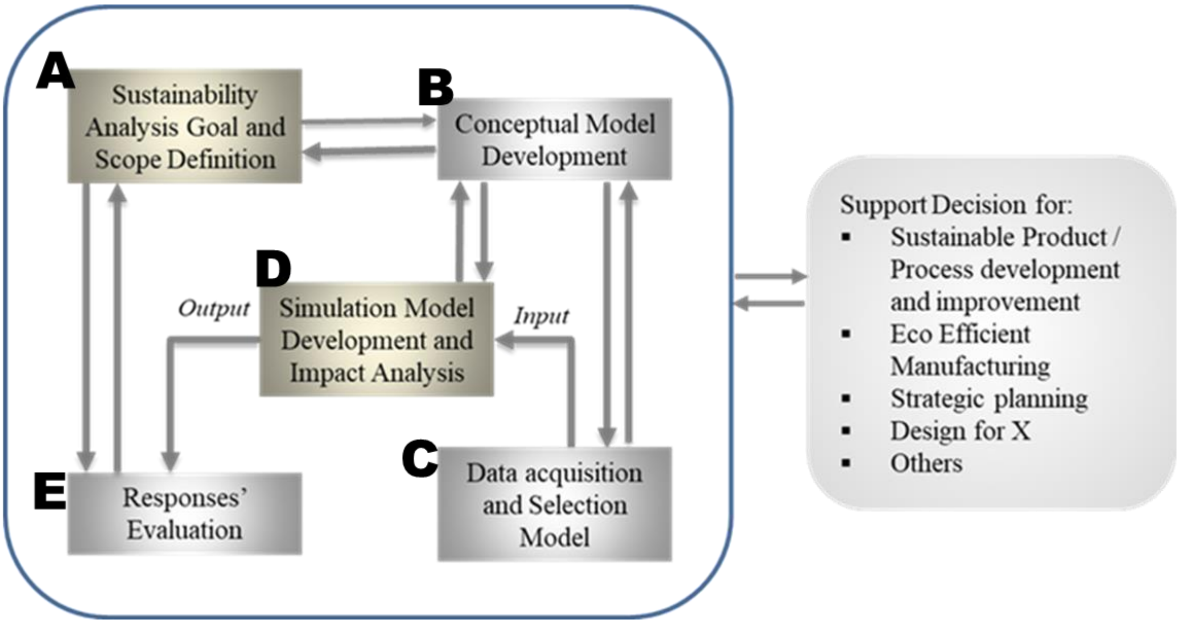


*Figure 5-11 The Descriptive Framework for Modelling Simulation-based Sustainability Impact Analysis*

## A. Sustainability Analysis Goal and Scope Definition

In this phase, the goal and objectives of performing the sustainability analysis are clearly stated. In relation to the goal, the depth and breadth of the study are documented in a form that can drive and guide the derivation of the conceptual model development **(ISO 14040:2006, no date; Robinson, 2008b)**, and serve as a reference all through the study. The activities in this phase include:

1. **The Problem situation or the general purpose and aims of conducting the study**: This is an important part of the study to define unambiguously the problem the sustainability analyst wants to address with the simulation-based framework. For example; an analyst may want to evaluate and analyse the sustainability impacts of different process options for fulfilling a particular function. This could include statements such as;

   > *"we are not sure of the best process configuration for the production of the new sustainable product in terms of energy usage, GHG emission, storage size, economic performance, and workers' social sustainability".*

2. **The intended application of the sustainability analysis results**: The analysis could be used for a comparative assertion, for example, to stress the preference or superiority of an alternative process over a competing process configuration that performs the same function. It could also be used for sustainable product/process development and improvement, strategic planning or decision-making for an alternative process.
3. **The system boundaries and contents**: Scope creeping is a critical issue and accounts for the major failure in projects including simulation projects. This part defines and establishes the breadth and width of the study such as the extent of the product lifecycle or stage to be studied, the sustainability dimensions that would be included, the stakeholders' category and impact subcategories, the indicators to be studied and the level of details required for the study.
4. **A clear description of the process, or system under study:** This help to set a clear border of the process, or the system being assessed. The components and the detailed activities of the components included in the process, or system are clearly stated and documented in this part of scope definition.
5. **The function of the process under study:** For example; to study the production process of a sustainable product development.

6. **The functional Unit** (e.g. 1000 hours of processing or 10,000 units of a product)
7. **Data requirements** (data categories, input and output data, data qualities..)
8. **Assumptions and limitations:** E.g. the selected product materials meet the regulatory and legislative guidance. (MET matrix, LCA, REACH, and Eco checklists and guidelines have been used to select the best environmentally friendly product and packaging materials during the product design phase). Also, the cost and social impacts of the product life cycle have been included in the initial cost estimation during the design phases.

## B. Conceptual Model Development

This phase involves the process of abstracting and representing a simplified model of a proposed or real-world situation (Figure 5-12). The aim is to capture a systematic flow of the proposed or real system in a simple visual representation which can be transformed into or represented in an executable simulation model of the study system. There are various methods and notations that are commonly used to represent conceptual models, such as Activity flow diagrams, Process flow diagrams, Event graphs, Petri nets, Unified Modelling Language (UML), Object models and Simulation activity diagrams. UML is most common amongst the modelling languages used in both software designs and modelling domains, and business process modelling, data modelling and system modelling.

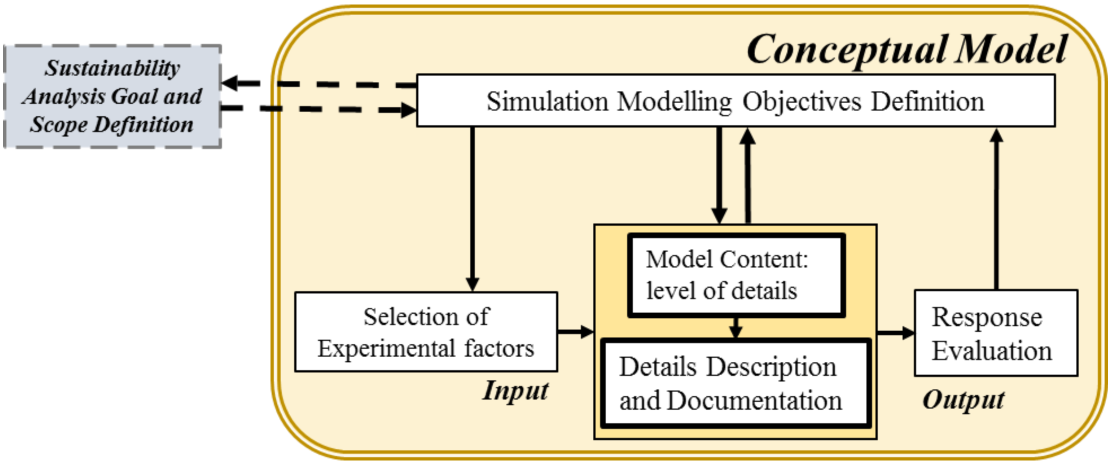


*Figure 5-12 Conceptual Model Development Process based on Robinson (2007)*

The activities in this phase are critical to the speed and effective design of a simulation model, and the quality of the result of the study. Major activities include:

1. **Clear definition of simulation modelling objectives:** The simulation objectives are obtained and streamlined from the problem situation as defined in the goal and scope phase. The defined objective is crucial to developing an appropriate model and it represents what the study hopes to achieve from the model. The process of defining the objective is iterative and evolves as the problem situations changes **(Robinson, 2008b)**. It is necessary to identify, evaluate and appropriately prioritise differing and conflicting objectives (such as cost, quality, environmental and social aspects, risk and ease of operations) of the key stakeholders and sign-off a consensus objective before commencing the modelling.

The modelling objective will usually be determined by various factors including the following:

a. The aim of conducting the sustainability analysis or what the result of the analysis is going to be used for.
b. The scope and the required detail anticipated for the process under study
c. The critical sustainability aspects to be analysed, the correlation with other aspects and those that can be approximated. For example; energy is an important environmental aspect in manufacturing and it has a direct correlation with the GHG emission.
d. The time for experimentation and optimisation required
e. The availability, sources, and integrity of input data.
f. The level of animation that would be required for validation and for presentation
g. The format of the expected result for example; graphical presentation, plots, video or documented report.

2. **Functional Specifications:** This aspect of the conceptual modelling describes in a document exactly what the study intended to cover and deliver, when, by whom, and how. The detail description and specification of each piece of equipment is detailed, this includes the setup time, processing time, teardown time and other aspects that may influence the performance of the model.
3. **Expected outputs:** The general objectives defined in the goal and scope phase is central to determining the expected output of the model. The outputs represent the sustainability indicators and help to determine if the model objectives have been achieved.

4. **Identification and selection of inputs:** The inputs are experimental factors of the model which are also determined from the general modelling objectives. The model objectives are achieved by changing the experimental factors (inputs) and evaluation of the responses in the output. The selected inputs determine the sources and acquisition of data for the model database. For example; inputs such as process specifications and materials' types can be obtained from the machine's parameters and eco-design data respectively.
5. **Model Content:** This involves the scope or level of details required for the model content, and any identified limitations and assumptions. A model that is too complex in terms of its contents will not only slow the speed of experimentation but may not provide an effective result and could create many unresolved bugs when simulated. Modelling objectives need to be specific and simple and probable sub-divided into two or model models for effective result. The depth of the details of the model is determined by the boundaries and objectives of the study.
6. **Details description and Documentation:** This part involves graphical representation and documentation of the model in a form that can be coded for computer simulation. Currently, there are many contemporary simulation software with inbuilt tools that assist in the static modelling.

### C. Data Acquisition and Selection Model

The core of conducting an effective integrated simulation-based sustainability impact analysis is credible input data which represents the objectives of the modelling. Figure 5-13 depicts various sources of quantitative and qualitative data that can be deployed to develop the input database for the realisation of the model objectives. The experimental factors or input data determine the sources for the data, that is; they are the limited subset of the model database. In an iterative process, this part of the framework helps to streamline the vast input data to specific inputs that account for the three sustainability dimensions as described in the goal, scope and model objectives.

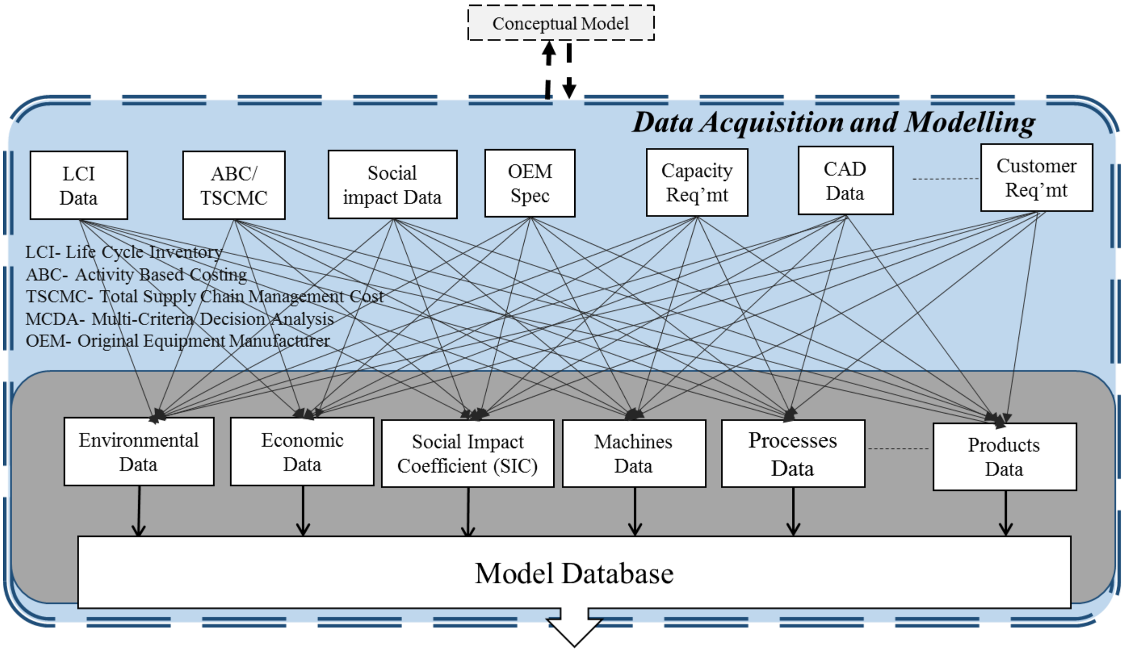


*Figure 5-13 Data acquisition and selection model based on goals, scope, and objectives*

The activities in this phase include:

1. **Input Data Inventory Analysis (Data Modelling):** This involves the identification and selection of the required input data and sources of the data. Data sources may include a standardised database, results of consultations or interviews with experts, data from Original Equipment Manufacturers (OEM), Computer Aided Design (CAD) data of eco-innovations, direct observation of the systems, and intelligent guesses. Table 5-2 shows an example of input data category collection.

*Table 5-2 Input data sources, data types and analysis requirements*

| Input Data Sources | Input Data Types | Input Data Analysis Requirements | | |
|---|---|---|---|---|
| | | Environmental aspects | Economic Aspects | Social Aspects |
| **Product Designers/ CAD** | Material types, design features and required processes. | Optimal energy and water consumption, and GHG emission for | Optimal cost of producing each of the design features | Optimal social impact coefficient |

| | | | | |
|---|---|---|---|---|
| | | each of the design features | | |
| **Production Engineer** | Details process layout for each design feature and material type, Part types, and routing, type of processing and processing rate | Optimal energy and water consumption, and minimal GHG emission for each of the design features | Optimal throughput for each of the design features | Optimal social impact coefficient |
| **Master Production Scheduler/ Capacity Requirement** | Job schedule for each batch of product, capacity requirement and the processing time, Activity Based Costing | Optimal energy and water consumption, and low GHG emission for each of the design features | Optimal cost for each batch process | The social impact coefficient |
| **Customer** | Critical to customer requirement:<br>Quality, Cost, Delivery time. | Optimal energy and water consumption, and minimum GHG emission for each product | Optimal cost and throughput | Optimal social impact coefficient |
| **OEM** | Machine specifications | Input voltage, current, energy factor | Processing speed | SIC: Manual or Automatic |
| **Stakeholders**<br>**(SI Data)** | Positive and negative social impact factors | Energy and water efficiency | Cost efficiency | Optimal social impact coefficient |

2. **Input Data Validation**: The activities in this part are to ensure the integrity of the input data through a comparison of data from different sources and cross-checking with the source

to ensure accuracy. Receiving sign-off from the information sources or experts before use is necessary in the validation process.

3. **Data Organisation (Model Database):** This involves the recording, storing, and organising the input data in a format that can easily be retrieved, and analytically updated when there is a change or alteration.

## D. Simulation Modelling Development and Impact Analysis

The simulation modeller codes or transforms the conceptual model into a dynamic representation of the real situation under study. The activities during the execution of the simulation are denoted in Figure 5-14 which include:

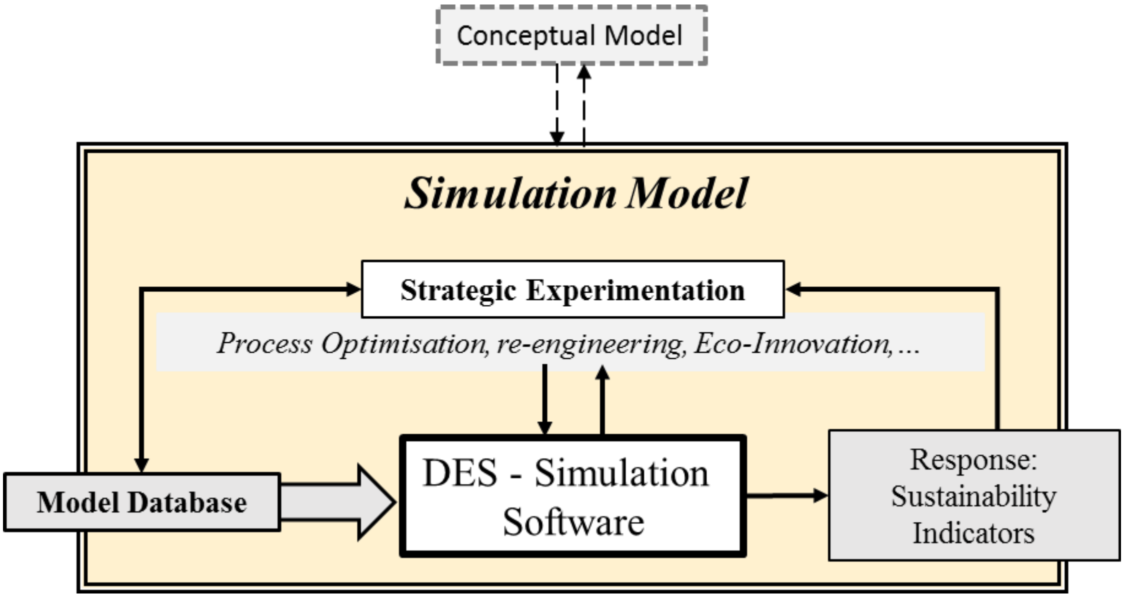


*Figure 5-14 Development computer simulation model and experimentation*

1. **Strategic Experimentation:** this is the experimental framework where the real world situation is experimented in an iterative process, observed, and optimised based on the behaviours of specific input and output **(Robinson, 2008a).** The process provides the opportunity for sustainability innovations, system re-engineering, and process optimisation that fosters sustainable manufacturing development.

2. **Model Database:** This provides input to the simulation software (in this case, we are considering a Discrete Event Simulation (DES) domain), and in an iterative process the DES experiments with the inputs to generate sustainable options for evaluation.
3. **Response or sustainability indicators:** The output from the DES provides feedback for the experimentation process and evaluation of sustainability options. The process is repeated until a preferred option or sustainable solution is achieved based on the study objectives.

## E. Simulation Response Evaluation

The Simulation Response evaluation phase enables the analysis of the output of the simulation experiments and examines if the simulation objectives are met (Figure 5-15). The response evaluation is based on the following two factors:

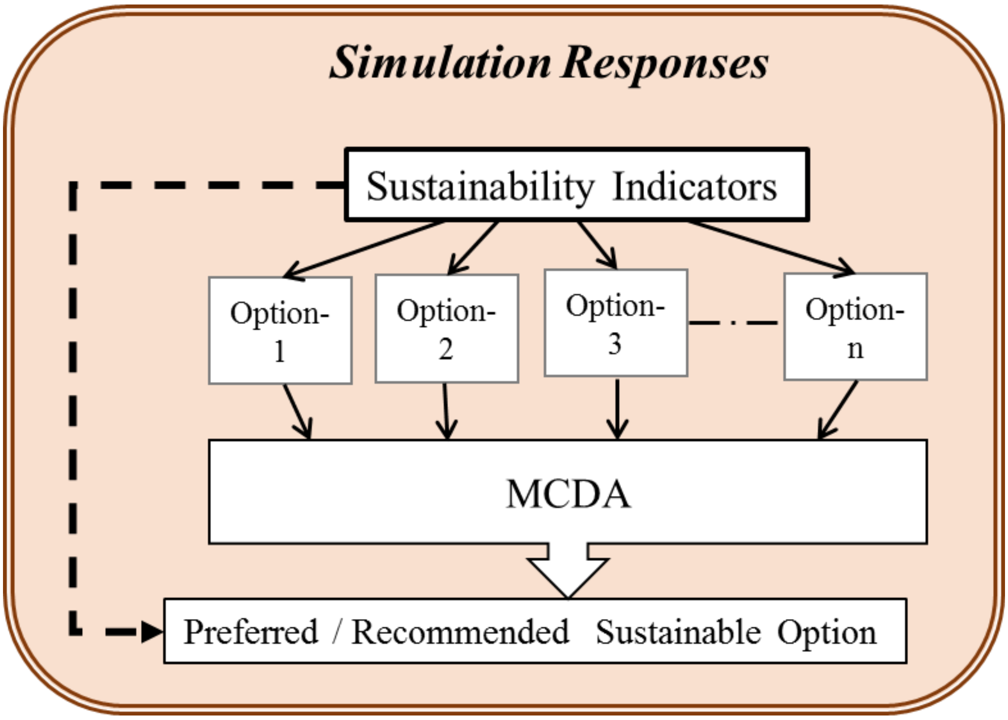


*Figure 5-15 Response evaluation and interpretation model*

1. **Output factors that determine the model objectives are being achieved**. For example; from the defined objectives above, we might be looking at energy consumption, GHG emission, workers' satisfaction, and throughput.
2. **Output factors that determine the reason why the model objectives are not met**. For example; the percentage of resource utilisations, waste generation, blockages, bottleneck, shortages, idle/broken machines, and workers' motivation. These factors are the essence of "Clean Production" and "Lean-green Manufacturing".

The sustainability indicators are the combinations of the two factors observed during the simulation experiments. Where a preferred sustainable option is not directly obtained, a Multi-Criteria Decision Analysis (MCDA) can be deployed for selected options of interest.

### ***5.6.*** *Summary and Conclusion*

This chapter presented the stage 1 of the two-stage methodical and detailed approach to the development of an integrated simulation-based impact analysis model for sustainable manufacturing design and management (stage 2 is presented in chapter 6). The chapter concentrates on an inductive-approach based on the grounded theory within a defined boundary and evaluation criteria. The process involves the synthesis and matching of theories, concepts, principles, approaches, and methodologies, and the evaluation of their strengths and weaknesses in order to explore the new phenomenon **(Fereday and Muir-Cochrane, 2006; Crabbé *et al.*, 2013; Deborah Gabriel, 2013)**. The focus of the framework development is to enable conceptual modelling of an integrated simulation-based sustainability impact analysis that supports the decisions for the manufacture of a sustainable product.

The contents and composition of each of the five components of the framework were described in section 5.5 but, can further be expounded into greater details when the goal and scope of a study are clearly identified and defined. The "Conceptual Modelling Development" phase is the key to building an effective simulation model that meets the study objectives and integrates the economic, environmental and social aspects of the process. "Data Acquisition Selection Model" is central to data inventory analysis and modelling for the three sustainability dimensions. A sustainability analyst with a broader knowledge in the fields of the three sustainability dimensions and the domain experts need to work with the modeller in defining and building both the input database and experimental factors.

# CHAPTER 6

## 6. DELPHI STUDY VALIDATION PROCESS AND RESULT

### *6.1. Introduction*

In this chapter, the second stage of the two-stage process for framework development (section 5.3) is presented as a Delphi study. The initial descriptive framework described in chapter 5, was developed in the first stage through the synthesis of systematic literature review and an inductive analysis of the existing approaches, methods, and framework for sustainable manufacturing. In this second stage, the initial framework is evolved through a Delphi study process that involved a panel of 24 experts and international researchers and practitioners in the field of sustainable manufacturing and related fields. A consensus was reached based on the four testing criteria and two rounds of study.

The next sections described the Delphi methodology and processes for the development and validation of the framework.

### *6.2. Introduction: Understanding the Classical Delphi Technique*

The term Delphi is synonymous with consulting for good judgment on matters; it has its origin with the Greeks myths and practices of consulting oracles to predict the future. This, however, has evolved over time to the classical methods for forecasting especially in the application areas where scientific laws have not been established or the influence of dominant personalities are likely on the outcome of results **(Keeney, McKenna and Hasson, 2011).** The classical Delphi method uses the anonymity of the participants and depends on individual statistical prediction rather than a face-to-face group prediction **(Chang *et al.*, 2010; Keeney, McKenna and Hasson, 2011)**. The first of this kind of technique was its application in the 1950s by RAND Corporation in predicting the possibilities and counter actions for enemy attack during the beginning of the cold war **(Hardy *et al.*, 2004; Keeney, McKenna and Hasson, 2011).** Delphi techniques are based on the premise that the opinions of a group of experts are more valid than that of an individual expert. The technique has now become an effective and broadening predicting tool commonly used across a wide range of field of studies including businesses, technologies, medical research, health, and nursing practices **(Bacon and Fitzgerald, 2001; Holsapple and Joshi, 2002; Chang *et al.*, 2010; Keeney, McKenna and Hasson, 2011).**

The classical Delphi deploys multi-staged survey techniques to achieve the most reliable consensus of the opinion of a group of experts on an issue. It involves a structured process through which information is collected and aggregated from the group of informed experts on specific issues **(Barrett, 1981; Hardy *et al.*, 2004)**. The group of experts constitutes a panel for which questions on the issues are posted, response collected, aggregated and fed back to the individual experts with the expectations for further considerations and judgments. The technique is an iteration process that is repeated until a level of consensus is reached amongst the group of the selected experts. According to **Powell (2003)** and **Keeney, McKenna and Hasson (2011)**, it involves a series of "intensive questionnaire interspersed with controlled feedback". Delphi techniques can be used to set priority, such as; which of the projects should we fund in the short, medium or long term? It can also be used to gain experts' opinion on specific issues **(Chang *et al.*, 2010)**. For example; **Bacon and Fitzgerald (2001)** used Delphi method to gain consensus of experts in the development of an information technology framework, **Holsapple and Joshi (2002)** deployed Delphi study for the development of Knowledge Manipulation framework, and **Hardy *et al.* (2004)** applied the Delphi technique in accessing experts' opinion on a bicultural clinical criteria. Either of these involves an iterative process to obtain agreement from a group of experts in the related field. Consensus level is always pre-determined in percentage, for example; it can be set to 75%, and once the group of experts has come to an agreement that reaches this percentage on the position of a statement, consensus is said to be reached (see **Hardy *et al.* (2004)** for limitations in variations of pre-determined consensus).

Generally, a Delphi process involves two or more iterative rounds of questionnaires administrated through post or email to a selected group of experts **(Chang *et al.*, 2010; Keeney, McKenna and Hasson, 2011)**. The first questionnaire is often designed in an open-ended manner to facilitate idea generation to elicit the opinion of the experts on the issues and once analysed by the researcher; it serves as a springboard for the rest of the process. New questionnaire is developed from the analyses of the data of the preceding round and posted to each panellist with the responses from other participants for review and reconsideration of their initial responses and send back to the researcher once satisfied. This is repeated for each round until a consensus is reached. According to **Keeney, McKenna and Hasson (2011),** this could be repeated until a diminishing return point is reached.

### ***6.2.1.*** *The make-up of Delphi Panellist*

The Delphi expert panel is makeup of a group of "informed individual" or specialists in a specific field or individual with advanced knowledge related to the topic under consideration with the aim of seeking their opinion or judgement on the specific issue **(Powell, 2003; Chang *et al.*, 2010; Keeney, McKenna and Hasson, 2011)**. In contrary to other survey methods that select participants randomly from a large population, the Delphi technique employs experts in an area related to the specific topic of interest to form a group of the panel. According to ***Chang et al. (2010)***, there is no specific requirement for the size of the group, however, the purpose, design method, data collection tool, costs and time frame determines the size and heterogeneity of the panel **(Hardy *et al.*, 2004; Keeney, McKenna and Hasson, 2011)**. Heterogeneity ensures reliable result through diversity and a wider spectrum of opinion. For example; experts selected from a different background such as industry and academia in the field of sustainable manufacturing ensures diversity of opinion and credible result of the process **Chang *et al.* (2010)**. Defining who an expert is could also create issues, thus often inclusion criteria are employed to create a clear boundary for experts' inclusion. The inclusion criteria include qualification of expert, number of publication in the area of expertise, years of practising experience in the related topic, and geographical location. Also, the selected experts must be interested in the examining topic and are willing to participate throughout the study process **(Chang *et al.*, 2010).** Though there may be the possibility of some participants to lose interest in the study and drop out after the first or second stage, it is important to guide against this at the beginning of the study.

## ***6.3.*** *Methodology: Stage 2 of the two-stages approach - Delphi Process for Framework Validation*

The Delphi technique was adopted in stage 2 (Figure 6-1) to seek the opinion of researchers and practitioners in the field of sustainable manufacturing for the review of the descriptive framework based on the defined evaluation criteria at the first phase in stage 1. The approach provided the opportunity to gather experts' perspectives and to revise the descriptive framework.

Following the first phase in stage 1, that is; the outline of the boundary conditions and evaluation criteria as depicted in Figure 5-2 of chapter 5, the second phase is to outline the criteria for selecting the panel of experts. This includes experts' employment process, the size of the experts' group, the consensus of opinion, iterative rounds, questionnaire development, and mode of communication for the Delphi study.

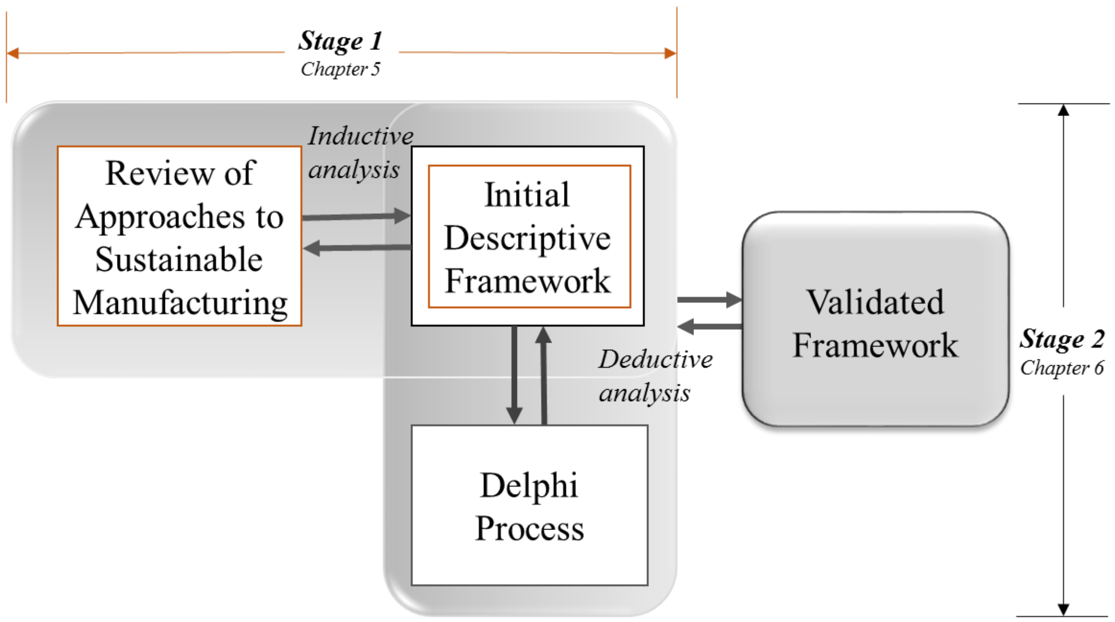


*Figure 6-1 Two-stage approach to framework development, adapted from Holsapple and Joshi (2002)*

### *6.3.1. Criteria for Selecting Participants*

A heterogeneous purposive sampling as used by **Holsapple and Joshi (2002)** to recruit members of the panel of the Delphi experts was adopted to ensure diversity in the panel of experts. At the initial stage, 72 leading experts in the field of sustainable development were identified and selected across the international borders. These include those who have substantially contributed to sustainable manufacturing through academic literature and conferences or have more than five years of practical experience in sustainable manufacturing or similar fields. Since Delphi process could take a long time which could increase attrition due to losses in the motivation of the participants, it is important to gain the interest and consents of the participants to commit to the study before the start of the process **(Hardy *et al.*, 2004).** Hence, the first set of personalised e-mails was sent out to each of the potential candidates to invite, and introduce the objectives of the researcher, the Delphi procedure, and the framework. It is important to note that Delphi study requires the time of the participants to critically study and evaluate the "study". It is also a new concept to many researchers and practitioners, hence, clear introduction and explicit description of the process was submitted to the potential participants.

Out of the 72 candidates invited, 24 (33.3%) agreed to study the descriptive framework and commit to participate in the study. The agreed 24 candidates included 21 (83%) leading academics at professorial, programme directorship and departmental head levels and 4 (16%) practitioners at managerial and consultancy levels. One of the participants is both a practitioner and an academics. At the time of the study, each of the candidates had experience in the field of sustainable manufacturing or in a related field that spans 5 to 25 years in either academics or as a practitioner, and his or her work cuts across international borders covering America, North America, and Europe. Appendix A contains the profile of the participants.

### ***6.3.2.*** *Data Collection*

An internet-based survey instrument (Survey Monkey) was subscribed to the design of the questionnaire. The survey monkey is an effective online survey instrument with the capability that enables researchers to design questionnaires in an interactive format, generate web-link to invite the respondents, collect responses and analyse or export to choice analytical software. The first questionnaire designed to elicit responses from the 24-member panellists was divided into four sections containing a set of structured questions in a four-point ("strongly agree"; "agree"; "disagree" and "strongly disagree") Likert-scale format with open-ended questions. The open-ended questions allow the participants the freedom to add comments, reasons for their disagreement or suggestions for the framework improvement **(Hardy *et al.*, 2004).** Each of the sections is designed to cover the defined evaluation criteria (Completeness, Correctness, Conciseness, and Clarity). The questionnaire was pilot tested and refined with colleagues and some academic staff to assess the clarity of the questions, timing and navigation styles.

A web-link to the questionnaires was generated from the survey monkey online instrument and forwarded with personalised e-mail, inviting each of the panellists to commence the study. All the participants were given five weeks to respond to the questionnaire. The responses were captured with the online survey instrument and organised into a numeric quantitative group and open-ended qualitative group. Each of the four-point Likert-scale was given weighted values according to the degree of agreement (“Strongly agree” = “4”, “Agree” = “3”, “Disagree” = “2”, and “Strongly disagree” = “1”). A response analysing document was then created as in **Holsapple and Joshi (2002)*;*** the open-ended comments of the first round were organised based on the items of the questionnaire and carefully reviewed, analysed and classified into two sections: (1) those to be considered in the revision of the framework and (2) those that are outside the boundaries of the study. The comments in the first section were further divided into two groups: (a) suggestions or concerns that occurred most frequently and or seemed to be of major importance (b) suggestions or concerns that occurred less frequently and or appeared to be of less importance. The analysis document guided and informed those concerns that required fundamental modifications, additional changes and further clarifications as narrated in the participants’ comments. In which case, an extensive review of the concepts and elements in the initial framework was detailed while considering suitable amendments of the concepts with relevant justification **(Bacon and Fitzgerald, 2001).** Further explanation was provided where the participants’ comments indicated a request for clarity of concepts.

The second round with a revised descriptive framework was initiated following the same procedure in the first round. Out of the 24 panellists that participated in the first round, 15 (62.5%) responded in the second round. The analysis of the numeric quantitative and the open-ended qualitative responses in the second round of the framework evaluation process showed consensus in the opinion of the panellists.

### *6.4. Descriptive Framework of Simulation-based Sustainability Impact Analysis*

The principles of Life Cycle Sustainability Analysis (LCSA) emphasised on the evaluation of environmental, economic, and social impacts of a product lifecycle. The evaluation process addresses the impacts of manufactured products throughout their life cycle, analyses the interdependencies of the three sustainability dimensions, and clarifies the trade-off and supports effective decision-making. Research has shown that the existing methodologies, approaches, and tools for sustainable manufacturing have not been able to integrate the three dimensions effectively.

The descriptive simulation-based sustainability impact analysis framework is an amalgamation of sustainability tools and approaches, the principles of LCSA, and simulation conceptual modelling frameworks. The principles of LCSA drive a holistic approach to sustainability assessment and the analysis of the interdependencies of the three sustainability dimensions. While the simulation conceptual modelling framework guides the building of a computer simulation model and enables integration and optimisation of the aspects of the three sustainability dimensions in an analytical environment. In the proposed simulation-based framework Figure 6.2, the four components of ISO 14040 LCA methodology are aligned with the key stages of building a simulation project as described in **Robinson (2008b and 2008a).** Studies have shown that contemporary computer simulation models consist of tools and elements that support the application of sustainability approaches such as energy modelling, value stream mapping, Lean-green, and competitive manufacturing.

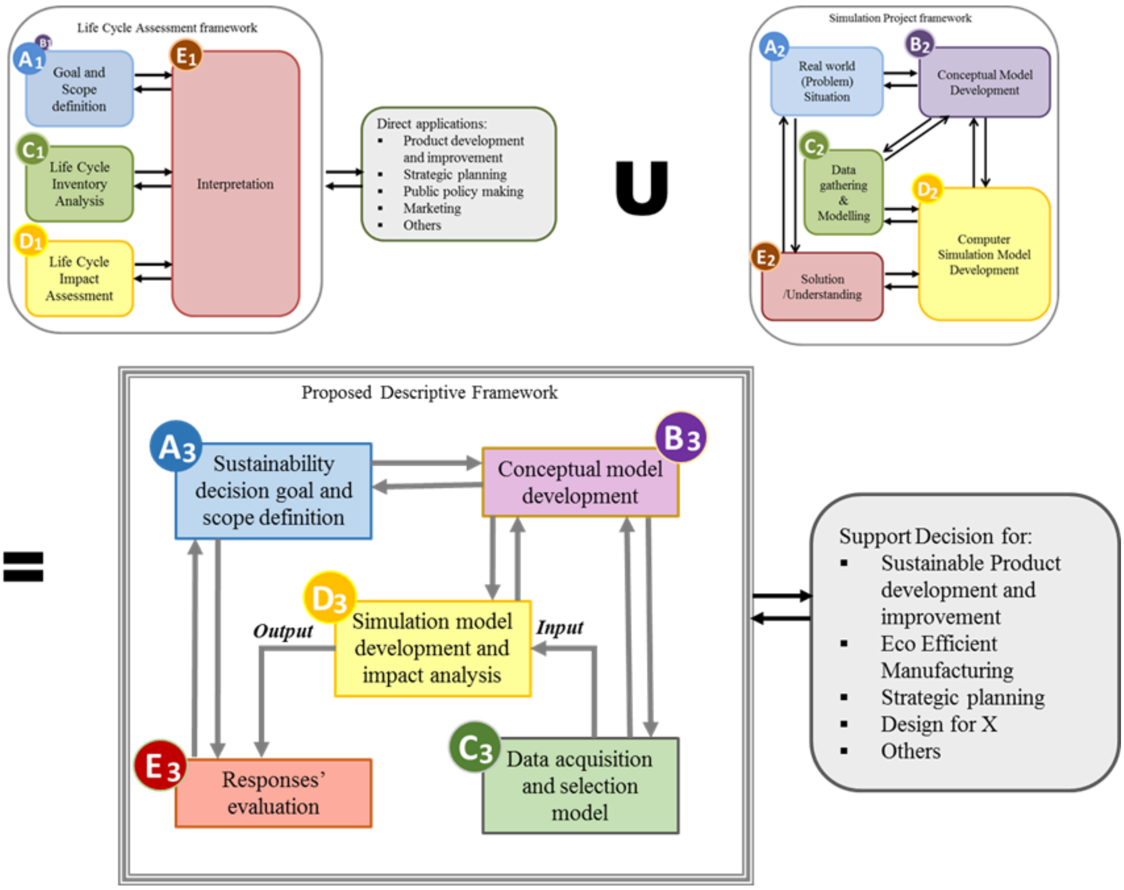


*Figure 6-2 Alignment of ISO 14040 LCA Methodology and key stages of building simulation project*

The descriptive simulation-based framework Figure 6-3 identifies major sustainable manufacturing activities such as the study goal, scope and objectives definition, development of a conceptual model, acquisition and selection of sustainability data, development of computer simulation model and impact analysis of sustainability variables to generate a new knowledge-base that supports decision making. The double arrows represent an iterative process between the activities while the single arrows represent a flow of information.

The proposed integrated simulation-based framework is both a decision supporting and management tool that provides the basis for modelling and analysing the sustainability impact of a manufacturing production process. It will provide a structured guideline for sustainability analysts and practitioners to gather product data effectively, and simulation modellers to model and experiment with variables and alternative solutions in order to support sustainability decision-making. A low-level descriptive diagram of the framework is depicted in Figure 6-4.

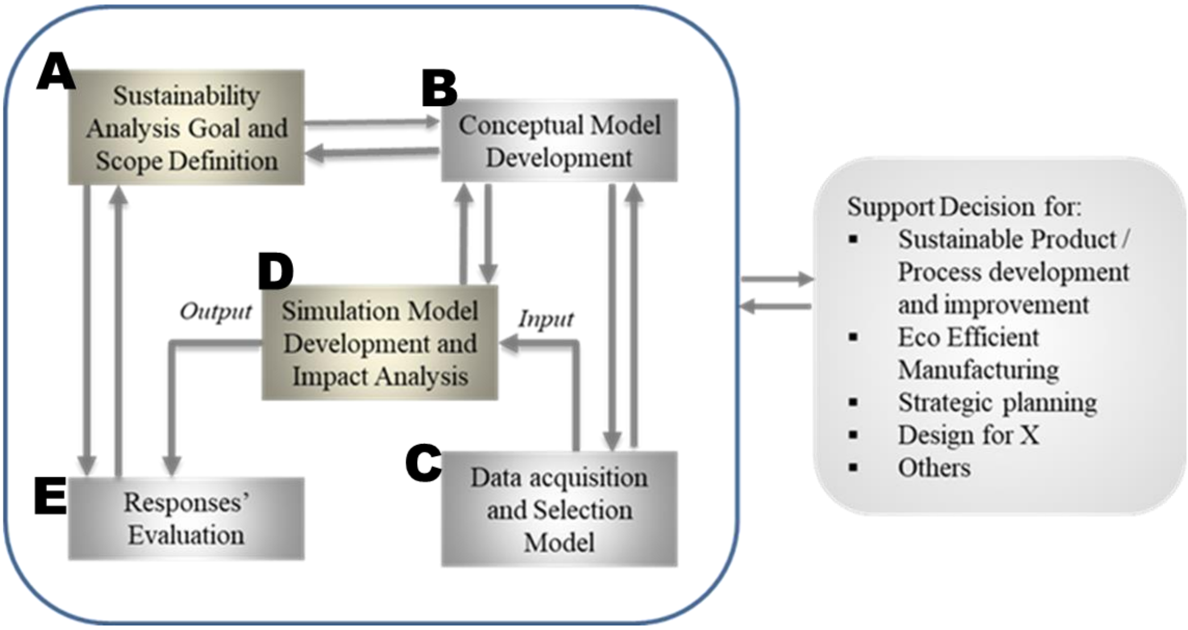


*Figure 6-3. A Framework for conceptual modelling of simulation-based sustainability impact analysis*

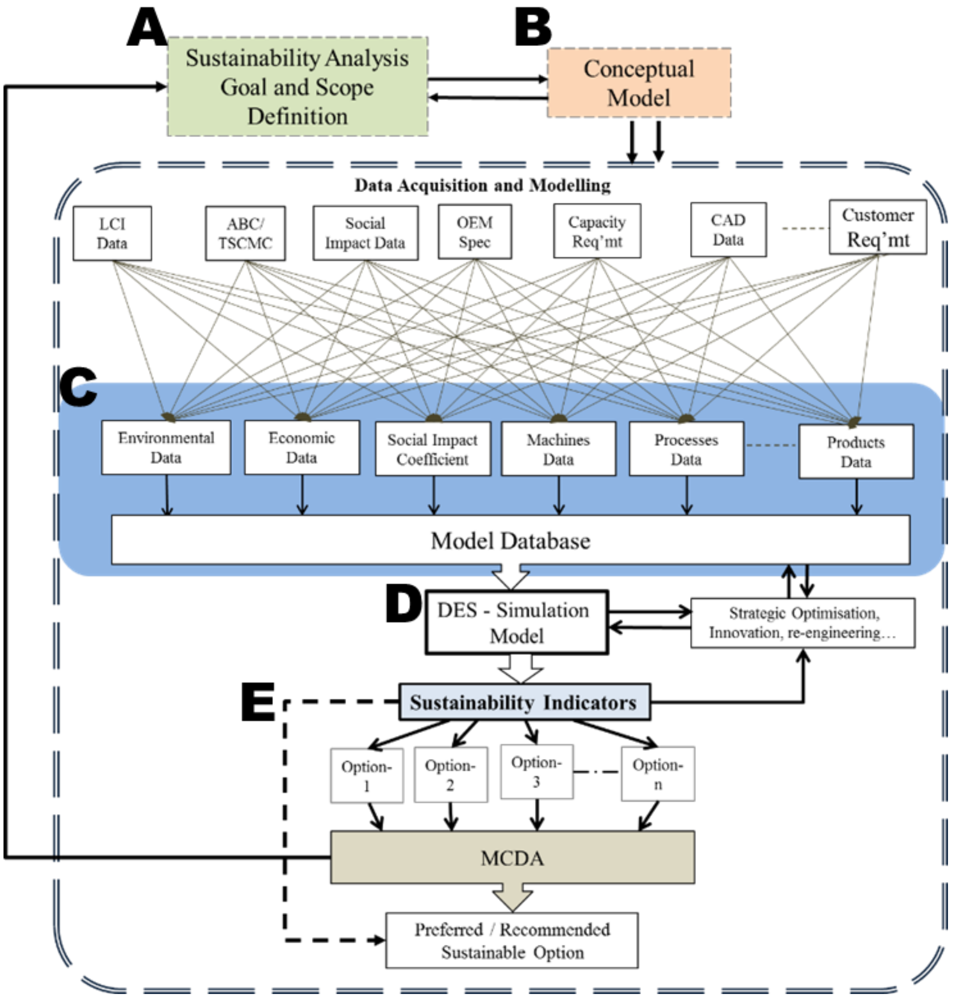


*Figure 6-4 A low-level diagram of the simulation-based sustainability impact analysis framework*

### *6.5. The Result and Analysis of responses to the Delphi Study*

The Delphi process was conducted in a two-round iterative process; the third round deemed not necessary after the reviewed responses and suggestions at the end of the second round indicated a consensus of the experts' opinion.

At the beginning of the study, an acceptable level for consensus was set to aggregated activities' weights rated 3 or above and value of respondents greater than 75% for each of the testing criterion **(Chang *et al.*, 2010).** The comments of the respondents in the open-ended questions were analysed based on the following two defined categories:

1. Suggestions relevance to the revision of the framework
2. Comments viewed to be outside the boundaries of the study.

The study design contained 42 questions and was organised to cover the four defined framework evaluation criteria:

1. Completeness
2. Correctness
3. Conciseness or Parsimony
4. Clarity

### *6.5.1. Round 1*

The analysis of the result of the 24 respondents in the first round achieved consensus for all the four criteria under test with no insuperable problem or major reservation as shown in Table 6-1. However, few concerns were raised which are related to the motivational theories, principles and applications of the framework.

*Table 6-1 The frequencies of participants' responses to the first round of study*

| **Evaluation Tests** | **Num. of Ques.** | **Participants Response Counts** | | | | **Aggregated Weighted Average** | **Total Response Counts** |
|---|---|---|---|---|---|---|---|
| | | Strongly Agree | Mostly Agree | Mostly Disagree | Strongly Disagree | | |
| **Completeness** | 15 | 111 | 135 | 22 | 11 | 3.24 | 279 |
| **Correctness** | 15 | 167 | 169 | 28 | 6 | 3.34 | 370 |
| **Conciseness** | 7 | 52 | 65 | 1 | 0 | 3.43 | 118 |
| **Clarity** | 5 | 44 | 89 | 8 | 3 | 3.21 | 144 |
| **Total** | 42 | 374 | 458 | 59 | 20 | 3.30 | 911 |
| **Aggregated Weights** | | 41.0% | 50.3% | 6.5% | 2.2% | | |
| **Proportion of Participants** | | **Agreed = 91.3%** | | **Disagreed = 8.7%** | | | |

#### 6.5.1.1. *Participants' comments on the open-ended questions*

1. Two of the participants expressed their concern about non-inclusiveness of the whole value chain of a product lifecycle in a gate-to-gate assessment, and another two were unclear what the gate-to-gate sustainability analysis stands for.

***Author's comment*:** The gate to gate approach is part of a systemic and integrated analysis which is needed for comprehensive sustainable manufacturing. It is the boundary approach to defining the scope of each stage of a product lifecycle. The approach is appropriate for simulation modelling since it is not feasible to model the whole value chain of a product lifecycle.

2. The following statements were identified by one or another panellist, requesting clarification or more explanation.
   a. The three sustainability dimensions are interdependent
   b. System Thinking and Life Cycle Thinking are congruent
   c. LCA methodology should be different for economic and social assessments
3. One respondent comments: "workers motivation depends on many factors and very difficult to associate with social performance".

***Author's comment*:** The UNEP/SETAC guidelines for S-LCA **(UNEP Setac Life Cycle Initiative, 2009)** stated two categories of social performance: 1) the performances with high opportunities of positive social impacts and 2) the performances with high risks of negative social impacts. Due to the scope of this study, the author has discussed the alignment of the two social impact categories with the two-factor Herzberg theory of motivation in section 4.4 of chapter 4 and in a publication **(Gbededo and Liyanage, 2018)**.

4. Another respondent state: "workers' motivation is an important part of the social performance, but not the only one. Social performance includes all kinds of benefits to the society, for example, the benefit to the neighbourhood, which has nothing to do with workers' motivation".

***Author's comment*:** The descriptive framework under study is built upon the analysis of literature in the manufacturing domain and the boundary within workers social stakeholders' category (section 2.4 and 4.4). Future study may include other stakeholder's categories such as local community, global society, customers, and supplier. In such cases, the "goal and scope definition" phase of the framework would explicitly define the appropriate social impact categories and subcategories.

5. One of the respondents declares: "Motivational theories and social development have different units of analysis and are very broad topics. More specificity is needed to make that claim".

***Author's comment*:** The factors of motivational theories and social aspects are both qualitative and related. The alignment of their elements and performances enable translation of the qualitative values into weighted values. The details of the alignment and conversion process are out of the scope of the framework development.

6. One respondent's states: "I doubt that sustainability can be dealt with only by using such models since the process seems to be socially under the complex. How are values, trade-offs, etc. dealt with in this model? And in any case, a personal discussion is needed".

***Author's comment*:** Sustainable manufacturing is "the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" *(US EPA, OA, no date).* The simulation-based framework focuses on the modelling of the manufacturing process for the sustainability impact analysis of the process level. The framework is an amalgamation of sustainability methodologies, methods, approaches and tools that address various part of sustainability.

7. One respondent states: "no direct link between economic and social performance".

***Author's comment*:** An organisation's social performance will result in workers' satisfaction if the positive social aspects are deployed as described in section 4.4. Job satisfaction, however, has a direct link with economic performance as posited in the theory of motivation.

8. Two respondents required clarity for the interconnections and the arrows in the figure:

***Author's comment*:** The double arrows in the framework represent an iterative process between the activities while the single arrows represent a flow of information.

Table 6-2 depicts the aggregated weights and the weighted averages of the participants' responses to the Likert-scale elements based on the framework evaluation criteria in the first round of the study. The result shows that over 90% of the respondents (ref to Table 6-1) signify a strong or moderate level of consent in respect of the four evaluation criteria. Those responses with "Strongly Agree" assessed the framework to be extremely successful, while "Agree" assessed the framework to be moderately successful. Figure 6-5 depicts a graphical representation of the relative frequency distributions of participants' responses to each degree of evaluation measures.

Majority of the responses were within the "Strongly Agree" and "Mostly Agree" range. Figure 6-6 shows the graphical representation of the relative frequency distribution of the participants' responses for each of the evaluation criteria. Comparing the respondents' view to the evaluation criteria, "Conciseness" and "Clarity" tests are considered to be highly successful compared to the "Completeness" and the "Correctness" tests. Figure 6-7 depicts the relative frequency distributions for the evaluation criteria.

*Table 6-2.The aggregates of weighted averages for evaluation criteria (1st round)*

| Evaluation Tests | Strongly Agree | Mostly Agree | Mostly Disagree | Strongly Disagree | Aggregated Weighted Average | % Aggregated W.Avg |
|---|---|---|---|---|---|---|
| Completeness | 39.78% | 48.39% | 7.89% | 3.94% | 3.24 | 81.00% |
| Correctness | 45.14% | 45.68% | 7.57% | 1.62% | 3.34 | 83.58% |
| Conciseness | 44.07% | 55.08% | 0.85% | 0.00% | 3.43 | 85.81% |
| Clarity Test | 30.56% | 61.81% | 5.56% | 2.08% | 3.21 | 80.21% |

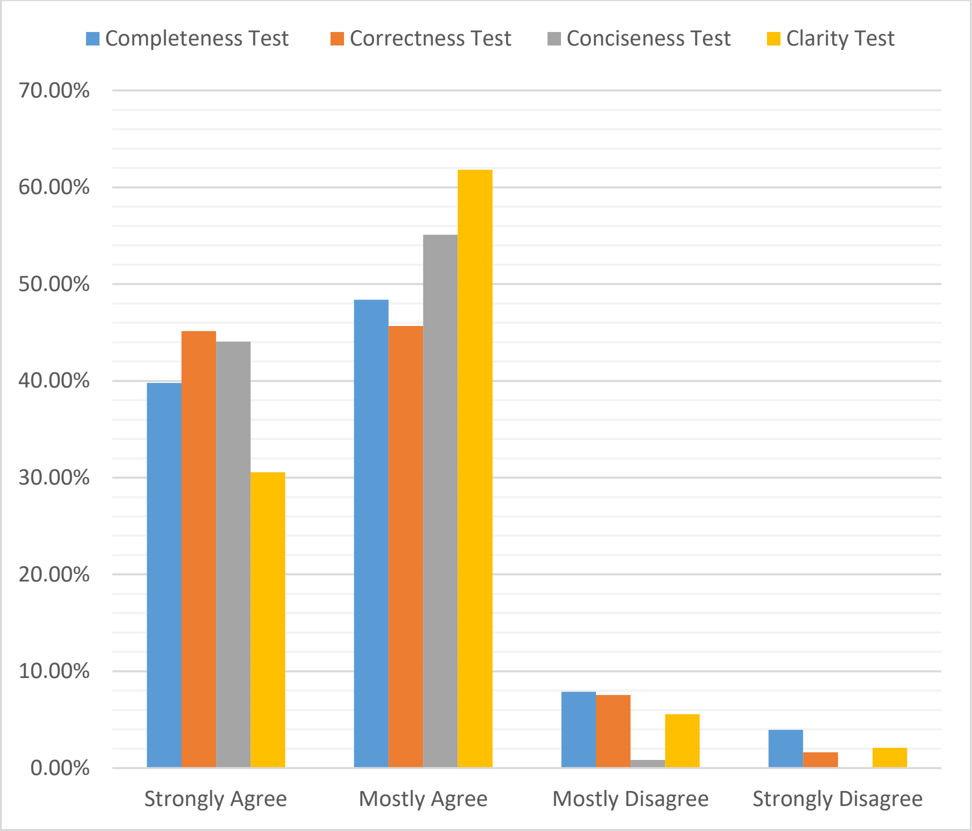


*Figure 6-5. Responses for each evaluation measures*

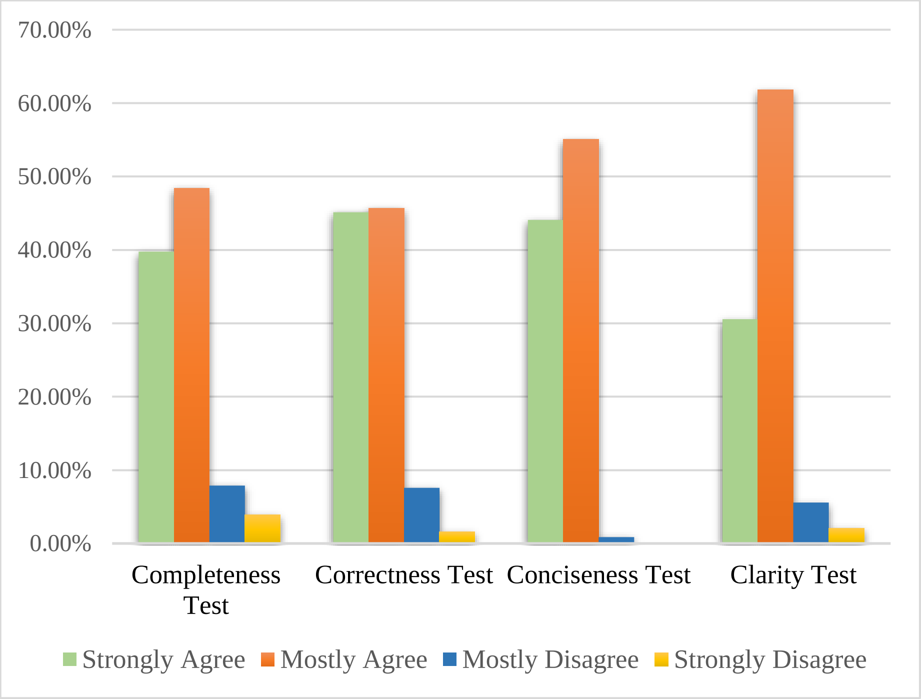


*Figure 6-6.Responses for framework validation criteria test*

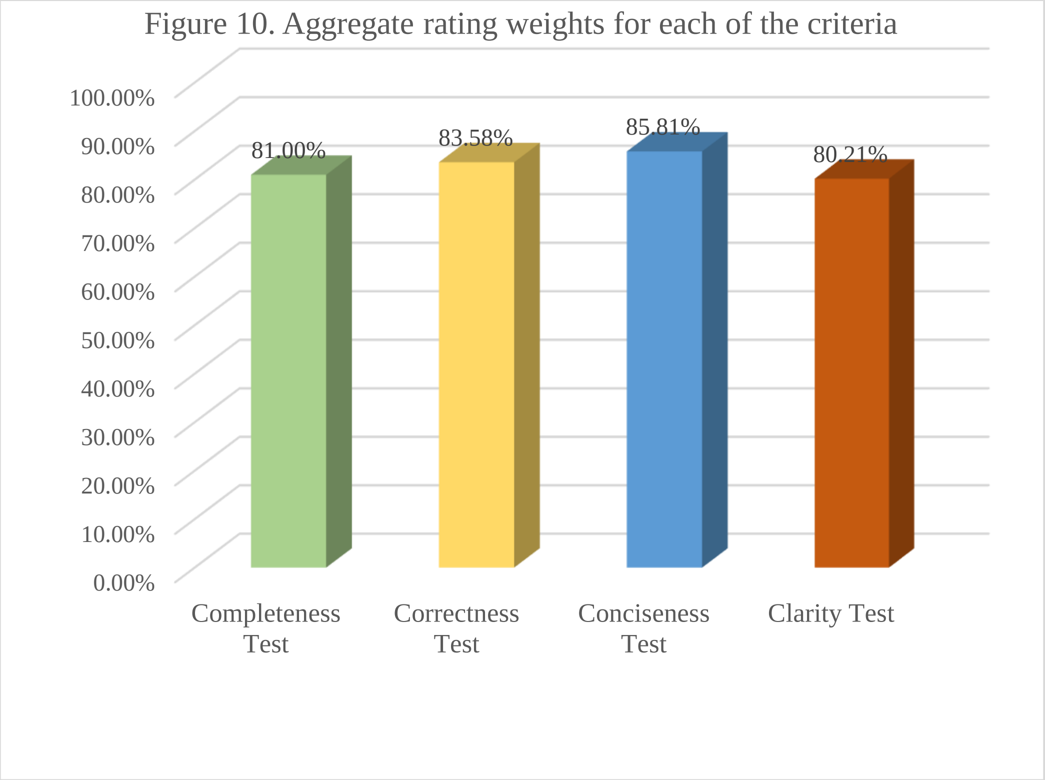


*Figure 6-7. Aggregate rating weights for each of the criteria*

### *6.5.2.* Round 2

In the follow-up to the participants' concerns above and the result analysis of the first study, the summary of the results was sent to the participants in the form of feedback and to seek if there would be a revision in the opinion of any of the participants. A second study containing four questions was then initiated to seek further consensus on some concerns which falls within the boundaries of the study. The questions were similar to the first study but are re-worded to clarify and summarise the tootling issues and arguments. Out of the initial 24 panellists who participated in the first round, 15 (62.5%) sent their responses within the two months period for the second round. Table 6-3 shows the weighted averages of the participant's responses to each of the major concerns and Figure 6-8 presents the relative frequency distribution of the participants' responses to each degree of the evaluation measures.

*Table 6-3. The aggregated weights and weighted averages for evaluation criteria (2nd round)*

| Evaluation Questions | Strongly agreed | Mostly Agree | Mostly Disagree | Strongly Disagree | **Weighted Averages** | **Response Counts** |
|---|---|---|---|---|---|---|
| Sustainability of the processes/actors in the upstream of an organisation may have a positive influence on the outcome of the sustainability assessment of the organisations' activities. | 11 | 4 | 0 | 0 | **3.73** | **15** |
| A product lifecycle assessment can be the aggregation of all the sustainability assessments of all the stages of the product lifecycle | 6 | 9 | 0 | 0 | **3.40** | **15** |
| It is not all social aspects that are regulated by the government or have legal implication | 9 | 6 | 0 | 0 | **3.60** | **15** |
| Effective use of some social aspects may have a positive impact on workers and their productivity. | 10 | 5 | 0 | 0 | **3.67** | **15** |
| Second Study Test | 36 | 24 | 0 | 0 | **3.60** | **60** |
| **Aggregated Weights** | **60.0%** | **40.0%** | **0.0%** | **0.0%** | | |

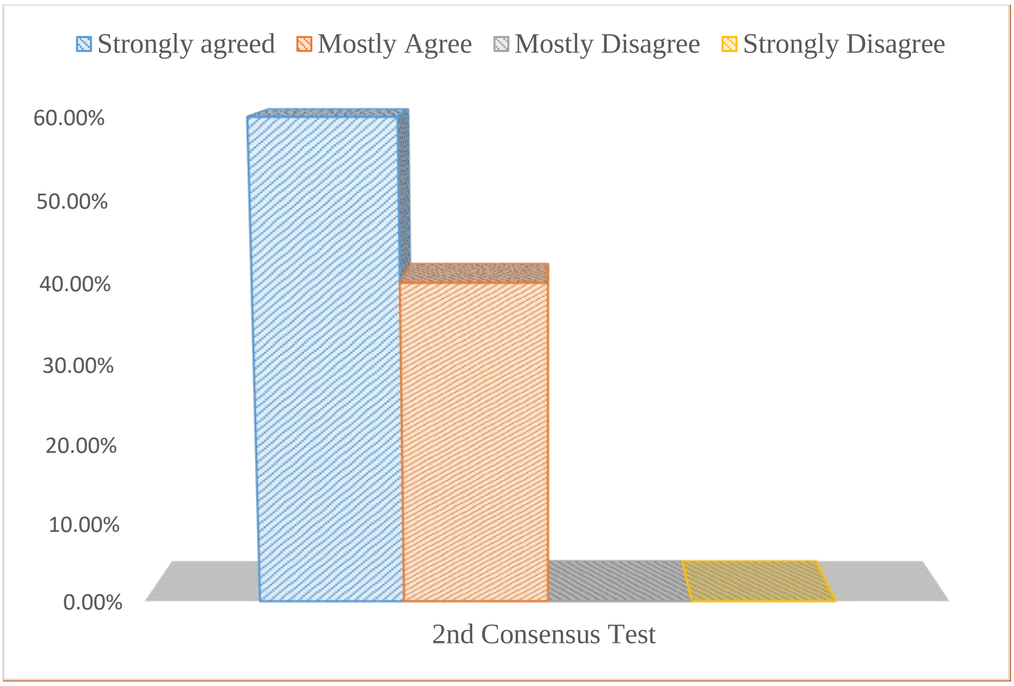


*Figure 6-8. Aggregated weights for the second round study*

## *6.6. Summary and Conclusion*

This chapter presented the stage 2 of the two-stage approach to the development of the integrated simulation-based impact analysis framework. The chapter described the Delphi study methodology deployed for the validation of the initial descriptive framework developed in stage 1 (chapter 5) and the results of the study. The Delphi method enabled a constructive and systematic process for the organisation of a group of experts both from the academics and industry, to study and evaluate the initial framework based on the four evaluation criteria: Correctness, Completeness, Conciseness, and Clarity. The outcome of the study indicated a success level above 80% for each of the evaluation criteria and aggregated weighted average above 3 (out of 4) from over 90% of the respondents.

The fields of study covered in the development of the framework make it robust in addressing the Life Cycle Sustainability Analysis objectives. The aggregation of the responses from all the participants enabled the opportunities to augment and provide a credible result. The study was also designed to give enough time for the participants to give thorough consideration to any statement or principles stated and applied, with links to articles and online materials to support the assertions in the initial descriptive framework.

The key contribution of this chapter and chapter 5 is the provision of a detailed framework for developing an integrated simulation-based impact analysis model for sustainable manufacturing design and management.

# CHAPTER 7

# 7. THE FRAMEWORK PRESENTATION: A CASE STUDY AND SIMULATION MODELLING.

## *7.1.* Introduction

The manufacturing industry is facing an increasing pressure to redesign its products and processes in order to comply with the goals and objectives of sustainable development ***(Brundtland, 1987),*** and at the same time maintains its competitive position. Though the manufacturing industries have high opportunities for both economic and social developments, its activities have been associated with high negative impacts on the environment. The use of limited natural resources such as raw materials, water and land, increasing emission of greenhouse gases, toxic gases and materials, and water and air pollutions are all risks and threats we face due to the manufacturing activities. The case study aims to demonstrate the applicability of the developed simulation-based framework and enable the researcher to reflect on its practicability in a real manufacturing environment. The outcome will provide the knowledge for sustainable manufacturing practitioners on how to build a conceptual model of a real or proposed situation and conduct a simulation-based impact analysis of the aspects of the three sustainability dimensions.  This study is the first to combine the aspects of environmental, economic and social dimensions of sustainability in a simulation-based analytical model. The model explores lean techniques, energy modelling, process optimisation and social impact coefficient to improve and assess the performance of the aspects of the three sustainability dimensions. The approach supports effective sustainability decision-making adopted by the case study.

The next section describes “Case Study” as a research approach method followed by section 7.3, a real manufacturing environment, the Burrow and Smiths case study. The case study aimed to demonstrate and validate the applicability of the developed framework.

## *7.2.* Case study as a research approach

A Case study is an in-depth investigation into a real-life situation or incident and within the context of the situation environment, examining alternative solutions, and using supporting pieces of evidence to propose the most preferred solution ***(Yin, 2003; Ridder, 2017)***. It "incorporates different scientific goals, data collection, and analysis" ***(Ridder, 2017)***. Case study enables a researcher to focus on one or a few aspects of a complex social situation and deal with the subtleties and intricacies of the social situation ***(Choy et al., 2011)***. In general, case study helps to discover and understand interconnections and interrelationships between various events of a real situation; it provides opportunities to discover relationships, structure, and processes in the real setting. However, some disadvantages are associated with conducting a case study. For example; it is often difficult to negotiate access to a case study setting partly due to high risks or data protection issues. A case study can also generate an overwhelming amount of complex data which may be difficult to handle within a short period of time. Another challenge with case study is that the operator been observed may act differently if they are aware they are been observed, this is referred to as "observers effect" ***(Choy et al., 2011),*** like many experiments, assumptions also need to be acknowledged and address in a case study ***(Yin, 2003)***.

The Burrows and Smith Limited case study represents a "microcosms" of an entire manufacturing production process to conduct sustainability impact analysis, and to identify areas for performance improvement and support decision for implementation of a sustainable solution. Normally, any type of production line could be used for the case study, but because of accessibility to specific simulation software, a discrete manufacturing process is selected for this case study. The main objectives of sustainable manufacturing were also considered in designing the case study. According to the US Department of Commerce "*sustainable manufacturing is the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound"* **(US EPA, OA, no date)**. Hence the following has been considered for the design of this case study

- Impacts of the manufacturing production process on the environment, economy and society
- Access to Discrete Event Simulation (DES) Software - SIMIO
- The dynamism of a manufacturing production environment
- Other related works in this area such as lean-green, and energy modelling.

Due to time limitation and the complexity of modelling some extended production processes, the case study would focus on the sustainability objectives by analysing the impacts of the production process on some aspects of the three sustainability factors. The result will provide recommendations that would support decision-making for the product or process designers.

## *7.3.* Case Study- A Real Manufacturing Environment: Burrows and Smith Limited

### *7.3.1. The Background of Burrows and Smith Company*

Burrows and Smith Limited (BSL) has been a leading component supplier since 1939; providing customer machining solutions such as bearing caps, mid-range cast iron sumps, elbows, gear covers & housings, water pumps, flywheels, and flywheels' housings **(BSL, no date)**. The company joined the Shield Group in 2007 and had since engaged in improving its customer focus including the relocation to a new purpose-built facility at Barkby Road Leicester. The company pride itself on an experienced management team and continuous good relationships with its suppliers in order to offer its customers high levels of quality products at globally competitive prices. Currently, the company delivers up to 75 tonnes of finished products a day on average shipment lead times of 6 hours, however, with the new facility with modern equipment at Leicester, the company is reckoned to be operating far below its full capacity.

This case study is carried out to investigate the sustainability of the company in maintaining its competitive position when the operation is in full capacity. The aim is to support the management decision in designing and managing the sustainability of BSL production process especially at infinite demands for finished products and an unlimited supply of materials. By being sustainable in this case, implies "the creation of the finished products by using processes that minimise negative environmental impacts, conserve energy, are safe for employees and are economically sound."

### *7.3.2. The Description of BSL Production Facility and Process*

BSL manufacturing system is designed as a cellular layout consisting of twenty-one (21) cells labelled as Cell 10, Cell 20, Cell 30 …….Cell 200 and Cell 210. Three (3) of the cells are used for Pre-Delivery Inspection (PDI), Washing and Packaging. Each of the remaining eighteen (18) cells consists of two industrial computer numerical control (CNC) machines and handling tools. Each of the CNC machines is configured to handle one or two part types without the need for a reconfiguration or setup downtime. The workstations of each of the cells are arranged in a form that the part must flow one way and connected by a conveyor. An operator is required to load and off-load each of the machines and the finished products are picked in batches by a 30 capacity forklift from the cells and transferred to the PDI area, Wash, Package then delivered consecutively.

BSL receives supplies of raw materials such as cast iron Flywheels, sumps, and Flywheel Housings, processes and delivers finished products based on the customer specifications **(BSL, no date)**. The processing of the cast irons involves different machining operations of metal removal such as Turning, Drilling, Milling, and Grinding.

**Turning:** This machining operation generates shape through the reduction of the diameter of a rotating work-piece. Examples of turning include straight turning, form turning, taper turning, chamfering, cutoff, contour turning, boring and threading.

**Drilling:** In this machining operation, a round hole is created into a work-piece through a rotating drill bits fed into the work-piece to remove materials. Examples of operations related to drilling include reaming, tapping, counter-boring, countersinking, centre drilling, and spot facing.

**Milling:** This machining operation generates shape through feeding a work-piece against a rotating cutter with multiple edges. Examples include plain or peripheral milling, and profile or face milling.

**Grinding:** This is a machining operation used for finishing processes such as in smoothening the surface of a work-piece or flatten, straighten, even-off or shining the work-piece. Other examples of the finishing process are honing and lapping.

*Multipurpose Machines:* Some machines come with multiple spindle bars attached with multiple tools to enable multiple parts to be machined at a time. These types of machines increase cutting tool utilisation and production rate and are often controlled by mechanical devices or computer program instructions consisting of alphanumeric codes. The modern CNC Lathe machine is an example of computer-controlled multiple-spindle automatic bar machines. BSL deploys two CNC machines in each of the materials processing cells. The processing rate of each of the CNC machines depends on the work-piece, types, quality and the number of machining operations it is configured to execute based on the customer specifications.

### *7.3.3. The Application of Simulation-based Impact Analysis Framework*

The developed integrated simulation-based sustainability impact analysis can be applied to support the decision for effecting improvement project on existing manufacturing assets or on implementing a new idea or production facility. Figure 7-1 shows a flowchart for engaging the simulation-based impact analysis in implementing sustainability goal. This case study focuses on the implementation phase of the developed framework.

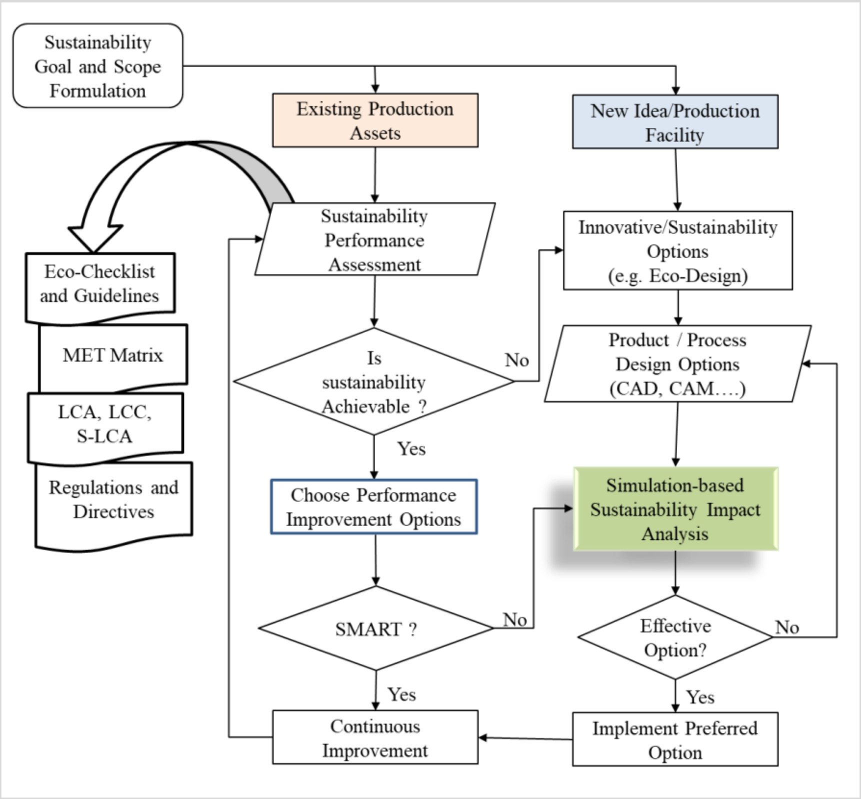


*Figure 7-1 A flowchart for engaging the sustainability impact analysis framework*

The application of the five-phases of the developed framework is carried out in an iterative process, so, no phase is done in absolute isolation of the other. The guidelines for documenting each of the phases have been thoroughly discussed in Sections 5.5.1 through 5.5.5. The following corresponding sections (as indicated in the Figure 7-2), therefore, summarises the outcome of each of the phases in regard to this case study.

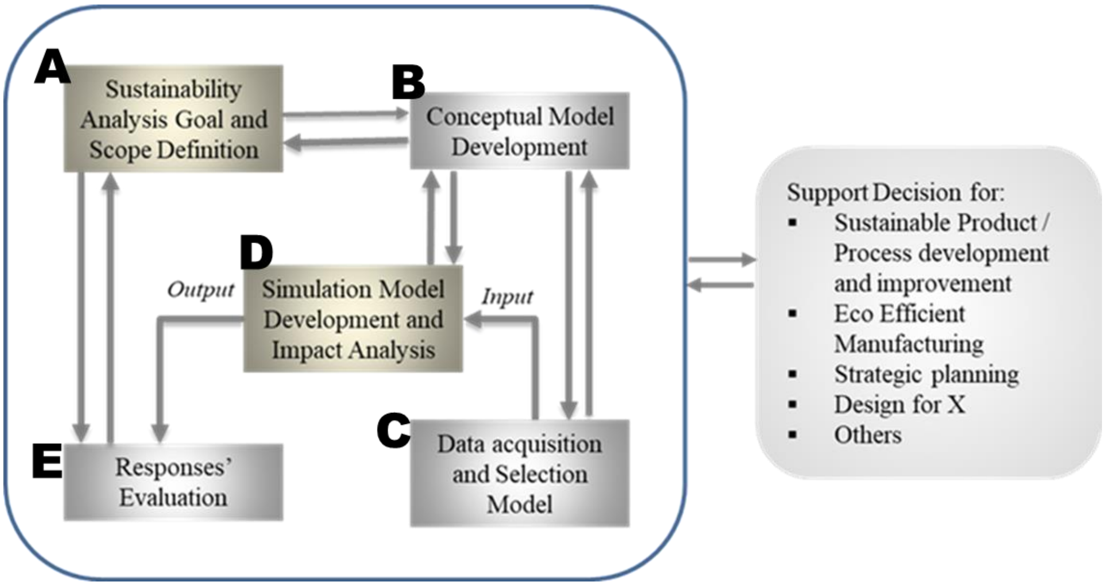


*Figure 7-2 A Framework for conceptual modelling of simulation-based sustainability impact analysis*

## A. Sustainability Analysis Goal and Scope Definition

i. **The purpose and aims of conducting the study**: BSL is not sure of the best sustainable process configuration for a fully operational capacity of the new production system. Hence, BSL wants to determine the optimal manufacturing design of the production facility that enables higher productivity, minimal energy consumption, socially and economically sound.

ii. **The intended application of the sustainability analysis results**: To support sustainability decision-making for an alternative process configuration.

iii. **The system boundaries and contents**: The analysis is limited to the production process within the manufacturing stage of the product lifecycle. The analysis could include water consumption, energy consumption, materials usage and GHG emission as the environmental indicators. Throughput, materials costs, resources costs, and productivity as economic indicators. Workplace hygiene factors, and Employees'motivation to work as the social indicator of sustainability.

iv. **The description of the process, or system under study:** The Cell150 processes the flywheel cast iron. The samples of the raw flywheel cast iron and the processed flywheel are shown in Figure 7-3 A and B respectively.

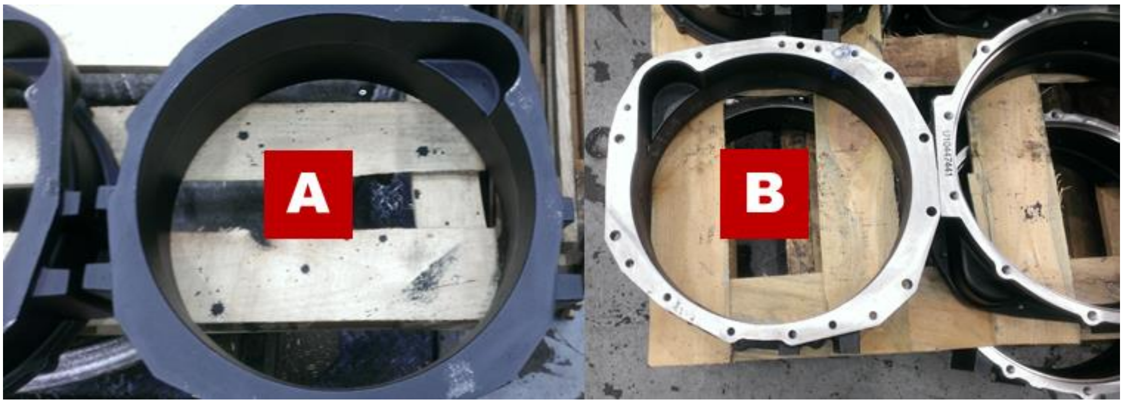


*Figure 7-3 Cell150 Work-piece - "A" flywheel raw cast iron, "B" processed flywheel*

The processing line consists of the Parts' Source, two CNC machines (M1 & M2), connected by a conveyor. Each of the machines is configured to carry out over five operations at a time; then, the work-piece is moved from Cell150 to the PDI, Wash, Package and a final Delivery. A schematic diagram of the processing line of Cell150 is depicted in Figure 7-4.

Parts arrived at the source and manually loaded on M1 which performs series of operations. On finishing, it is manually off-loaded and placed on the conveyor that conveys the work-piece to the input of M2. Work-piece is manually loaded on M2 which also performs series of operations and on completion; the work-piece is off-loaded and placed unto a pallet. A 30 capacity forklift picks the work-piece from Cell 150 on demand to the PDI for inspection, then to the Wash, Package and the final Delivery. At the PDI, the work-piece is tested for quality, work-piece that failed the quality test are reworked and then send to Wash and Packaged for delivery.

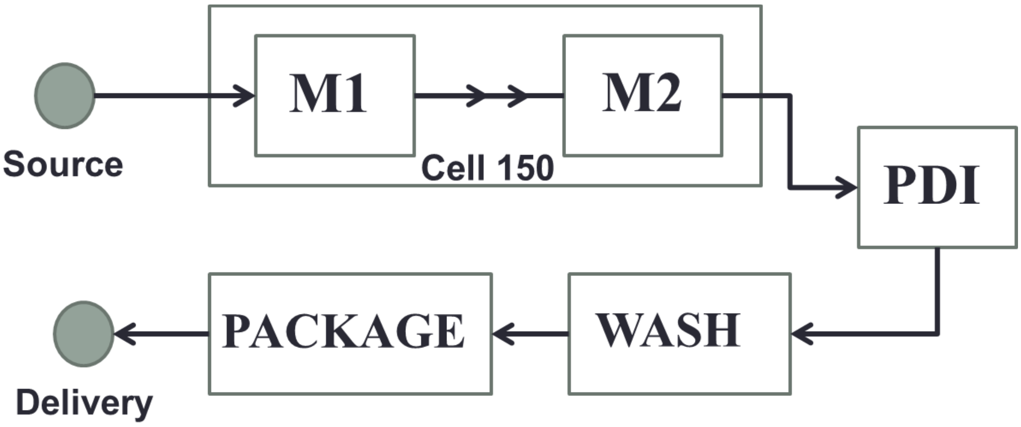


*Figure 7-4 Schematic diagram showing the layout of flywheel cast iron processing line*

v. **The function of the process under study:** The production process of a flywheel cast iron.

vi. **The functional Unit:** 100 hours of processing

vii. **Data requirements:** Processing Rate, Loading Time, Off-loading Time, Inter-Arrival-Rate, Materials handling capacity, Secondary Resources, Routing Information, Input Voltage and Current of the CNC machining equipment, buffer capacity, and Workers' Social Impact Coefficient.

viii. **Assumptions and limitations**: It is assumed that similar work-piece is processed at the other 17 cells simultaneously with an infinite supply of parts and unlimited demand for finished products. All part passed quality test, hence, there is no need for a rework station.

## B. Conceptual Modelling of the Process

i. **Simulation Modelling objectives:** In setting the modelling objectives, the organisation's long-term and short-term sustainability strategies were considered. Another constraint in determining the model objectives is the time required to run a complex model and the likelihood of complications in data handling. Table 7-1 shows the long-term, mid-term and short-term plan for conducting the sustainability impact analysis. Where the objectives of the company span all the identified impact categories, the modelling are done in succession to avoid over complication of the models.

Hence, the summary of the short-term objectives of this case study is to maximise the throughput of the production process at minimal cost and energy consumption and in a stable and socially sustainable manufacturing environment. As discussed in chapter 4, the focus is on the dynamic energy consumption.

*Table 7-1 Classification of the long-term and short-term simulation modelling objectives*

| **Sustainability Dimensions** | **Process level Impact Categories** | **Objectives** | | |
|---|---|---|---|---|
| | | Long-term | Mid-term | Short-term |
| Environmental | Energy Consumption | √ | | √ |
| | Water Consumption | √ | √ | |
| | GHG emission | √ | √ | |
| | Materials Usage | √ | | |
| | Waste elimination | √ | | √ |
| Economic | Labour costs | √ | √ | |
| | Energy Costs | √ | √ | |
| | Throughput | √ | | √ |

| | | | | |
|---|---|---|---|---|
| Social | Productivity | √ | | √ |
| | Workplace Hygiene | √ | | √ |
| | Employees’ motivation | √ | | √ |

The modelling objectives are functions of some input or decision variables. It is, therefore, the task of a simulation analyst to identified the optimal set of values of the decision variables that can achieve the objectives. Figure 7-5 depicts examples of the simulation modelling objectives and some decision variables that may influence the objectives.

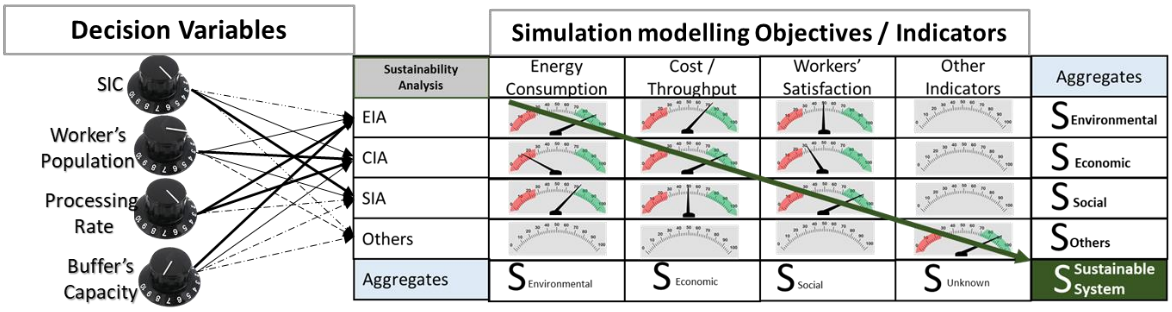


*Figure 7-5 Examples of sustainability impact analysis modelling objectives and decision variables*

ii. **Functional Specifications**: As detailed in section 7.3.2, 7.3.3.1 and 7.3.3.3

iii. **Expected outputs:** Optimal Social Impact Coefficient (SIC), Total Energy Consumed and Throughput

iv. **Identification and selection of input variables:** Number of workers, Buffers’ capacity, Processing rate and SIC.

v. **Model Content:** Modelling of the process, energy consumption and social impact of the production Cell 150.

***Assumption:*** Other 17 Cells process similar material at the same rate and simultaneously.

***Limitation:*** The complexity of the model content determines time to run and test different experiments.

***Constraints:*** System stability in relation to the number of parts in the system or work-in-progress (WIP)

vi. **Details graphical description of the model:** This stage involves graphical representation and documentation of the model in a form that can be coded for computer simulation. Currently, there is a couple of contemporary simulation software with inbuilt tools that can assist in the static modelling.

Figure 7-6 represents the graphical description of the system to be coded in the simulation modelling software.

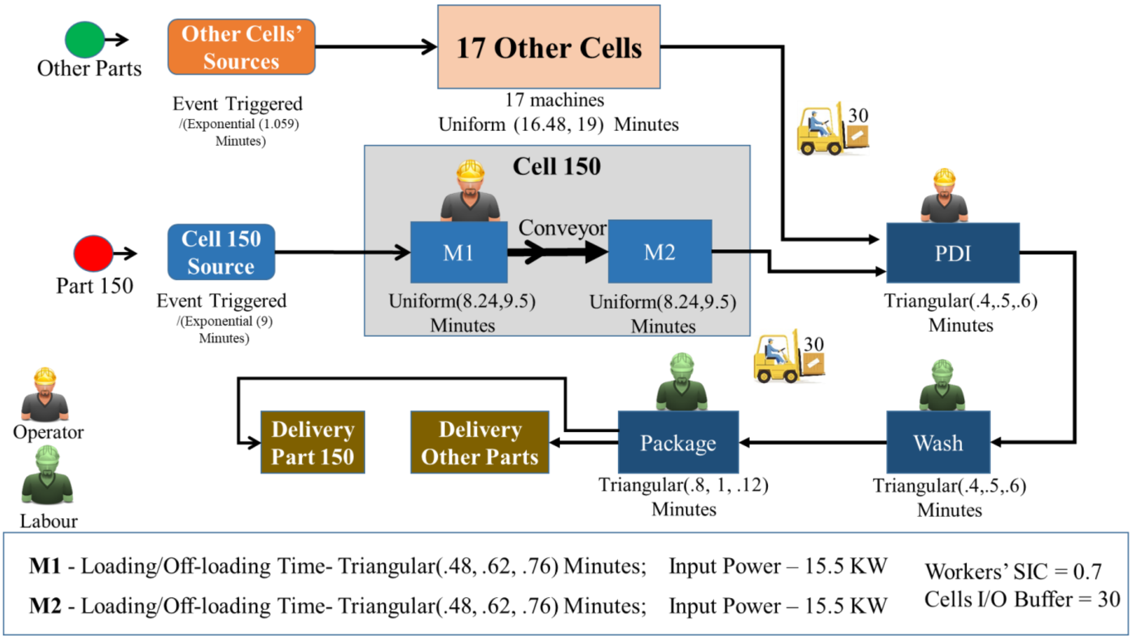


*Figure 7-6 Description of BSL manufacturing system conceptual model*

## C. *Data Acquisition and Selection Model: Requirement and Data Gathering*

i. **Manufacturing system and processing data:** For this case study, an average processing rate of 9 minutes per unit part is calculated for each of M1 and M2 during observation and recording. Each of the CNC machines requires a worker to load and off-load the work-piece at an average of 37 seconds per activity. The Inspection and Washing takes an average of 0.5 minutes per product, and the Packaging takes an average of 1 minute to pack a finished product. The Inspection, Wash, and Packaging use human resources to process each of the activities. Raw casted irons are delivered in batches of 30 to the cells in a Just-In-Time (JIT) technique. Each of the cells has input and output buffer capacity of 30. Two forklifts with each capacity of 30, picks finished products from the cells and transferred to the PDI area for inspection, then, to Wash and Package successively.

Based on the JIT approach, the arrival of the entity “Part150” is triggered by an event. This occurs when the work-piece exits the output of Workstation “M1” which is approximately equal to M1 processing time. That is; 1 Part every 9 minutes or Inter-Arrival-Time (IAT) of 6.666 parts per hour (60/9) when there is no blockage from the succeeding process.

Similarly, the arrival of entity “Other Parts” is triggered when the work-piece exits the output of the Server “Other Cells”. This is approximately equal to the Server processing time which is estimated to 18 minutes. That is; 17 parts every 18min or 1 part every 1.059min. The Inter-Arrival-Time (IAT) is therefore 56.666 parts per hour in an unhindered workflow process.

ii. **Equipment data:** The CNC operations and other auxiliary resources consume energy. The energy consumed $E_{cons}$ is a function of the power generated (P), time of operation (t) and efficiency of the machines and human resources (U) (Efficiency/Utilisation in percentage)

$$E_{cons} = f(P, t, U)$$

$$E_{cons} = P \text{ x } t \text{ x } U$$

The Electrical Power (P) equation is given by

$$P = V\, I \cos \varphi$$

Where “P” is Power in watts, “V” is Voltage in volts and “I” is current in amperes (DC).

Where “I” is AC, the power factor PF = cos φ and φ = the phase angle between the voltage and amperage. Hence, at a power factor angle of 0, that is; for a purely resistive load, cos φ = 1.

$$P = V\, I$$

$$E_{cons} = V \text{ x } I \text{ x } t \text{ x } U$$

Time (t) is measured in hours; Efficiency (U) is measured in percentage, and Energy Consumed ($E_{cons}$) is measured in watt-hours, or Kilowatt-hours (kWh).

Where the input voltage (V) is a three-phase voltage, the equation is multiplied by the square root of three, that is;

$$P = 3^{1/2}\ V\ I\ \cos\varphi$$

The CNC machine in this case study is the Mazak Variaxis i-800, a three-phase AC voltage input of 415V as indicated on the OEM datasheet Figure 7-7.

*Figure 7-7 OEM specification for Mazak Variaxis i-800 CNC machine*

The 3-phase input current AC (I) was measured with a clamp meter as shown in Figure 7-8 when the machine is on full load. An average of 21.5 Amperage was recorded under multiple observation of machining operations for the flywheel Part Type U10447441 at the Cell 150.

Hence, for a pure resistive load, the power factor = 1, Voltage (V) = 415 volts, and AC current (I) = 21.5 Amps

The Power (P) can be calculated as

P= $3^{1/2}$ (415 V) (21.5 A) 1

Square root of 3 = 1.7320508075689

P = 15454.22 W = <u>**15.5kW**</u>

The energy consumption of the Mazak Variaxis i-800 CNC machines per unit process can, therefore, be calculated as

$$E_{cons} = P \text{ x } t \text{ x } U$$

$$E_{cons} = 15.5 \text{ x } t \text{ x } U$$

Where Time (t) is the processing time for the unit and Efficiency (U) is the percentage utilisation of the machinery.

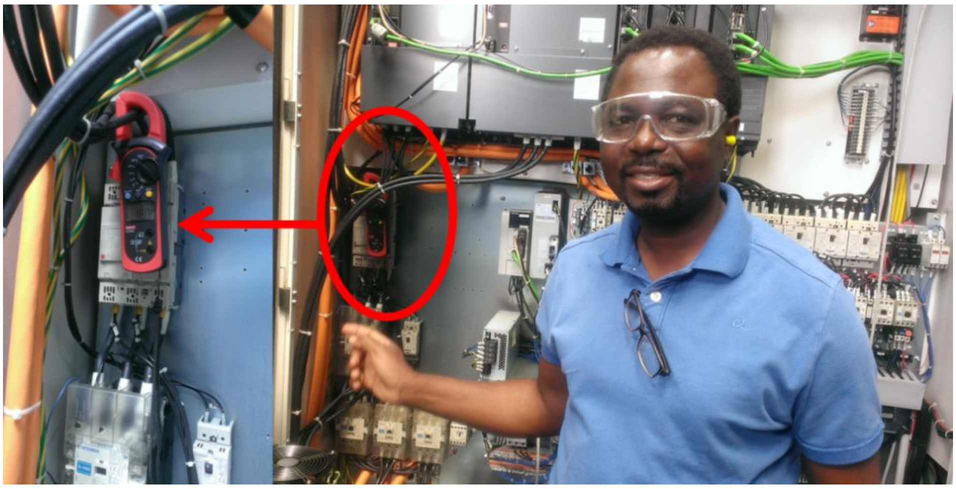


*Figure 7-8 Clamp meter connected to the 3-phase source to measure the input current on the load*

iii. **Social Impact Data: The** operation of semi-automated machines often require the support of human resources such as in loading and off-loading parts and for maintenance except in a situation where we have fully automated systems or perpetual machines.

In this case study, workers are required for loading and off-loading of parts and manual inspection, washing, and packaging of the finished products. Optimising the efficiency of the workers is therefore vital to the overall productivity of the operation. In the section 4.4.4, employees' Productivity Factor (PF) is discussed under the Social Impact Coefficient (SIC) and shop floor workers' motivation and satisfaction at work. The aim of gathering social impact data is to calculate the SIC in order to assess the workers' social impacts on productivity and the level of corporate social responsibility towards the employees.

The following social impact calculation is estimated for BSL due to lack of access to complete information and data protection policy.

### *a. Social Impact Category Selection and Data Collection Procedure*

The following sections describe the Social Impact Category selection, data collection procedure, SIC calculation and documentation process in reference to Figure 4-9. Table 7-2 summarises the goal and scope of the study and describes the selected impact subcategories for social assessment with their corresponding impact types, while Table 7-3 shows arbitrary values allocated to the aggregated weighted values of each of the selected social aspects with the related calculations.

*Table 7-2 SIA summary information sheet.*

**Goal & Scope**

- To model the most efficient and sustainable production process for a production line
- Analyse the impacts of alternative process configurations on the three sustainability aspects in order to choose the best process option.
- ***The Object of Study:*** Manufacturing stage (as discussed in Section 4.4.4)
- ***Boundary 2:*** Production line (process level assessment), End of the assessing year
- ***Functional Unit***: Process time (100 running hours)

**Stakeholder Category:** Employees/Workers

| **Selected Impact Subcategories** | | **Indicators (Ref: GRI, 2016 Equations)** | **Impact Types** | |
|---|---|---|---|---|
| | | | +Ve | −Ve |
| S1 | Investment in Human Resources | Aggregated percentage of FT employee benefits | √ | √ |
| S2 | Onsite Social Initiatives | Number of social amenities on site | √ | - |
| S3 | Training and Education | Average training hour per employee | √ | - |
| S4 | Labour /Management Relations | Effectiveness of labour/management relations | √ | √ |
| S5 | Occupational Health and Safety | Percentage of workers representatives at formal joint H & S meetings | - | √ |

| | | | | |
|---|---|---|---|---|
| S6 | Freedom of association and collective bargaining | Risk of the right to exercise freedom of association or collective bargaining | √ | √ |
| S7 | Diversity and Equal Opportunity | The ratio of basic salary of men to women | √ | √ |
| S8 | Non-Discrimination | Effective Non-discrimination policy and procedure | - | √ |
| S9 | Child Labour | The risk for incidents of child labour | - | √ |
| S10 | Forced or Compulsory Labour | The risk for incidents of slave or bond labour | - | √ |

(Social impact types: positive is denoted by +Ve and negative by −Ve).

With the aid of the Global Reporting Initiative **(GRI -400 Series, 2016)** guidelines for reporting and calculation of social impacts, the aggregated weights of social performance of the selected quantitative and qualitative impact subcategories were calculated. The result data presents different units which need to be normalised in order to be used in the analytical equation. First, an organisation can benchmark with the data from a best-in-class in the industry or set an internal baseline to grade the performance of each of the calculated social aspects. In this case, an arbitrary baseline was set to estimate the scores.

The scores are then attributed to the aggregated weights using values based on a reference scale 1 to 9 and 0 for the worst scenario. In this case, the following weighted scale-based referencing for the social score were used:

Excellence = 9; Very good = 7; Good = 5; Bad = 3; Very Bad = 1; Worst = 0

The odd numbers enable a flexible grading option in a situation where performance is judged to be in-between two grades. For example; if an organisation performance of a social aspect is judged to be neither “Good” nor “Bad”, it will be graded as “6”.

*Table 7-3 SIC Data Sheet.*

| ***Graded Social Scores of Aggregated Social Weights (Scale-Based Referencing)*** | | |
|---|---|---|
| ***Aspects Counts (Number of Occurrences):*** | $C_{a+} = 6$ | $C_{a-} = 8$ |

| **Social Aspects** | **Positive Aspects** $(\boldsymbol{W}_{\mathbf{a}+})$ | **Negative Aspects** $(\boldsymbol{W}_{\mathbf{a}-})$ |
|---|---|---|
| S1 | 6 | 3 |
| S2 | 7 | |
| S3 | 8 | |
| S4 | 7 | 7 |
| S5 | | 4 |
| S6 | 5 | 8 |
| S7 | 4 | 6 |
| S8 | | 6 |
| S9 | | 9 |
| S10 | | 9 |
| Total Weighted Values | **37** | **52** |
| Total Highest Possible Weighted Values | (6 × 9) = **54** | (8 × 9) = **72** |
| Percentage of Average weighted values | 68.52% | 72.22% |
| The ratio of Social Aspect Types | 0.4286 | 0.5714 |
| Relative Social Impacts Index | 0.2937 | 0.4127 |
| Social Impact Coefficient $(\boldsymbol{\beta})$ | $\mathbf{0.7064}$ | |

### *b. Calculation of the Social Impact Coefficient*

The Social Impact Coefficient is calculated from the Social Impact indices of the positive and negative social impacts. A social impact index is a normalised weighted average measuring the relative weight of all the identified social aspect types. This can be calculated using a formula similar to relative price index equation:

$$Social\ Impact\ Index = \frac{\sum(W_a \times C_a)}{\sum(W_A \times C_A)}, \tag{4}$$

where $\boldsymbol{W}_{\mathbf{a}}$ is the weighted value of a social aspect type (+/−); $\boldsymbol{W}_{\mathbf{A}}$ is the highest achievable weighted value of a social aspect type; $\boldsymbol{C}_{\mathbf{a}}$ is the count of an identified social aspect type (+/−), and $\boldsymbol{C}_{\mathbf{A}}$ is the total count of all the identified social aspect types.

Equation (4) can be simplified into Equation (5) for easy calculation.

$$\text{Social Impact Index} = \frac{\sum \mathrm{W_a}}{\sum \mathrm{W_A}} \times \frac{\sum \mathrm{C_a}}{\sum \mathrm{C_A}}, \tag{5}$$

From the data in Table 7-3:

*Number of occurrence of Positive aspects* $(C_{a+}) = \mathbf{6}$; *Negative aspects* $(C_{a-}) = 8$

$\text{Hence}, \mathrm{C_A} = (6+8) = 14\ ;\ \mathrm{W_A} = 9$ (Weighted value for excellence performance)

$$P\text{ositive Social Impact Index } (\gamma) = \frac{37}{54} \times \frac{6}{14} = 0.6852 \times 0.4286$$
$$= 0.2937$$

$$N\text{egative Social Impact Index } (\alpha) = \frac{52}{72} \times \frac{8}{14} = 0.7222 \times 0.5714$$
$$= 0.4127$$

$$\text{Social Impacts Coefficient } (\boldsymbol{\beta}) = \gamma + \alpha = (0.2937 + 0.4127) = \mathbf{0.7064}$$

## D. *Simulation Modelling and Sustainability Impact Analysis*

This case study deploys SIMIO Discrete Event Simulation (DES) software to model and demonstrates the applicability of the developed simulation-based sustainability impact analysis framework in a real manufacturing environment. Simio DES software provides a flexible and user-friendly environment for modelling in 2D or 3D graphics view. The following steps are taken in this process:

i. The simulation model is coded from the conceptual model in section 7.3.3.2 above in an iterative process and in conjunction with the other three phases of the framework.
ii. The initial simulation model is verified with a static queuing model to ensure the simulation model works as expected.
iii. The simulation input parameters are updated and verified with some expected results, and the AS-IS of the manufacturing process is captured.

iv. Specific sustainability analysis experiments are performed and reviewed with the output parameters. This part is also used to demonstrate the interdependencies of the aspects of the three sustainability dimensions.

v. Optimisations of the variables are experimented to achieve the stated objective of the simulation.

***Step I: Coding of the initial simulation model.***

The initial simulation model is coded with the mean values (not distribution values) of the recorded real manufacturing parameters (Figure 7-6) in order to verify the performance of the model. The 2D view of the initial simulation model is presented in Figure 7-9, while Figure 7-10 depicts the instance when the simulation model is run with gauges to monitor the energy consumption of M1 and M2.

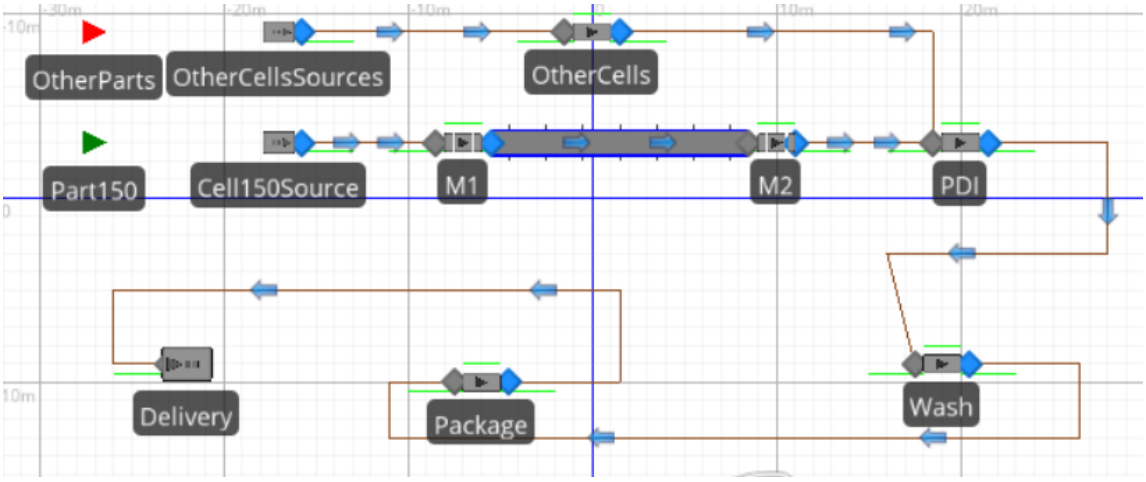
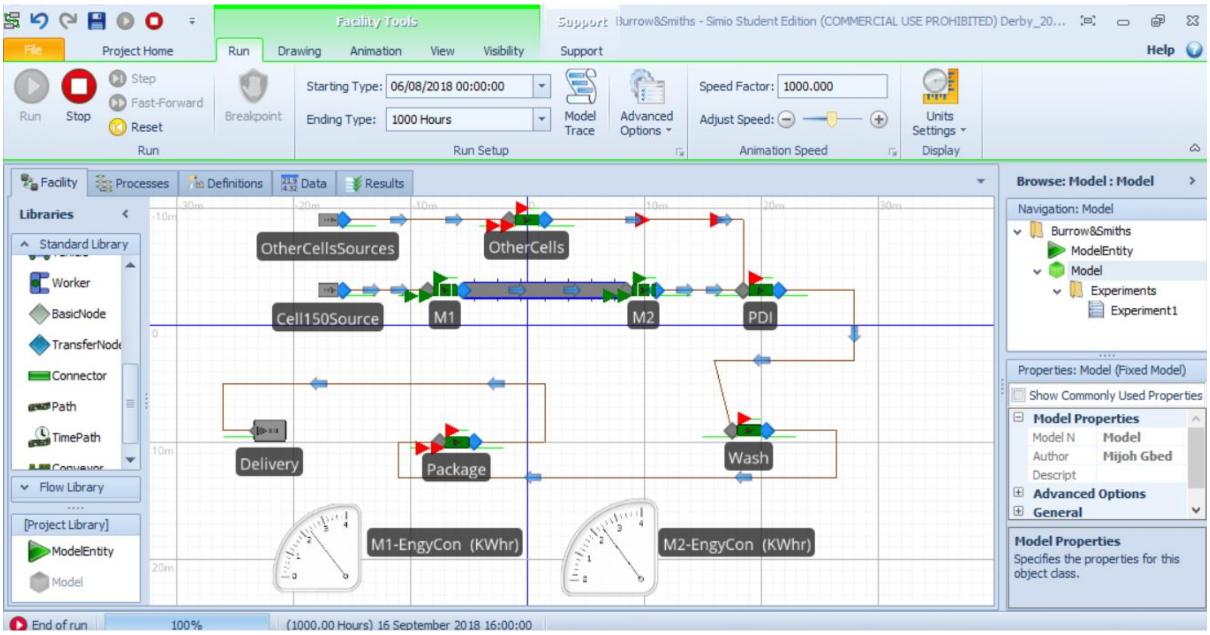


*Figure 7-9 The 2D view of the initial simulation model for verification*



Starting Type: 06/08/2018 00:00:00

Ending Type: 1000 Hours

Speed Factor: 1000.000

Adjust Speed:

Model N Model

Author Mijoh Gbed

Descript

Model Properties
Specifies the properties for this object class.

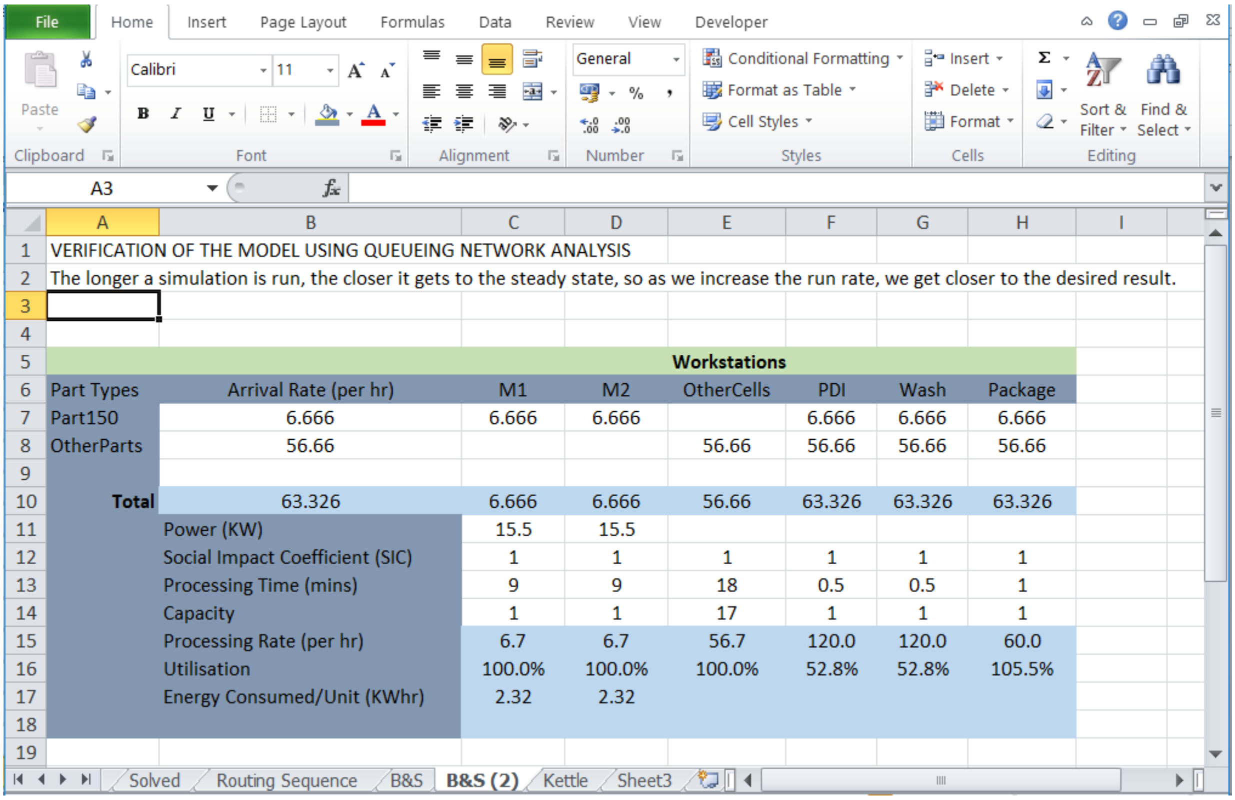
End of run 100% (1000.00 Hours) 16 September 2018 16:00:00

*Figure 7-10 The running of the initial simulation model on a Simio software*

### *Step II. Verification of initial simulation model using Static Queuing Model*

The purpose of the verification exercise is to ensure the simulation model is behaving as expected and to provide the opportunity to debug if the coding of the simulation software is not giving the expected results.

A static queuing model was developed using Microsoft Excel sheet. The Excel sheet was formatted for queuing network analysis with the same parameters as the simulation model. Figure 7-11 is the caption of the developed queuing static model.



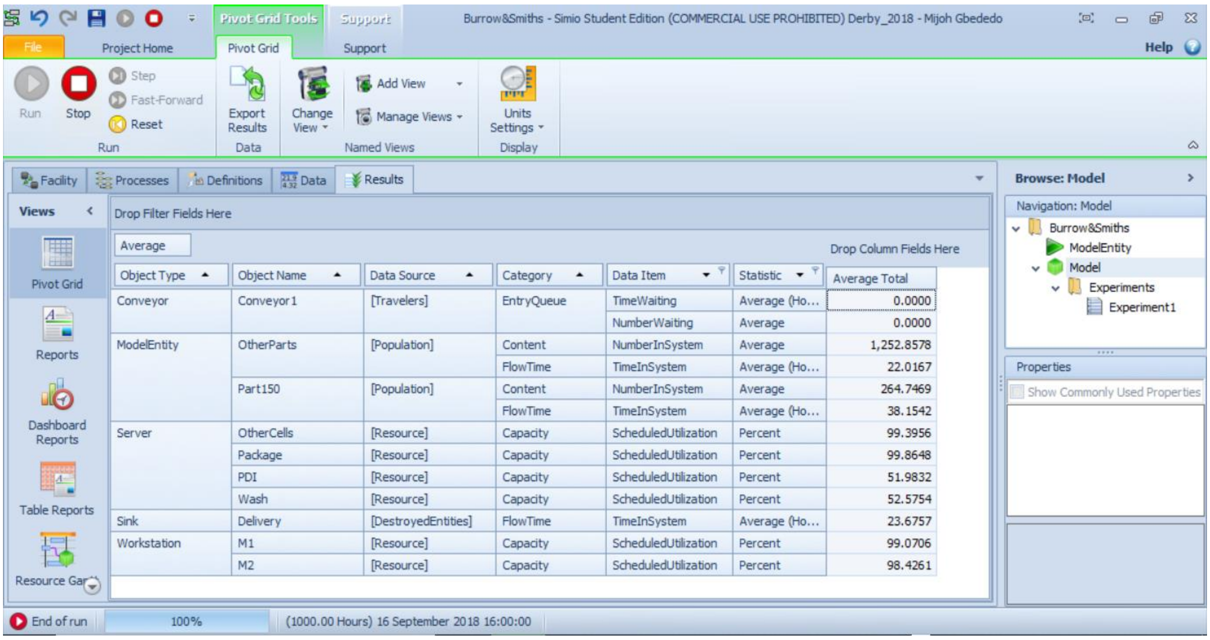
VERIFICATION OF THE MODEL USING QUEUEING NETWORK ANALYSIS

The longer a simulation is run, the closer it gets to the steady state, so as we increase the run rate, we get closer to the desired result.

| | | Workstations | | | | | |
|---|---|---|---|---|---|---|---|
| Part Types | Arrival Rate (per hr) | M1 | M2 | OtherCells | PDI | Wash | Package |
| Part150 | 6.666 | 6.666 | 6.666 | | 6.666 | 6.666 | 6.666 |
| OtherParts | 56.66 | | | 56.66 | 56.66 | 56.66 | 56.66 |
| | | | | | | | |
| Total | 63.326 | 6.666 | 6.666 | 56.66 | 63.326 | 63.326 | 63.326 |
| | Power (KW) | 15.5 | 15.5 | | | | |
| | Social Impact Coefficient (SIC) | 1 | 1 | 1 | 1 | 1 | 1 |
| | Processing Time (mins) | 9 | 9 | 18 | 0.5 | 0.5 | 1 |
| | Capacity | 1 | 1 | 17 | 1 | 1 | 1 |
| | Processing Rate (per hr) | 6.7 | 6.7 | 56.7 | 120.0 | 120.0 | 60.0 |
| | Utilisation | 100.0% | 100.0% | 100.0% | 52.8% | 52.8% | 105.5% |
| | Energy Consumed/Unit (KWhr) | 2.32 | 2.32 | | | | |

*Figure 7-11 Queuing static model for verification of the simulation model*

***Comparing the Simulation Model result with Queuing Model Result*** **-** The results of the simulation model run is similar to the static queuing model results as shown on the pivot grid table Figure 7-12.

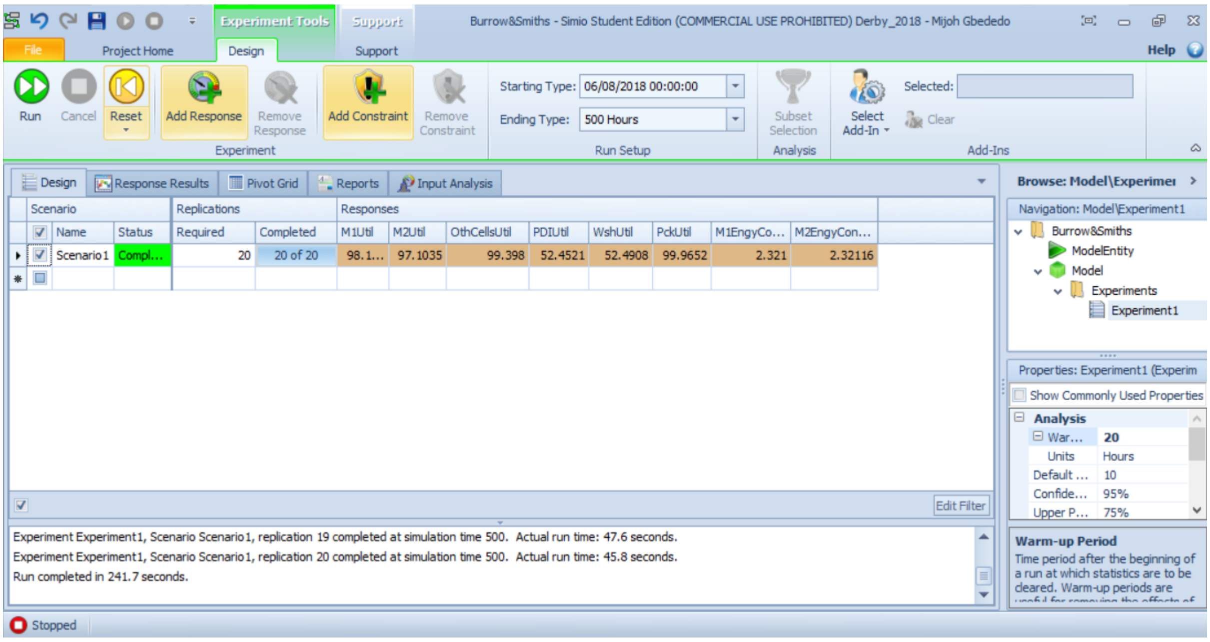


| Object Type | Object Name | Data Source | Category | Data Item | Statistic | Average Total |
|---|---|---|---|---|---|---|
| Conveyor | Conveyor1 | [Travelers] | EntryQueue | TimeWaiting | Average (Ho… | 0.0000 |
| | | | | NumberWaiting | Average | 0.0000 |
| ModelEntity | OtherParts | [Population] | Content | NumberInSystem | Average | 1,252.8578 |
| | | | FlowTime | TimeInSystem | Average (Ho… | 22.0167 |
| | Part150 | [Population] | Content | NumberInSystem | Average | 264.7469 |
| | | | FlowTime | TimeInSystem | Average (Ho… | 38.1542 |
| Server | OtherCells | [Resource] | Capacity | ScheduledUtilization | Percent | 99.3956 |
| | Package | [Resource] | Capacity | ScheduledUtilization | Percent | 99.8648 |
| | PDI | [Resource] | Capacity | ScheduledUtilization | Percent | 51.9832 |
| | Wash | [Resource] | Capacity | ScheduledUtilization | Percent | 52.5754 |
| Sink | Delivery | [DestroyedEntities] | FlowTime | TimeInSystem | Average (Ho… | 23.6757 |
| Workstation | M1 | [Resource] | Capacity | ScheduledUtilization | Percent | 99.0706 |
| | M2 | [Resource] | Capacity | ScheduledUtilization | Percent | 98.4261 |

(1000.00 Hours) 16 September 2018 16:00:00

Figure 7-12 Pivot grid result of a 1000 hours simulation model run

Further, the results of the simulation model run experiments at 500 hours and 1000 hours are also shown in Figures 7-13 and Figure 7-14 respectively. These indicate that the longer the simulation is run, the closer the expected results obtained on the static queuing model. Hence, it can be confirmed that the simulation model coded in Figure 7-10 works as expected.



Starting Type: 06/08/2018 00:00:00

Ending Type: 500 Hours

| Scenario | | | Replications | | Responses | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ☑ | Name | Status | Required | Completed | M1Util | M2Util | OthCellsUtil | PDIUtil | WshUtil | PckUtil | M1EngyCo… | M2EngyCon… |
| ☑ | Scenario1 | Compl… | 20 | 20 of 20 | 98.1… | 97.1035 | 99.398 | 52.4521 | 52.4908 | 99.9652 | 2.321 | 2.32116 |
| ☐ | | | | | | | | | | | | |

Analysis

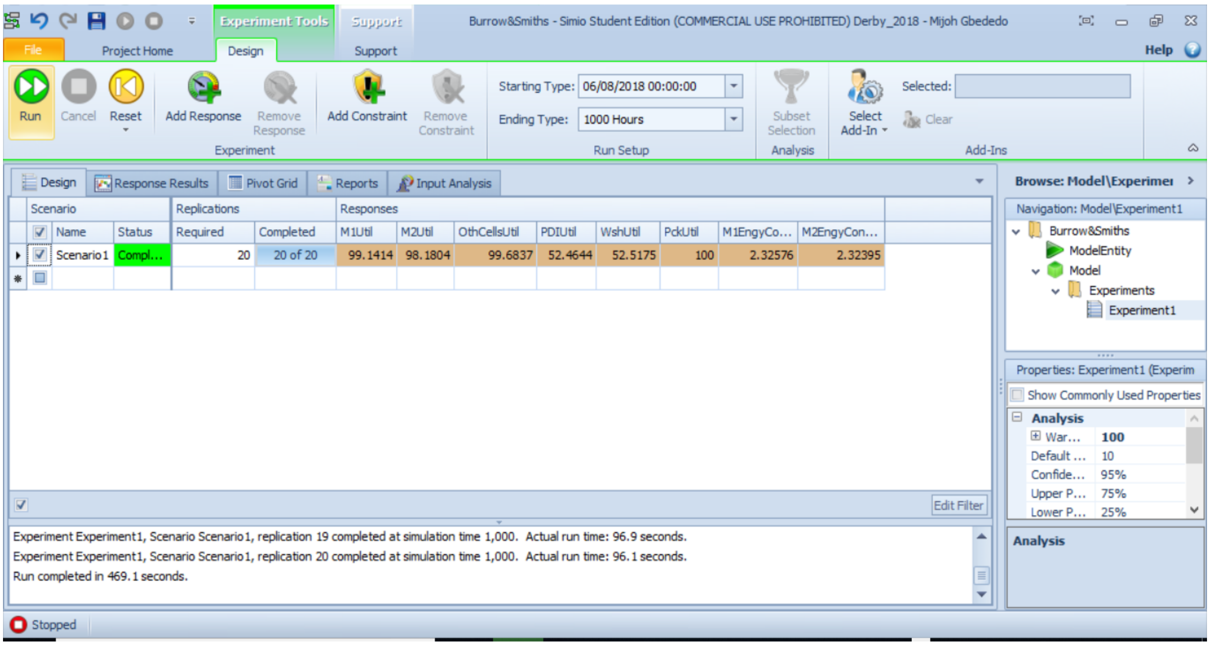
| | |
|---|---|
| War… | 20 |
| Units | Hours |
| Default … | 10 |
| Confide… | 95% |
| Upper P… | 75% |

**Warm-up Period**

Time period after the beginning of a run at which statistics are to be cleared. Warm-up periods are

```
Experiment Experiment1, Scenario Scenario1, replication 19 completed at simulation time 500.  Actual run time: 47.6 seconds.
Experiment Experiment1, Scenario Scenario1, replication 20 completed at simulation time 500.  Actual run time: 45.8 seconds.
Run completed in 241.7 seconds.
```

Figure 7-13 Result of a 500 hours-run experiment for the verification of the simulation model



Starting Type: 06/08/2018 00:00:00

Ending Type: 1000 Hours

| Scenario | | | Replications | | Responses | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ☑ | Name | Status | Required | Completed | M1Util | M2Util | OthCellsUtil | PDIUtil | WshUtil | PckUtil | M1EngyCo... | M2EngyCon... |
| ☑ | Scenario1 | Compl... | 20 | 20 of 20 | 99.1414 | 98.1804 | 99.6837 | 52.4644 | 52.5175 | 100 | 2.32576 | 2.32395 |

| Analysis | |
|---|---|
| War... | 100 |
| Default ... | 10 |
| Confide... | 95% |
| Upper P... | 75% |
| Lower P... | 25% |

```
Experiment Experiment1, Scenario Scenario1, replication 19 completed at simulation time 1,000.  Actual run time: 96.9 seconds.
Experiment Experiment1, Scenario Scenario1, replication 20 completed at simulation time 1,000.  Actual run time: 96.1 seconds.
Run completed in 469.1 seconds.
```

*Figure 7-14 Result of a 1000 hours-run experiment for the verification of the simulation model*

The static queuing model energy consumption results are also compared with the results of the real-time energy monitoring panel attached to the CNC machine M1 of Cell150. The results are very close to average power generated on load - 2.4KW and 3.3KW as shown in Figure 7-15.

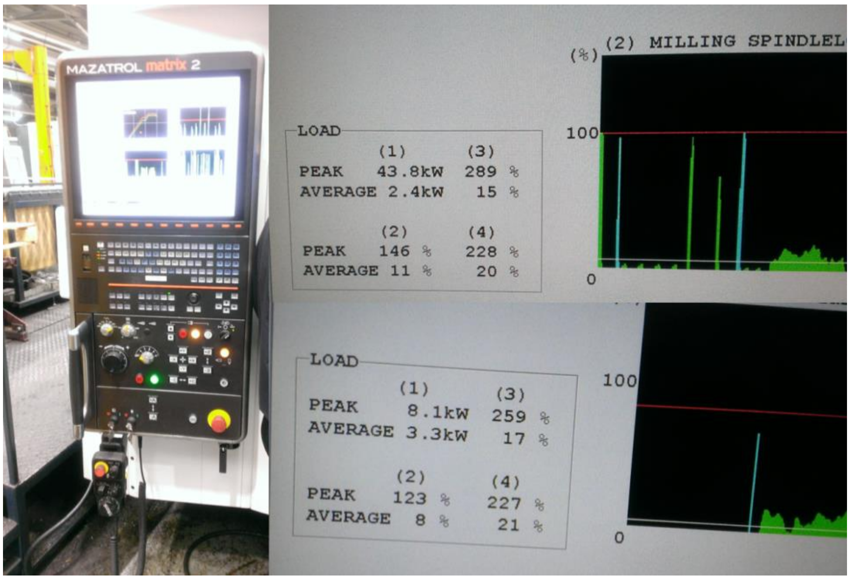


*Figure 7-15 Real-time energy consumption monitor of Mazak Variaxis i-800 CNC machine*

### *Step III: Update of the simulation input data with the actual probabilistic distribution parameters*

In this stage, having verified the simulation model with the static queuing model, the simulation objects were updated with the actual input parameters indicated in Table 7-4. This is to demonstrate the AS-IS state of the manufacturing production process.

*Table 7-4 Simulation model coding parameters*

| Object Type | Description | Coding | |
|---|---|---|---|
| **Server** | Other Cells | Expression (minutes) | Uniform(16.48, 19) |
| | PDI | | Triangular(.4,.5,.6) |
| | Wash | | Triangular(.4,.5,.6) |
| | Package | | Triangular(.8, 1, 1.2) |
| **Workstation** | M1 | | Random(8.24, 9.5) |
| | M2 | | Random(8.24, 9.5) |
| **Source** | Other Cells Sources | Arrival mode: Triggered by event | Output@OtherCells.Exited |
| | Cell150 Source | | Output@M1.Exited |
| **Workers** | Labour | Secondary resources for: | Wash and Package |
| | Operator | | M1, M2, and PD1 |
| | | Load and Offload Times (minutes) | M1 and M2<br>Triangular( .48, .62, .76) |
| **Vehicles** | Forklift1 | Transferred node transport logic: True | Other cells and M2 |
| | Forklift2 | | PDI and Wash |
| **Model Entity** | Other Parts | Initial Capacity | 17 |
| | Part 150 | | 1 |
| **Sink** | Delivery Other Part | | |
| | Delivery Part 150 | | |

The delivery of Part150 is separated from the Other Parts delivery in order to account for the activities of Part150 relatively to Other Parts in the system.

In order to achieve this, the following procedures were taken:

i) A new *Integer state* for the finished parts of Cell150 named *“FinPart150”* was created and a state assignment was configured at the machine M2 to increment the new “ModelEntity.FinPart150” by 1 before a work-piece exit the output of M2.

ii) A tally element “NumOfFinPart150” was created on the Model in order to record the tally statistics of the “ModelEntity.FinPart150” as it enters the input buffer of the “Delivery Part150”.

iii) The selection weight of the “Path” from “Package” to “Delivery Part150” was configured to “ModelEntity.FinPart150 = =1” while the selection weight of the “Path” from “Package” to the “Delivery Other Parts” was configured to “ModelEntity.FinPart150 < 1”. With these configurations, only finished parts from Cell150 are delivered to the “Part150 Delivery”. Figure 7-16 shows a 2D view of the updated simulation model.

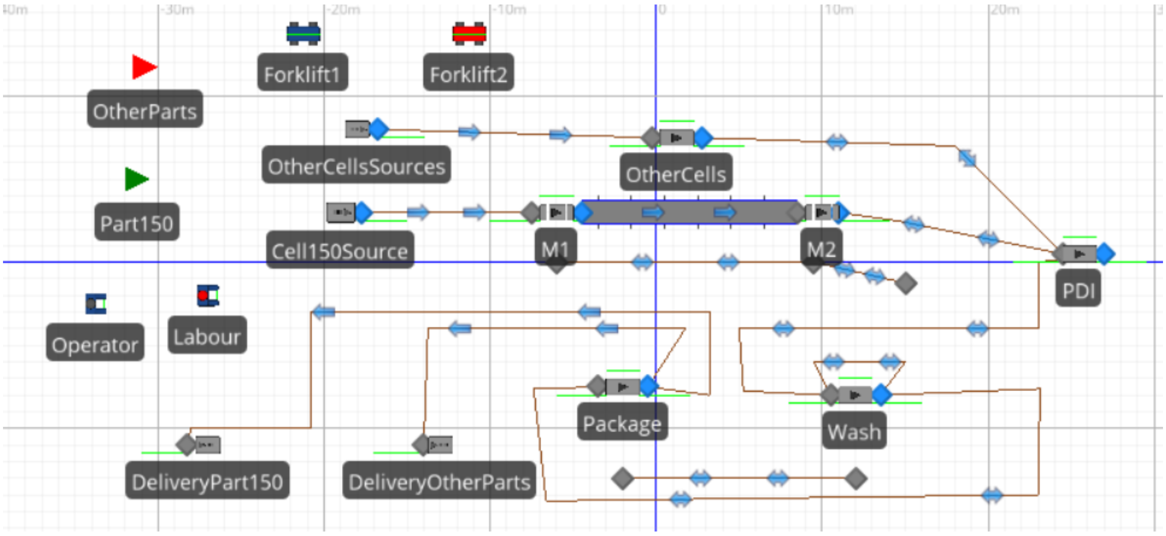


*Figure 7-16 A 2D view of the updated simulation model*

The advanced coding expressions for each of the sub-category indicators or simulation responses are shown in Table 7-5. The expressions were used to determine the current status of the BSL manufacturing process and were varied to investigate the behaviour of the system in the following experimentation sections.

*Table 7-5 Simulation model coding expressions for experimenting*

| **Response Descriptions** | **Display name** | **Coding Expression** |
|---|---|---|
| M1 Utilisation (%) | M1Util | M1.Capacity.ScheduledUtilization |
| M2 Utilisation (%) | M2Util | M2.Capacity.ScheduledUtilization |
| M1 Energy Consumed per unit (kWh/Unit) | M1EC | 15.5 * (Run.TimeNow - Run.WarmUpPeriod) * (M1.Capacity.ScheduledUtilization) / (100 * (M2.InputBuffer.NumberEntered)) |
| M2 Energy Consumed per unit (kWh/Unit) | M2EC | 15.5 * (Run.TimeNow - Run.WarmUpPeriod) * (M2.Capacity.ScheduledUtilization) / (100 * (M2.OutputBuffer.NumberEntered)) |
| Total Energy Consumed per unit (kWh/Unit) | TotalEC | 15.5 * (Run.TimeNow - Run.WarmUpPeriod) * (M1.Capacity.ScheduledUtilization) / (100 * (M2.InputBuffer.NumberEntered)) + 15.5 * (Run.TimeNow - Run.WarmUpPeriod) * (M2.Capacity.ScheduledUtilization) / (100 * (M2.OutputBuffer.NumberEntered)) |
| PDI Utilisation (%) | PDIUtil | PDI.Capacity.ScheduledUtilization |
| Wash Utilisation (%) | WshUtil | Wash.Capacity.ScheduledUtilization |
| Package Utilisation (%) | PkgUtil | Package.Capacity.ScheduledUtilization |
| Throughput of Part 150 | Thruput150 | DeliveryPart150.InputBuffer.NumberEntered / (Run.TimeNow - Run.WarmUpPeriod) |
| System Stability (%) | SysStablity | (DeliveryPart150.InputBuffer.NumberEntered / (M2.OutputBuffer.NumberEntered)) * 100 |

The results of the current sustainability state of the BSL manufacturing production process is captured in Table 7-6. The total energy consumption per unit is 5.5kWh/unit. The throughput per hour is calculated to be in the average of 3.8 units, and the system stability is within 89.54%. The system stability accounts for the Work-In-Progress (WIP) and the effectiveness of the Lean green techniques in reducing “wastes”. Hence, the Lean-green or stability of the system is determined by the system stability percentage.

*Table 7-6 The result of the AS-IS state of the BSL manufacturing production process*

| Sub-Category Indicators | AS-IS Results |
|---|---|
| SIC | 0.7 |
| M1 Energy Consumed/unit (kWh/unit) | 2.750 |
| M2 Energy Consumed/unit (kWh/unit) | 2.740 |
| Total Energy Consumed/unit (kWh/unit) | 5.500 |
| Throughput | 3.819 |
| System Stability (output/input) (%) | 89.54 |
| Input/Output Buffer Capacities | 30 |

### *Step IV: Sustainability Impact Analysis and Simulation model Experiments*

In this stage, the simulation experiments are performed to examine the interdependencies of three sustainability dimensions and to determine the preferred optimal option of the combination of the three.

The experiment is carried out based on the following stated simulation modelling objectives, decision variables and constraints. This is also graphically demonstrated in Figure 7-17.

***Defined Simulation Objectives:***

a. Maximise throughput
b. Minimise energy consumption
c. Ensure workers' satisfaction

***Identified Decision Variables:***

a. Buffers' capacity (Experiment 1)
b. Social Impact Coefficient (SIC) (Experiment 2)
c. Numbers of workers (Experiment 3)
d. Processing rate or efficiency

***Defined Constraint:***

a. System stability- This could be ensured by controlling any of the following:
   i. Number of Parts in System
   ii. Time in System
   iii. WIP
   iv. The ratio of Parts exited to Parts created

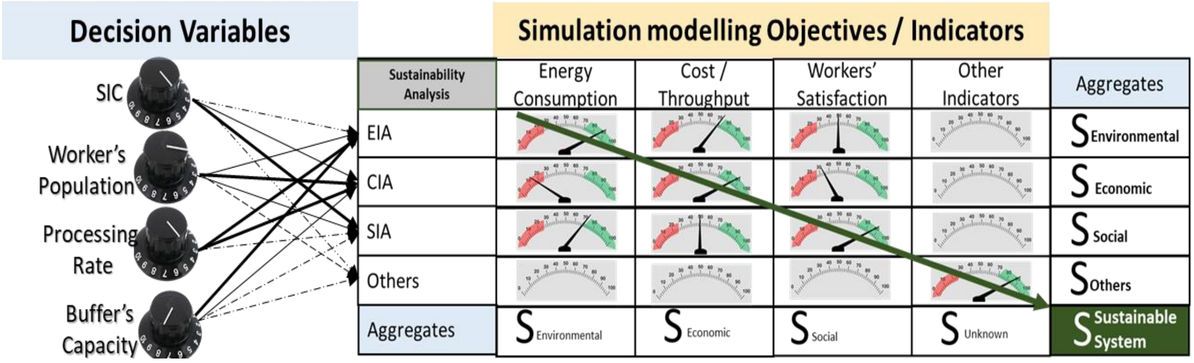


*Figure 7-17 Concept diagram of the simulation-based sustainability impact analysis*

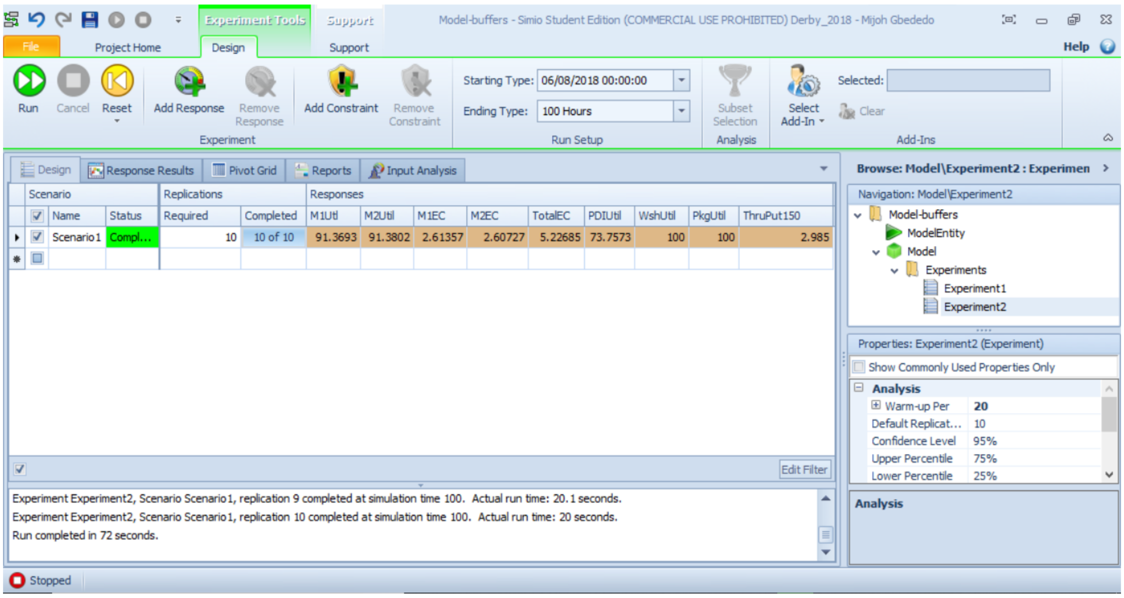
**Experiment 1:** *The impact of varying the buffer capacity on the sustainability aspects*

The BSL practices lean manufacturing techniques and have optimised its buffer capacity based on the constraints of the forklifts (transport) capacity. Hence, this was not an issue with the current model. However, to confirm the impact of different levels of the buffer capacity on the system's performance, the input and output buffer capacities were experimented with the corresponding transport capacities.

***Results and Interpretation of Experiment 1:***

The experiments were carried out to examine the impact of varying the buffer capacities at the input and output of each of the processing cells (work-stations) on the energy consumption and throughput.

The first experiment at this stage was carried out to examine the impact of having unlimited buffer capacities at the input and output of the cells. Figure 7-18 shows the result of the response table at a 100 hours run. The graphical representation of the relationship between the energy consumption and the throughput is also depicted in Figure 7-19.



Starting Type: 06/08/2018 00:00:00

Ending Type: 100 Hours

| Scenario | | | Replications | | Responses | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ☑ | Name | Status | Required | Completed | M1Utl | M2Util | M1EC | M2EC | TotalEC | PDIUtil | WshUtil | PkgUtil | ThruPut150 |
| ☑ | Scenario1 | Compl... | 10 | 10 of 10 | 91.3693 | 91.3802 | 2.61357 | 2.60727 | 5.22685 | 73.7573 | 100 | 100 | 2.985 |

Warm-up Per 20
Default Replicat... 10
Confidence Level 95%
Upper Percentile 75%
Lower Percentile 25%

```
Experiment Experiment2, Scenario Scenario1, replication 9 completed at simulation time 100.  Actual run time: 20.1 seconds.
Experiment Experiment2, Scenario Scenario1, replication 10 completed at simulation time 100.  Actual run time: 20 seconds.
Run completed in 72 seconds.
```

*Figure 7-18 Experiment 1 response view for i/o buffer capacities = infinity*

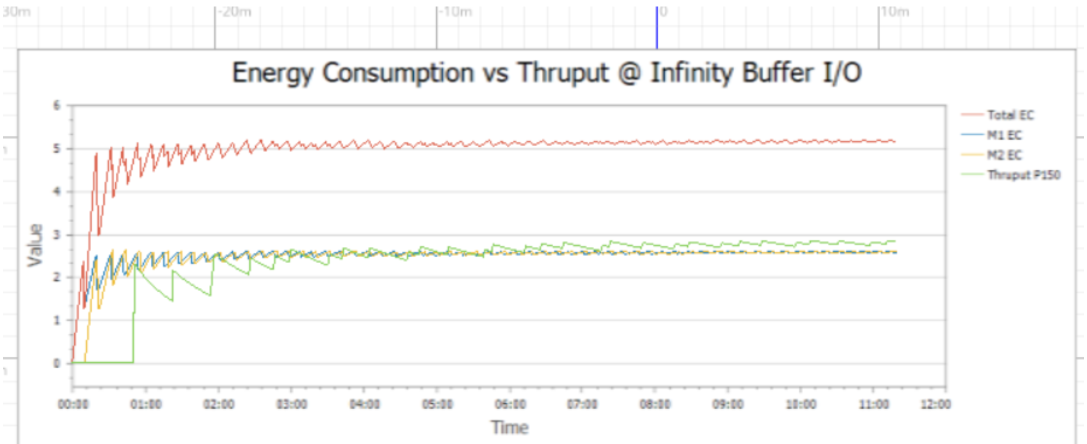


*Figure 7-19 Graph showing energy consumption vs throughput at infinite i/o buffer capacities*

The input-output (i/o) buffer capacities experiment were then carried out for equal i/o buffer and transport capacities. The results are summarised in Table 7-7 below.

The results indicate an increase in the throughput from the capacity of 20 to 50. The energy consumption is affected but not in a consistent manner. This may be due to the system stability which is influenced by the number of items in the system, the WIP levels or the ratio of the percentage of the number of items exited the system to the number of the items created. The succeeding experiments will help to examine these multi-objective requirements.

*Table 7-7 Summary of experiment 1 responses*

| **Experiment Responses** | **Equal Transport and I/O Buffer Capacity** | | | | | |
|---|---|---|---|---|---|---|
| **Cell150** | 0 | 20 | 30 | 40 | 50 | Infinity |
| M1 Energy Consumed/unit (kWh/unit) | 0 | 2.620 | 2.619 | 2.618 | 2.616 | 2.614 |
| M2 Energy Consumed/unit (kWh/unit) | 0 | 2.602 | 2.605 | 2.606 | 2.603 | 2.607 |
| Total Energy Consumed/unit (kWh/unit) | 0 | 5.232 | 5.233 | 5.232 | 5.269 | 5.227 |
| Throughput | 0 | 3.313 | 4.069 | 4.218 | 4.237 | 2.985 |

The BSL works with “Transports” (forklifts) which has the maximum capacity of 30. Hence, the input/output buffer capacities of the workstations are set to 30 as the standard for the rest of the experiments. Figure 7-20 shows the graphical relationship between the energy consumption and the throughput for buffer capacities of 30. The corresponding response table for the experiment is shown in Figure 7-21.

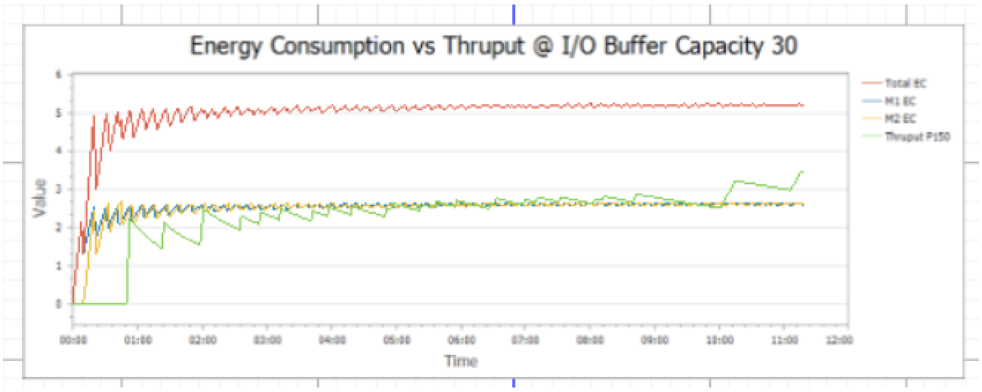
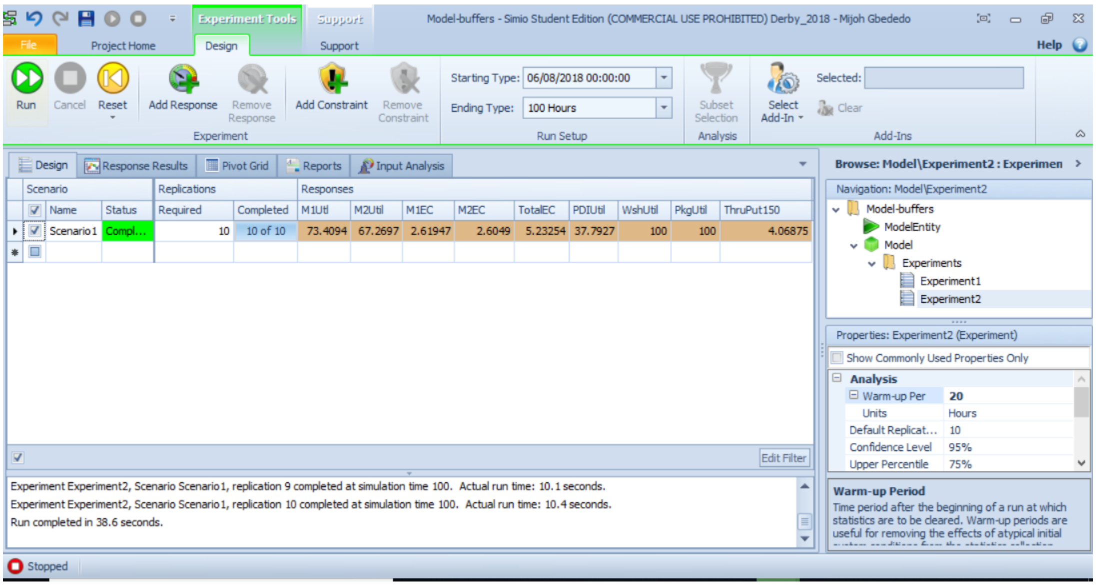


*Figure 7-20 Graph showing energy consumption vs throughput at i/o buffer capacity = 30*



Starting Type: 06/08/2018 00:00:00

Ending Type: 100 Hours

| Scenario | | | Replications | | Responses | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ☑ | Name | Status | Required | Completed | M1Utl | M2Util | M1EC | M2EC | TotalEC | PDIUtil | WshUtil | PkgUtil | ThruPut150 |
| ☑ | Scenario1 | Compl... | 10 | 10 of 10 | 73.4094 | 67.2697 | 2.61947 | 2.6049 | 5.23254 | 37.7927 | 100 | 100 | 4.06875 |
| ☐ | | | | | | | | | | | | | |

```
Experiment Experiment2, Scenario Scenario1, replication 9 completed at simulation time 100.  Actual run time: 10.1 seconds.
Experiment Experiment2, Scenario Scenario1, replication 10 completed at simulation time 100.  Actual run time: 10.4 seconds.
Run completed in 38.6 seconds.
```

| | |
|---|---|
| Warm-up Per | 20 |
| Units | Hours |
| Default Replicat... | 10 |
| Confidence Level | 95% |
| Upper Percentile | 75% |

**Warm-up Period**
Time period after the beginning of a run at which statistics are to be cleared. Warm-up periods are useful for removing the effects of atypical initial

*Figure 7-21 Experiment 1- response view for i/o buffer capacities = 30*

**Experiment 2:** *The impact of varying the Social Impact Coefficient (SIC) on other sustainability aspects.*

The social impact coefficient of BSL was estimated at 0.7 as discussed in (section 7.3.3.3-iii). This implies BSL has the opportunity to increase her SIC from 0.7 to 1.0 by improving on the workers' motivation. The activities to increase SIC may include improving workers welfare packages, improving and increasing the onsite amenities, and training of workers. The impact of these activities and the SIC on other sustainability dimensions is examined by varying the value of SIC in this simulation experiment.

***Results and Interpretation of Experiment 2:***

The results of the impact of SIC on other sustainability aspects are summarised in Table 7-8 below. The result indicates that the value of the SIC influences the energy consumption and throughput. The throughput and the system stability increases as the value of the SIC increases. For example; for SIC = 0.7, the throughput was 3.819, and the system stability was 89.54%, whereas, when the SIC = 1.0, the throughput increased to 4.080 and the system becomes more stable at 91.02%.

*Table 7-8 Experiment 2 responses*

| **Cell 150 Experiment Responses** | **Social Impact Coefficients (SIC) Values** | | | |
|---|---|---|---|---|
| | **0.7** | **0.8** | **0.9** | **1.0** |
| M1 Energy Consumed/unit (kWh/unit) | 2.750 | 2.700 | 2.654 | 2.619 |
| M2 Energy Consumed/unit (kWh/unit) | 2.740 | 2.685 | 2.640 | 2.606 |
| Total Energy Consumed/unit (kWh/unit) | 5.500 | 5.390 | 5.302 | 5.232 |
| Throughput | 3.819 | 3.855 | 4.000 | 4.080 |
| System Stability (output/input) (%) | 89.54 | 90.71 | 90.48 | 91.02 |

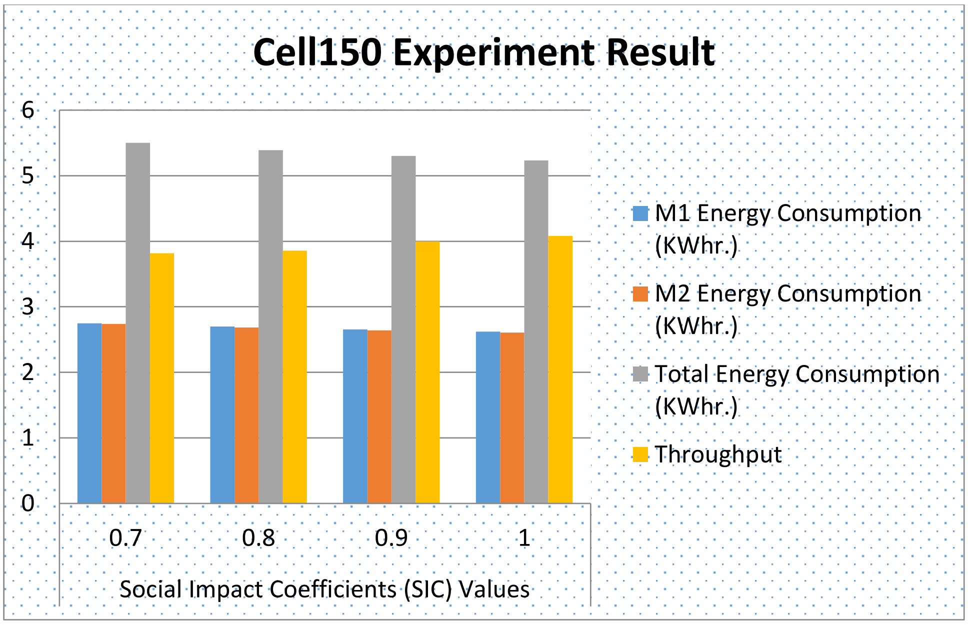


*Figure 7-22 Relationships between sic, energy consumption and throughput*

It was also observed that the SIC influences the energy consumption and throughput; the higher the SIC, the lower the energy consumption and the higher the throughput Figure 7-22. The comparison of the graphs shown in Figure 7-23 and Figure 7-24 shows that the energy consumption of M1 and M2 decreases as the SIC increased from 0.7 to 1.0. The experiment indicates that BSL can increase its throughput and at the same time reduces its energy consumption by engaging in initiatives that can increase the organisation workers' social impact coefficient.

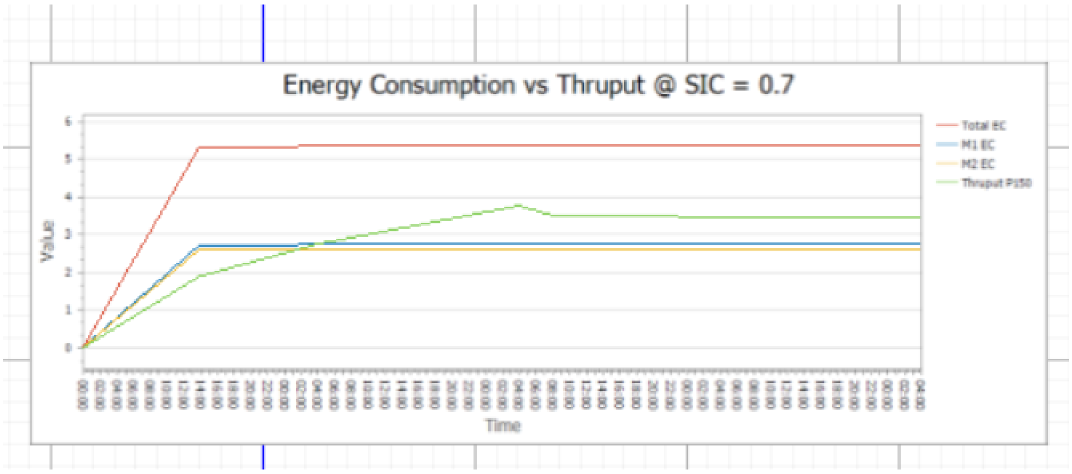


*Figure 7-23 Relationship between energy consumption and throughput at SIC = 0.7*

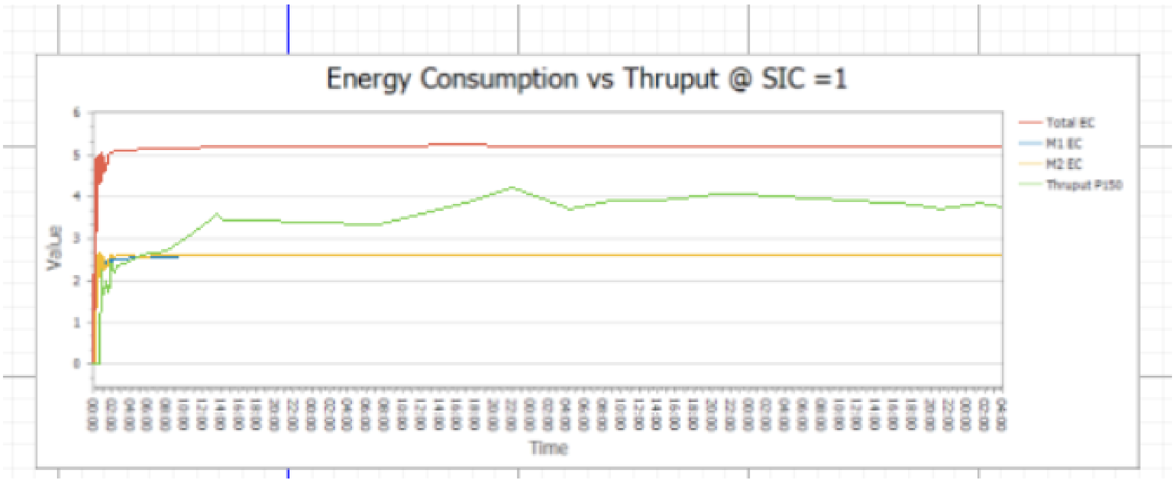
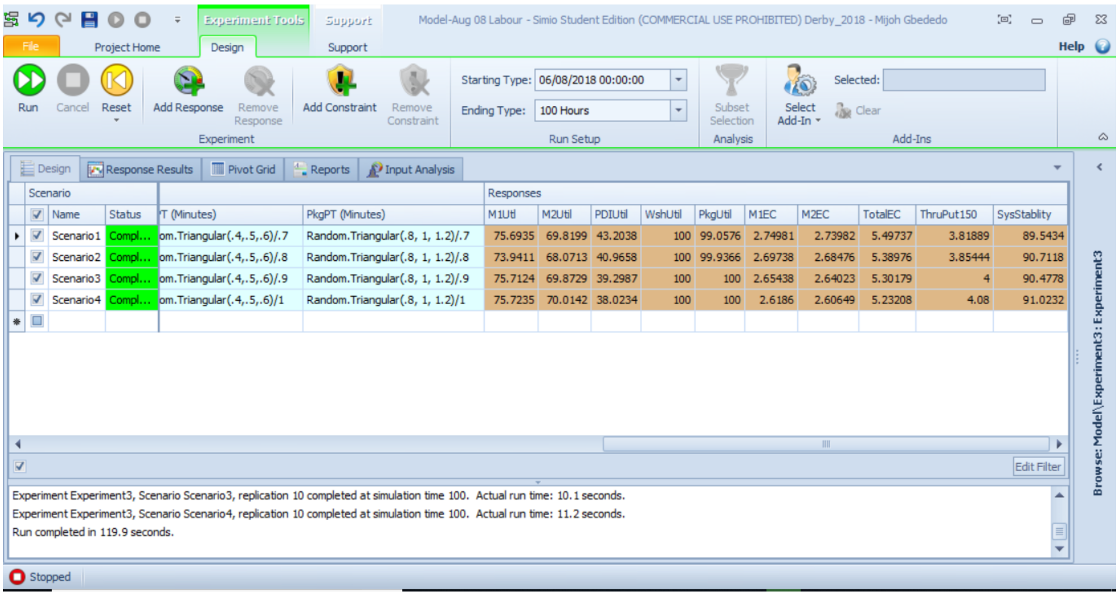


*Figure 7-24 Relationship between energy consumption and throughput at SIC = 1*

The impact of the SIC on the other aspects such as the processing rate and resource utilisation is shown in the Figure 7-25. It can be seen in the response table that the resources at Wash (WshUtil) and Package (PkgUtil) are being over utilised and the preceding resources such as M1 (M1Util), M2 (M2Util) and PDI (PDIUtil) are underutilised. The effect can be read from the pivot grid, indicating blockage from the Wash and Package. This effect is investigated in the next experiment by increasing the number of workers at the Wash and Package. Figure 7-26 is 2D of a simulation run showing the accumulation of parts at the PDI and Wash stations. The Wash and Package stations are also seen to be idle at this instance indicating overuse of resources and the likely cause of the blockage.



Starting Type: 06/08/2018 00:00:00

Ending Type: 100 Hours

Selected:

| | Scenario | | | | Responses | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ☑ | Name | Status | 'T (Minutes) | PkgPT (Minutes) | M1Utl | M2Util | PDIUtil | WshUtil | PkgUtil | M1EC | M2EC | TotalEC | ThruPut150 | SysStablity |
| ☑ | Scenario1 | Compl... | om.Triangular(.4,.5,.6)/.7 | Random.Triangular(.8, 1, 1.2)/.7 | 75.6935 | 69.8199 | 43.2038 | 100 | 99.0576 | 2.74981 | 2.73982 | 5.49737 | 3.81889 | 89.5434 |
| ☑ | Scenario2 | Compl... | om.Triangular(.4,.5,.6)/.8 | Random.Triangular(.8, 1, 1.2)/.8 | 73.9411 | 68.0713 | 40.9658 | 100 | 99.9366 | 2.69738 | 2.68476 | 5.38976 | 3.85444 | 90.7118 |
| ☑ | Scenario3 | Compl... | om.Triangular(.4,.5,.6)/.9 | Random.Triangular(.8, 1, 1.2)/.9 | 75.7124 | 69.8729 | 39.2987 | 100 | 100 | 2.65438 | 2.64023 | 5.30179 | 4 | 90.4778 |
| ☑ | Scenario4 | Compl... | om.Triangular(.4,.5,.6)/1 | Random.Triangular(.8, 1, 1.2)/1 | 75.7235 | 70.0142 | 38.0234 | 100 | 100 | 2.6186 | 2.60649 | 5.23208 | 4.08 | 91.0232 |
| ☐ | | | | | | | | | | | | | | |

```
Experiment Experiment3, Scenario Scenario3, replication 10 completed at simulation time 100.  Actual run time: 10.1 seconds.
Experiment Experiment3, Scenario Scenario4, replication 10 completed at simulation time 100.  Actual run time: 11.2 seconds.
Run completed in 119.9 seconds.
```

*Figure 7-25 Experiment 2 response showing impacts of SIC on different sustainability aspects*

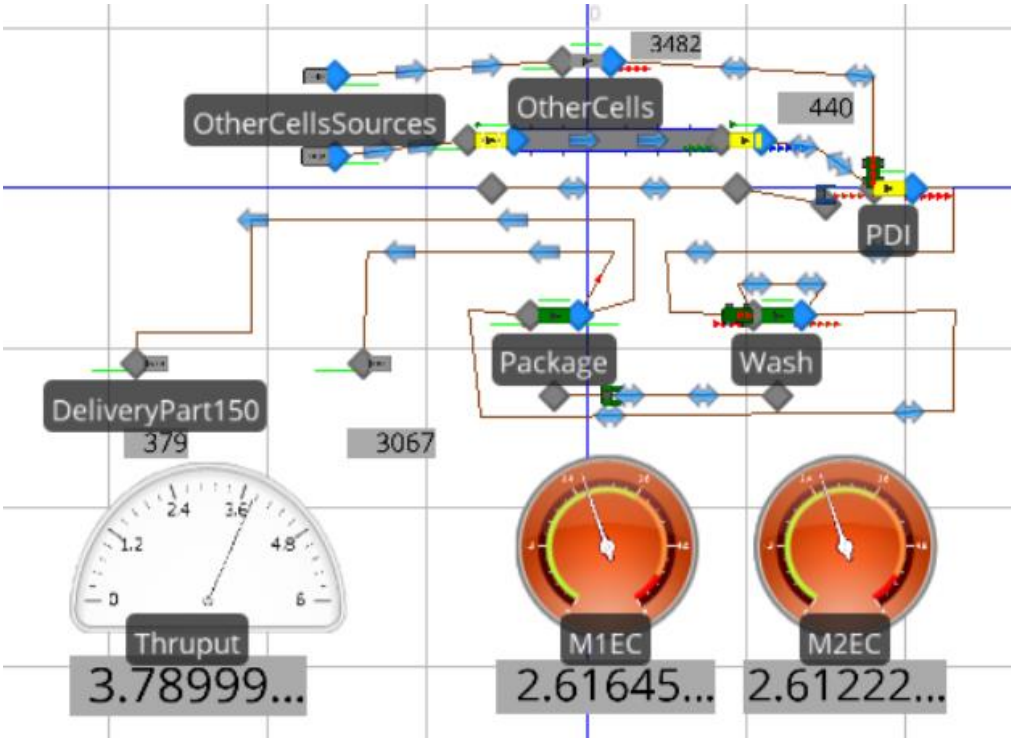


*Figure 7-26 Simulation model showing accumulation of parts at the station during a run*

**Experiment3:** *The impact of varying the population of workers on the sustainability aspects*

The result of experiment 2 indicates an opportunity to improve on the throughput based on one of the objectives of the case study. This experiment is performed by varying the numbers of workers in the system. Particular interest was placed on the worker “Labour” due to the overutilisation of the resources at the Wash and Package as indicated in the response table of experiment 2.

***Results and Interpretation of Experiment 3:***

The result of the experiment response shown in Table 7-9 and Figure 7-27 indicates an improvement both in the throughput and energy consumption when the population of the worker “labour” increased from 1 to 2. However, the system becomes less stable at 96.86%. Thus, the decision for the preferred option will require some trade-off. Increasing the workers’ population further does not have any additional effect as indicated on the table and Figure 7-28.

*Table 7-9 Summary of experiment 3 responses*

| **Experiment Responses**<br>**Cell 150** | **SIC=1; Operator = 1** | | |
| --- | --- | --- | --- |
| | **Population of Labour** | | |
| | 1 | 2 | 3 |
| M1 Utilisation (%) | 75.72 | 91.30 | 91.30 |
| M2 Utilisation (%) | 70.01 | 91.39 | 91.39 |
| PDI Utilisation (%) | 38.02 | 71.01 | 71.01 |
| Wash Utilisation (%) | 100 | 50.34 | 50.34 |
| Package Utilisation (%) | 100 | 100 | 100 |
| M1 Energy Consumed per unit (kWh/unit) | 2.619 | 2.612 | 2.612 |
| M2 Energy Consumed per unit (kWh/unit) | 2.606 | 2.613 | 2.613 |
| Total Energy Consumed per unit (kWh/unit) | 5.232 | 5.225 | 5.225 |
| Throughput | 4.080 | 5.251 | 5.251 |
| System Stability (output/input) (%) | 98.27 | 96.86 | 96.86 |

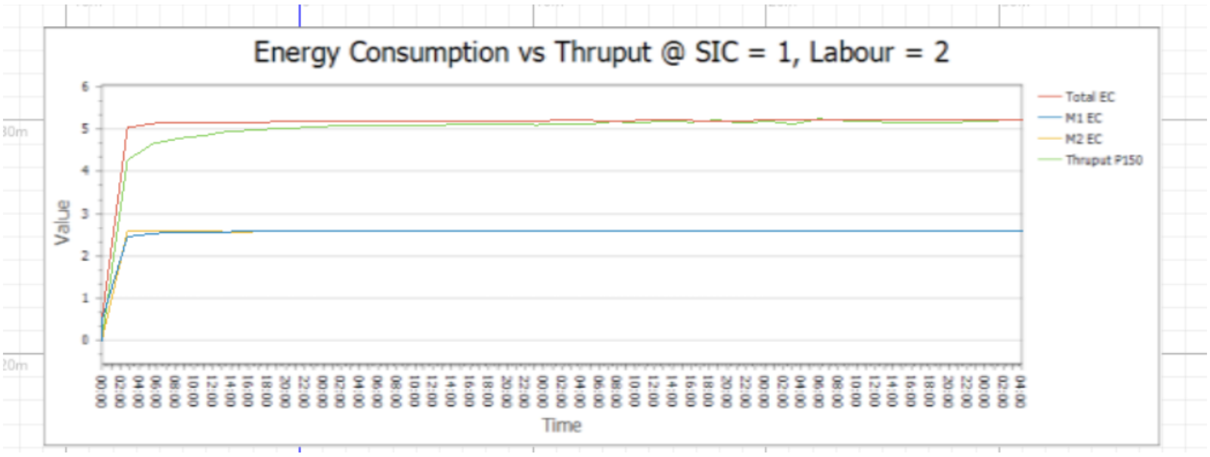
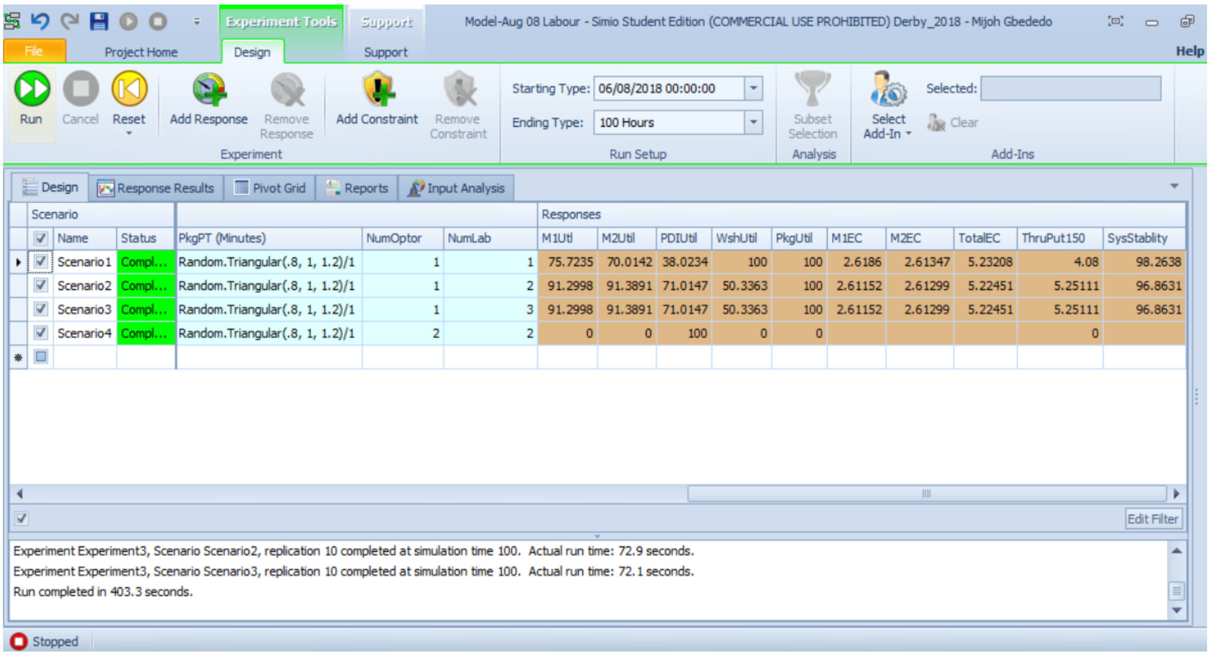


*Figure 7-27 Graph showing the impact of increasing workers' number on sustainability aspects*



Model-Aug 08 Labour - Simio Student Edition (COMMERCIAL USE PROHIBITED) Derby_2018 - Mijoh Gbededo

Starting Type: 06/08/2018 00:00:00

Ending Type: 100 Hours

| Scenario | | | | | | Responses | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ☑ | Name | Status | PkgPT (Minutes) | NumOptor | NumLab | M1Utl | M2Util | PDIUtil | WshUtil | PkgUtil | M1EC | M2EC | TotalEC | ThruPut150 | SysStablity |
| ☑ | Scenario1 | Compl... | Random.Triangular(.8, 1, 1.2)/1 | 1 | 1 | 75.7235 | 70.0142 | 38.0234 | 100 | 100 | 2.6186 | 2.61347 | 5.23208 | 4.08 | 98.2638 |
| ☑ | Scenario2 | Compl... | Random.Triangular(.8, 1, 1.2)/1 | 1 | 2 | 91.2998 | 91.3891 | 71.0147 | 50.3363 | 100 | 2.61152 | 2.61299 | 5.22451 | 5.25111 | 96.8631 |
| ☑ | Scenario3 | Compl... | Random.Triangular(.8, 1, 1.2)/1 | 1 | 3 | 91.2998 | 91.3891 | 71.0147 | 50.3363 | 100 | 2.61152 | 2.61299 | 5.22451 | 5.25111 | 96.8631 |
| ☑ | Scenario4 | Compl... | Random.Triangular(.8, 1, 1.2)/1 | 2 | 2 | 0 | 0 | 100 | 0 | 0 | | | | 0 | |

```
Experiment Experiment3, Scenario Scenario2, replication 10 completed at simulation time 100.  Actual run time: 72.9 seconds.
Experiment Experiment3, Scenario Scenario3, replication 10 completed at simulation time 100.  Actual run time: 72.1 seconds.
Run completed in 403.3 seconds.
```

*Figure 7-28 Experiment 3 response; the impacts of workers number on the sustainability aspects*

## E. **Response Evaluation**: *Trade-off and optimisation of the sustainability aspects*

The experiments 1, 2 and 3 demonstrate the interdependencies of the aspects of the three sustainability dimensions and have presented optimal values for each of the sustainability dimensions relative to the other dimensions.

The challenge of the multi-criteria objectives as demonstrated in the three experiments above can be resolved by multi-criteria decision analysis (MCDA) or other Multi-criteria analysis methods. Simio DES software provides a similar multi-criteria optimisation technique called "OptQuest" which is deployed as shown in the optimisation experiment below.

The aim is to presents the preferred-optimised option of the combinations of the aspects of the three sustainability dimensions under the defined conditions or constraint.

***Optimisation Experiment Parameters:***

The control variables are set to reference the population of the workers (operators and labours) in the system. The objective is to experiment with a combination of the workers as the decision variables for optimum throughput and energy consumption at SIC = 0.7 and SIC =1 and under minimum system stability of 95% as shown in Table 7-10.

*Table 7-10 Simio simulation OptQuest parameters for process optimisation*

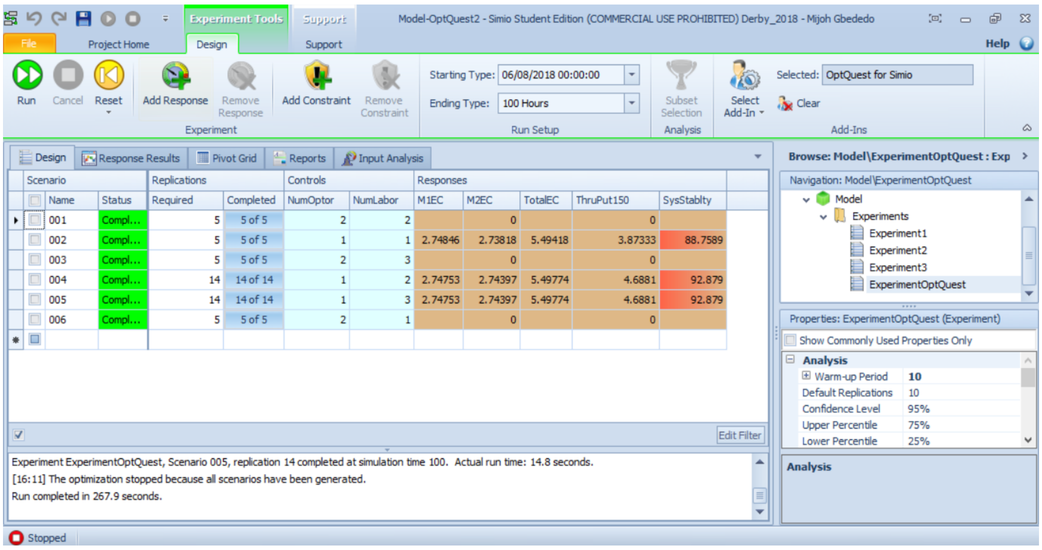
| Control Variables | Experiment Objectives | Parameters |
|---|---|---|
| Number of Operators (NumOptor) | Optimise | Range: 1 to 2 |
| Number of Labours (NumLabor) | Optimise | Range: 1 to 3 |

| Responses | Experiment Objectives | Parameters |
|---|---|---|
| M1 Energy Consumption (M1EC) | Minimise | No limit |
| M2 Energy Consumption (M2EC) | Minimise | No limit |
| Total Energy Consumption (TotalEC) | Minimise | No limit |
| Throughput (Thruput) | Maximise | No limit |
| System Stability (SysStablty) | Constraint | Minimum value: 95% |

***Results and Interpretation of the Optimisation Experiment 1:***

Each of the experiments was set to run for a maximum of 300 scenarios with minimum replications of 5 and maximum 20.

The result of the experiment for SIC = 0.7 is depicted in Figure 7-29 highlighting all the values of the possible energy consumption and throughput falls below the defined threshold of 95% system stability. The result shows the current state of BSL and the constraint the current value of SIC (0.7) places on the possible improvement.



Starting Type: 06/08/2018 00:00:00
Ending Type: 100 Hours
Selected: OptQuest for Simio

| Scenario | | Replications | | Controls | | Responses | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Name | Status | Required | Completed | NumOptor | NumLabor | M1EC | M2EC | TotalEC | ThruPut150 | SysStablty |
| 001 | Compl... | 5 | 5 of 5 | 2 | 2 | | 0 | | 0 | |
| 002 | Compl... | 5 | 5 of 5 | 1 | 1 | 2.74846 | 2.73818 | 5.49418 | 3.87333 | 88.7589 |
| 003 | Compl... | 5 | 5 of 5 | 2 | 3 | | 0 | | 0 | |
| 004 | Compl... | 14 | 14 of 14 | 1 | 2 | 2.74753 | 2.74397 | 5.49774 | 4.6881 | 92.879 |
| 005 | Compl... | 14 | 14 of 14 | 1 | 3 | 2.74753 | 2.74397 | 5.49774 | 4.6881 | 92.879 |
| 006 | Compl... | 5 | 5 of 5 | 2 | 1 | | 0 | | 0 | |

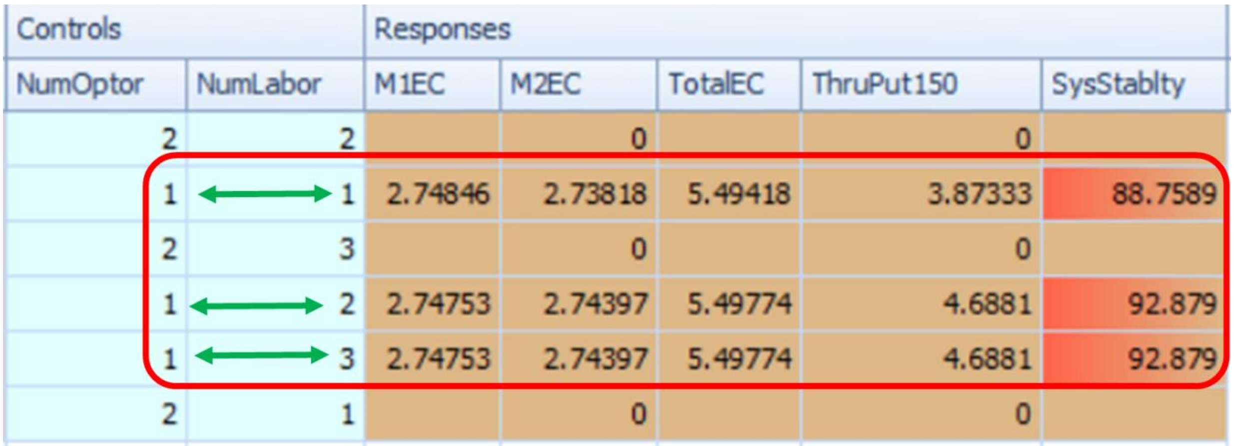
☐ Show Commonly Used Properties Only

| Analysis | |
|---|---|
| Warm-up Period | **10** |
| Default Replications | 10 |
| Confidence Level | 95% |
| Upper Percentile | 75% |
| Lower Percentile | 25% |

```
Experiment ExperimentOptQuest, Scenario 005, replication 14 completed at simulation time 100.  Actual run time: 14.8 seconds.
[16:11] The optimization stopped because all scenarios have been generated.
Run completed in 267.9 seconds.
```

*Figure 7-29 The result of Simio OptQuest multi-criteria optimisation experiment for SIC=0.7*

As shown in Figure 7-30 the combination of 1 "Operator" with 2 "Labours" can increase the throughput from 3.87 to 4.69. However, the total energy consumed per unit will increase from 5.494kWh/unit to 5.498kWh/unit and the system stability still falls below the specified 95%.

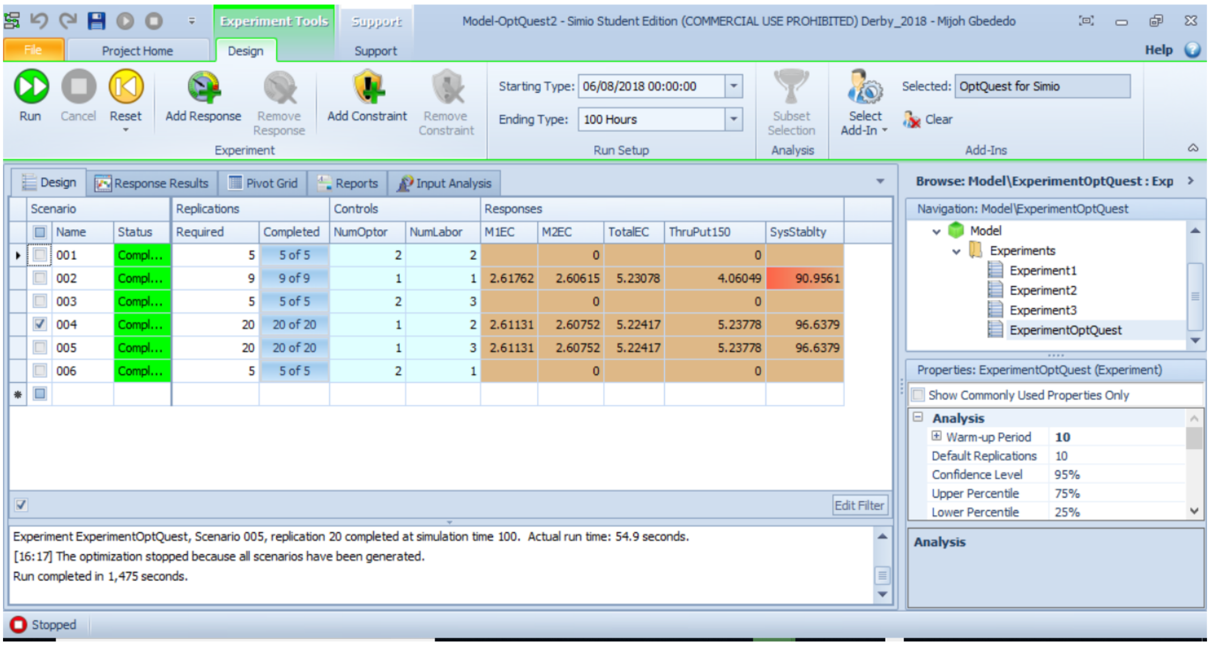


| Controls | | Responses | | | | |
|---|---|---|---|---|---|---|
| NumOptor | NumLabor | M1EC | M2EC | TotalEC | ThruPut150 | SysStablty |
| 2 | 2 | | 0 | | 0 | |
| 1 | 1 | 2.74846 | 2.73818 | 5.49418 | 3.87333 | 88.7589 |
| 2 | 3 | | 0 | | 0 | |
| 1 | 2 | 2.74753 | 2.74397 | 5.49774 | 4.6881 | 92.879 |
| 1 | 3 | 2.74753 | 2.74397 | 5.49774 | 4.6881 | 92.879 |
| 2 | 1 | | 0 | | 0 | |

*Figure 7-30 Multi-objectives optimisation result and possible options for SIC =0.7*

***Results and Interpretation of the Optimisation Experiment 2:***

The results of the second optimisation experiment for SIC = 1 is depicted in Figure 7-31 highlighting the value of possible energy consumption and throughput that falls below the threshold of 95% in the System stability column.



Starting Type: 06/08/2018 00:00:00

Ending Type: 100 Hours

Selected: OptQuest for Simio

| Scenario | | | Replications | | Controls | | Responses | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ☐ | Name | Status | Required | Completed | NumOptor | NumLabor | M1EC | M2EC | TotalEC | ThruPut150 | SysStablty |
| ☐ | 001 | Compl... | 5 | 5 of 5 | 2 | 2 | | 0 | | 0 | |
| ☐ | 002 | Compl... | 9 | 9 of 9 | 1 | 1 | 2.61762 | 2.60615 | 5.23078 | 4.06049 | 90.9561 |
| ☐ | 003 | Compl... | 5 | 5 of 5 | 2 | 3 | | 0 | | 0 | |
| ☑ | 004 | Compl... | 20 | 20 of 20 | 1 | 2 | 2.61131 | 2.60752 | 5.22417 | 5.23778 | 96.6379 |
| ☐ | 005 | Compl... | 20 | 20 of 20 | 1 | 3 | 2.61131 | 2.60752 | 5.22417 | 5.23778 | 96.6379 |
| ☐ | 006 | Compl... | 5 | 5 of 5 | 2 | 1 | | 0 | | 0 | |

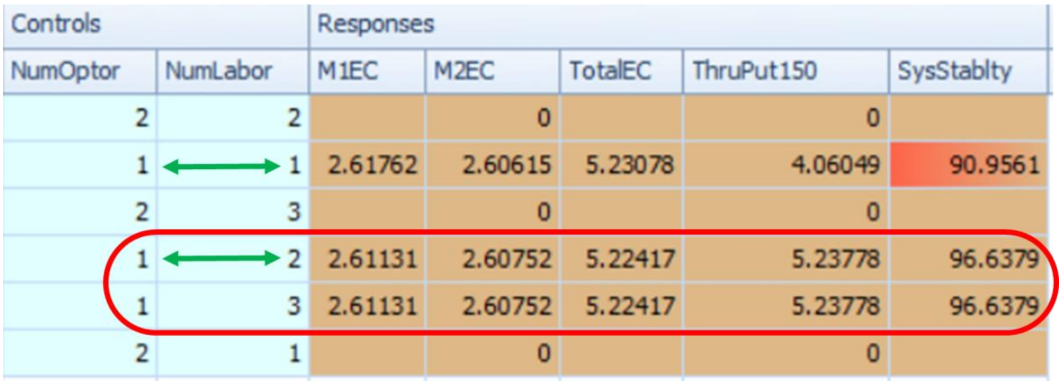
Experiment ExperimentOptQuest, Scenario 005, replication 20 completed at simulation time 100. Actual run time: 54.9 seconds.
[16:17] The optimization stopped because all scenarios have been generated.
Run completed in 1,475 seconds.

| Analysis | |
|---|---|
| Warm-up Period | 10 |
| Default Replications | 10 |
| Confidence Level | 95% |
| Upper Percentile | 75% |
| Lower Percentile | 25% |

*Figure 7-31 The result of Simio OptQuest multi-criteria optimisation experiment for SIC=1*

The result shows two options that meet the defined system stability of a minimum of 95% as in Figure 7-32. This provides the support for deciding for the configuration that would best serve the organisation’s goal and objectives. It is evident from the circled highlighted results that the responses are the same except for the numbers of the Labours which is 2 and 3 in each result but the same Operator’s number - 1. Hence, a combination of one operator and two labours will give the same throughput of 5.238 Units/h., total energy consumed per unit of 5.224kWh/unit with the system stability of 96.64%, as one operator and three labours.

However, the organisation may want to evaluate the cost of employing an additional worker (Labour) and opt for a lower throughput of 4.06 Units/h with the corresponding lower system stability of 90.96%. BSL can achieve this by improving on the SIC value of the current situation. It can also be noted that improving the level of SIC also reduced the energy consumption from 5.230KWh to 5.224KWh.



| Controls | | Responses | | | | |
|---|---|---|---|---|---|---|
| NumOptor | NumLabor | M1EC | M2EC | TotalEC | ThruPut150 | SysStablty |
| 2 | 2 | | 0 | | 0 | |
| 1 | 1 | 2.61762 | 2.60615 | 5.23078 | 4.06049 | 90.9561 |
| 2 | 3 | | 0 | | 0 | |
| 1 | 2 | 2.61131 | 2.60752 | 5.22417 | 5.23778 | 96.6379 |
| 1 | 3 | 2.61131 | 2.60752 | 5.22417 | 5.23778 | 96.6379 |
| 2 | 1 | | 0 | | 0 | |

*Figure 7-32 Multi-objectives optimisation result and possible options for SIC =1*

### 7.3.3.1. *Comparing the AS-IS to the TO-BE states of BSL*

The summary of the three experiments is discussed in the comparative analysis of the initial state (AS-IS) of BLS production process with the expected preferred state (TO-BE). This is summarised in Table 7-11 below

*Table 7-11 Summary of the initial and expected states of the BSL production process*

| Sub-Category Indicators | AS-IS | TO-BE | Diff | Remark |
|---|---|---|---|---|
| Social Impact Coefficient (SIC) | 0.7 | 1.0 | 0.3 | Improved |
| M1 Energy Consumed/unit (kWh/unit) | 2.750 | 2.611 | 0.139 | Improved |
| M2 Energy Consumed/unit (kWh/unit) | 2.740 | 2.607 | 0.133 | Improved |
| Total Energy Consumed/unit (kWh/unit) | 5.500 | 5.224 | 0.276 | Improved |
| Throughput | 3.819 | 5.237 | 1.418 | Improved |
| System Stability (output/input) (%) | 89.54 | 96.64 | 7.1 | Improved |
| Input/Output Buffer Capacities | 30 | 30 | | |

### i. Expected Improvement in BSL Productivity

The difference between the Cell150 throughputs of the initial state of BSL and the expected state is 1.418 Units per hour. Hence, for the 18 Cells in operation, the throughput would be increased by 1.418 x 18 = 25.524, and the equivalent 100 hours run is shown in Table 7-12.

*Table 7-12 The equivalent improved throughput values for the 18 Cells and at 100 hours run.*

| **Throughput /hour** | | | **Throughput for 100 hour runs for the 18 Cells** |
|---|---|---|---|
| **1 Cell** | **18 Cells** | | |
| 1.418 | 25.524 | | 2552.4 |

In a continuous run of 24-hour shift in 365 days (8,760 hours), BSL would have increased her productivity by 1.418 x 8760 = 12, 421.68 units per cell. This is equivalent to additional 223,590.24 units for the 18 operational Cells.

### ii. Expected Energy Savings in kWh of BSL Production Line

The total energy savings of Cell150 is 0.276 kWh per Unit. Hence, the savings when the throughput is 5.237 Units would be 0.276 x 5.237 = 1.445kWh. The total savings per hour for the 18 Cells in operation would be 1.445kWh x 18 = 26.017kWh. Table 7-13 shows the equivalent energy savings at 100 hours run.

*Table 7-13 The equivalent energy savings relative to the throughput and at 100 hours run*

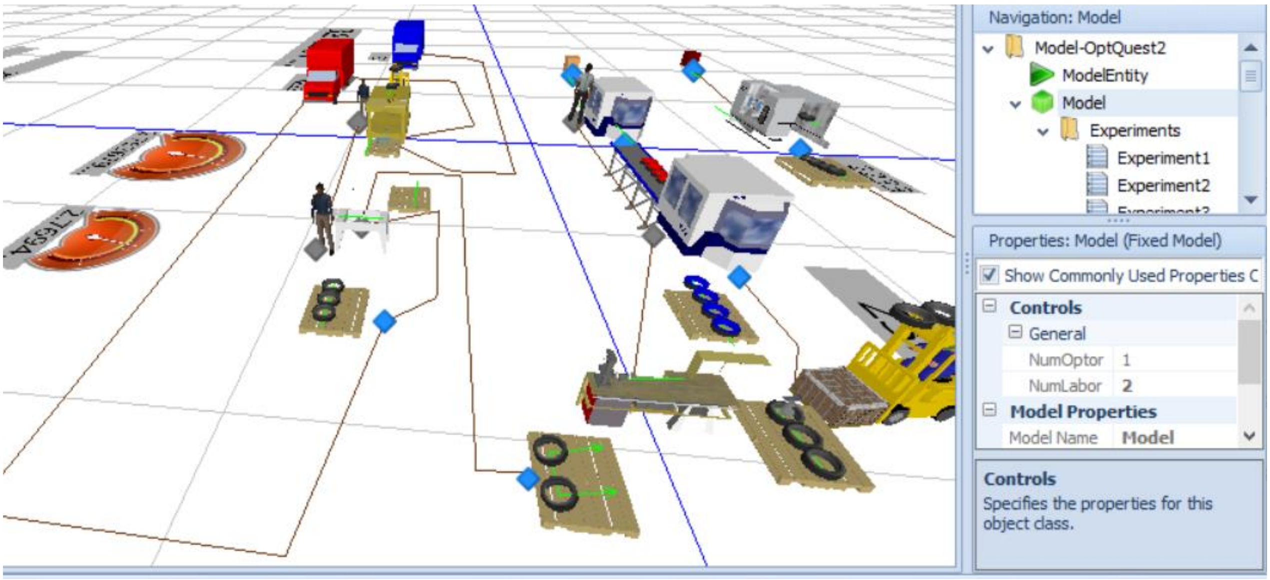
| | Unit of Finished Products | | Energy saving for 100 hours run (kWh) |
|---|---|---|---|
| **Number of Cells** | **1** | **5.237** | |
| **1** | 0.276 | 1.445 | 144.5 |
| **18** | 4.968 | 26.017 | 2602 |

Similarly, in a continuous run of a 24-hour shift in 365 days (8,760 hours), BSL would have saved her total energy consumption by 26.017 x 8760 = **227,908.92 kWh**

At an average kWh unit price of 12.5pence, BSL has the potential to save up to £28,488.62 per annum.

### iii. The Opportunity to Improve the Workers' Social Sustainability

The difference of 0.3 for the SIC between the AS-IS and the TO-BE state of the case study provides a wide window of opportunity for the social impact improvement and in effecting improvement in the other aspects. The expected cost savings from the productivity, costs of energy, and the motivation to conserve energy would support the sustainability analyst in preparing a credible business case and in making holistic sustainability decisions. The animated 3D view of the proposed preferred option is shown in Figure 7-33 below. The use of the animated 3D model will support the presentation of the sustainability business case.



☑ Show Commonly Used Properties

Controls

General

NumOptor 1

NumLabor 2

Model Properties

Model Name Model

**Controls**
Specifies the properties for this object class.

Figure 7-33 3D view of the simulation model for BSL proposed sustainable production process

The sustainability business case is expected to include opportunities for improving the social impact coefficient from the current 0.7 to the desired 1.0. The organisation may focus on activities that would promote employees' satisfaction and motivation to work. For example; investing in the onsite amenities and workers training and employability will lead to increase in the SIC score.

### *7.4. The Chapter Summary*

In this chapter, the framework for integrated simulation-based impact analysis for sustainable manufacturing design and management was presented. The chapter started with the introduction of the economic, social and environmental challenges faced by the industries and the need for useful decision support tools. The chapter introduction was followed by a brief discussion on the use of case study as a research method.

A case study of a UK based manufacturing company (Burrow and Smiths Limited) was then presented with a step by step application of the integrated simulation-based sustainability impact analysis framework. The process demonstrated the practical knowledge required and enabled the researcher to reflect on the practicability of the framework in a real manufacturing environment. The procedure also provided sustainability analysts and practitioners with the required knowledge for sustainability based requirements' gathering, conceptual modelling and simulation modelling of a real manufacturing process. The application of the framework enabled the experimentation of sustainability multi-criteria objectives, analysis of the interdependencies of the aspects of the three sustainability dimensions and the optimisation of the modelling objectives.

The short-term objectives set by the business and the defined modelling objectives limited the types of aspects of the three sustainability dimensions included in the model. For example; the energy consumption is of the significant environmental issue in this case study. Other environmental aspects such as the greenhouse gas (GHG) could be modelled by writing the "expression" that defines the functional relationship between energy consumption and the GHG (Wang, Huang and Zou, 2016; Elkadhi, Kalai and Ben Hamida, 2017). Additional economic aspects can also be analysed by using the ABC model which is included in most of the simulation software.

The outcome of the three experiments and the optimisation results were summarised to demonstrate the potential improvement that can be achieved in the stated simulation modelling objectives of the experiments.

The SIC (β) calculated value; 0.7064 (70.64%) represents the intensity of the utilisation of a worker or the workers' productivity factor. The result demonstrates the effect of the social impacts' scores on productivity (see Table 7-3). The higher the social impacts' scores, the higher the value of SIC and the more effective the workers' productivity or efficiency of the production process. Businesses such as BSL can assess their corporate social commitment by reviewing the negative and positive social impacts' scores and set new objectives. An organisation, which desires to improve productivity as in this scenario, needs first to remove negative aspects such as occupational health and safety (scored 4 out of 9) that represent a threat to the business. A focus on the positive social aspects with higher improvement opportunities such as investment in human resources (scored 6 out of 9) and onsite social initiatives (scored 7 out of 9) can lead to increase in the value of the SIC.

# CHAPTER 8

## 8. SUMMARY, CONCLUSION AND FUTURE WORK RECOMMENDATIONS

### Introduction

The previous chapter demonstrated and detailed the procedure for the practical application of the integrated simulation-based sustainability impact analysis framework and concluded the research execution and assessment phase. This chapter presents the research outcome and contributions phase of the thesis.

The first section of this chapter summarises the thesis under three sub-sections: (1). Section 8.1.1 discusses the research findings; (2). Section 8.1.2 details the contribution of the research and (3). Section 8.1.3 discusses the limitation of the research.

The second section presents the conclusion and the future work recommendation under two sub-sections: (1). Section 8.2.1 discusses the outcomes of the research in relation to the research objectives and provides the direction for future research and (2). Section 8.2.2 presents the future work recommendation and the conclusion of the thesis.

### *8.1. The Summary of the Thesis*

This section discusses contributions of this research, and the limitations of this research.

### *8.1.1. The contributions of this research*

The main contribution of this research is the development of a holistic integrated simulation-based impact analysis framework for sustainable manufacturing design and management. However, the research also contributes to the research process, knowledge, the concept of social impact coefficient, refinement of the product design concept and the practical application of sustainability impact analysis.

### **8.1.1.1.** *Contribution to the research process and publication*

The strength of the systematic process adopted in the development of this research is evidenced in the outcome and conclusion of each of the research stages that supported the thesis objectives.

The systematic literature review carried out in Chapter 2 reviewed the existing approaches to sustainable manufacturing which led to the identification of the research gaps of knowledge. The analysis of the research gaps underpins the development of the research question, research aim and objectives and a logical research methodology in chapter 3. The systematic literature review has been evaluated by a wider research community in international conference proceedings and peer-reviewed Journal.

Further, Chapter 4 provided additional literature review and evaluation of the sustainability impact assessments methods which led to the identification of key sustainability indicators for the process level of sustainable manufacturing. Part of the outcome of this chapter which relates to social impact indicators has been reviewed and refined by the wider research community in a peer-reviewed Journal. Chapter 5 provided a detailed process of the first stage of a two-stage approach to the development of the descriptive framework for simulation-based sustainability impact analysis. The framework development approach is based on an inductive analysis and built on the two techniques of sustainable manufacturing (SPA and SPD) which were identified in the analysis of the systematic literature review of chapter 2. The approach emphasised the amalgamation of the SPA and SPD with other sustainability methodologies in a simulation-based model. The resulting descriptive framework was presented to a panel of 24 sustainability experts in a Delphi study for verification, evaluation, and review. This is detailed in chapter 6. The Delphi study represents a deductive analysis and the second stage of the two-stage to the framework development. The verified simulation-based sustainability impact analysis framework was further validated in a case study based on a real manufacturing environment. The importance of the interconnections and interdependent analysis of the three sustainability dimensions were central to and emphasised throughout the execution of the research process.

In addition to the published research outcomes in the international peer-reviewed journals and conference proceedings, this research ensured the quality of result through the selection of sustainability experts internationally from both the academia and industry to validate the framework in the Delphi study.  A relevant case study was also selected in the empirical study to validate the applicability of the developed framework. Both the Delphi study and case study validate the completeness, conciseness, correctness, and clarity of the framework.

#### **8.1.1.2.** *Contribution to knowledge*

This research has produced a number of contributions to knowledge which includes:

1. The development of a new approach for simulation modelling of a sustainable manufacturing process. The novel approach integrates the concepts and principles of the existing sustainability methodologies and frameworks and the simulation modelling construction process into a common framework for process level assessment. Thus, the approach enables the impact analysis and optimisation of the aspects of the three sustainability dimensions (Chapter 5, and 6).
2. The development of a holistic integrated simulation-based sustainability impact analysis framework to guide sustainability practitioners and analysts through the construction of an integrated simulation-based sustainability impact analysis. In an iterative process, the framework enables the definition of a clear sustainability goal and scope, development of conceptual model of a manufacturing process, requirement gathering and the collection of data related to the three sustainability dimensions, the building of a simulation model and the experimentation of defined input variables and evaluation of the results for a preferred sustainable solution. This procedure provides the opportunity for simultaneous and interdependent analysis of the aspects of the economic, environmental and social dimensions of a manufacturing process. Through this technique, the key indicators of the three sustainability dimensions are captured and analysed to support effective sustainability decision-making (Chapter 5, 6, and 7).
3. The use of functional relationships to identify and itemise the interrelationships amongst the aspects of the three sustainability dimensions. The approach enabled the coding or writing of simulation model “expressions” for interdependent analysis of the aspects of the three sustainability dimensions.
4. The identification and clear definition of the two distinct approaches to sustainable manufacturing (SPD and SPA) and the development of a new approach that brings together these two distinct approaches to support the decision for effective sustainable product design and performance assessment (chapter 2 and 5).
5. The use of simulation in a new holistic context for sustainable manufacturing design. There is no existing guideline for integrating the aspects of the three sustainability dimensions simultaneously in a simulation model.

#### **8.1.1.3.** *Contribution to the concept of social impact coefficient*

The introduction of the concept of the social impact coefficient (SIC) is novel in the parlance of sustainable development and provides a new approach to measuring the social sustainability of an organisation. The challenge of the existing research has been the inability to integrate the social aspects of sustainability with the other sustainability dimensions in an analytical equation. The challenge, before this research, has resulted in the partial approach to sustainable manufacturing and the inability to simultaneously analyses the interdependencies of the aspects of the three sustainability dimensions. The new concept of SIC is an approach that enables the identification of the affected stakeholders' categories, measure the resultant weighted value of the negative and positive impact indices and use the result to determine its influence on the other aspects of sustainability. This new approach was deployed in this research to integrate social aspects of sustainability into the simulation model. The SIC in this instance was identical to the workers' productivity factor and helped to determine the efficiency of the input resources of the shop floor workers. Varying or improving the value of SIC is found to have an impact both on the economic and environmental sustainability (Chapter 4 and 7).

#### **8.1.1.4.** *Contribution to the refinement of the product design concept*

This research brings a refined approach to the existing product design concept to enable effective integration of sustainability approaches into the product development process. This new approach enables simultaneous deployment of the lifecycle thinking and strategic thinking in an iterative process during the concept design and process modelling stages. This modified product design concept enables the generation of optimal-eco-product-designs and corresponding optimal-clean-process-models (Chapter 5).

#### **8.1.1.5.** *Contribution to the practical application of sustainability impact analysis*

The practical application of the sustainability impact analysis as demonstrated in this thesis provides many benefits for the research towards sustainable development and manufacturing.

1. The development and application of the simulation-based sustainability impact analysis framework provide a solid foundation for achieving the Life Cycle Sustainability Analysis (LCSA) goal. This means there is a high possibility to extend the framework to the system level and product lifecycle level.

2. The effectiveness of the practical application enables sustainability analysts to build a model of an integrated simulation-based sustainability impact analysis, experiment with different input variables, predict the process sustainability performance and provides suitable optimised options that can support effective sustainability decision-making.
3. The outcome of the practical application could enable re-engineering or re-design of a manufacturing process for process sustainability. This means the analyst could set a sustainability objective, experiment with different decision input variables, examines the impacts and optimise the parameters. The preferred optimised options could be used to support decision-making or implemented to achieve sustainable manufacturing goal.
4. The practical application of sustainability impact analysis can be used to analyse the impact of a strategic decision on the process sustainability. This means the application can be used to analyse the impact of an organisation's strategic decision such as capital investment on the economic performance, social performance, and environmental performance.

### *8.1.2. Limitation of this Research*

This section identifies some limitation of the research reported in this thesis, which can be associated with the complexity of the sustainability analysis topic and the scope of this research.

The research into the simulation-based sustainability impact analysis of the manufacturing process is a microcosm of the broader sustainability analysis topic and limited by the number and scope of activities that can be modelled at a time for simulation. The activities of a product lifecycle could span international and continental borders and may impact various categories of stakeholders. The lack of standardised data and the time required to collect data for analysis further increases the complexity of the sustainability analysis topic. This research has, therefore, focused on the manufacturing production process within the manufacturing stage of a product lifecycle, and the worker's stakeholder's category. Hence, the range of the data collected for the literature review, case study and the category of stakeholders included were selected within the constraints of this research scope. In the context of this, the following summarises the limitation of this research.

1. ***The set of data which underpins the development of the framework***

   The sets of data collected and synthesised for the inductive analysis stage of the descriptive framework development were selected under the constraints of some inclusion criteria which were discussed in Section 2.4.3. In an ideal situation, the set of data that underpins the development process of the sustainability analysis framework ought to span both the continuous and discrete manufacturing and include the system and product levels of assessment. This limitation has been identified and outlined in Section 8.2.2 as one of the scopes for the future research.
2. **The process deployed to demonstrate the practicability of the framework**

   The number of the real manufacturing case study deployed to demonstrate the practicability of the framework was limited to one and constraint by time and the amount of information the organisation was willing to divulge. Typically, a higher number of real manufacturing case studies would have been deployed to test the practicability of the framework in different types and situations of the production process. As such a further demonstration of the sustainability impact analysis, requirement gathering and data collection processes would have been conducted to include other sustainability aspects such as the raw materials' usage, level of carbon emission, costs of resource usage and capital costs.
3. **The parameters for determining the workers' social impact of the case study**

   This research successfully negotiated access into the settings of the case study presented in this thesis; however, due to the data protection issues (section 7.2) the workers' social parameters of the case organisation were estimated as discussed in section 7.3.3.3 -iii. The result, therefore, does not represent the exact social impact coefficient value of the case organisation. The social data collection model and the guideline are included in Appendix **B** to support sustainability data analyst in both data gathering and analysis.

## *8.2.* Conclusion and Future Work Recommendation

This section concludes the outcomes from this research in correspondence with the research objectives and provides direction for future research. Finally, concluding remarks are stated

### ***8.2.1.*** *Summary and evaluation of research achievements against objectives*

As stated at the beginning of this thesis, the main aim of this research is to develop a holistic, integrated simulation-based impact analysis framework that supports decision-making for sustainable manufacturing design and management. The research has achieved this by developing a framework which provides guidelines for sustainability analysts and practitioners to build a simulation model that integrates the aspects of the three sustainability dimensions of a manufacturing process. The framework also enables simultaneous analysis of the impacts on the three sustainability dimensions.

### *8.2.2. Future Work Recommendation and the Final Conclusion of the Thesis*

The development and application of the integrated simulation-based sustainability impact analysis framework focused on the discrete manufacturing production process due to the scope covered by this research. Hence there is still a clear gap for research coverage based on the following:

1. The process level assessments include the sustainability impact analysis of the processes and sub-processes at the product lifecycle stages such as the production process, logistics process, distribution process, reverse logistics process. There is, therefore, the need for similar research and application of the developed framework at these other processes.
2. The system level assessments which include the impact analysis of the organisation's enterprise or the supply chain on the aspects of the three sustainability dimensions.
3. The product level assessment which covers the entire product lifecycle from the cradle to the end of life options. According to the context of this research, the impact analysis at the process level and system level would build the foundation for the Life Cycle Sustainability Analysis.
4. This research is constraint within the discrete manufacturing production process due to the research scope and available simulation modelling software. Hence, an extended research an application of the simulation-based sustainability impact analysis framework into the continuous manufacturing production process is still an open area.

Another visible gap in the current research is the challenge of aggregating and translating various social aspects of different stakeholders' categories. In this research, the author has discussed the process of calculating the productivity factor and weighted social impact coefficient (SIC) relating to the workers' stakeholders category. The method enabled the translation and aggregation of the employees' social impact into a quantitative weighted value.

The result provided a coefficient for analytical integration and interdependent analysis of the workers' social aspects with the quantitative environmental and economic aspects. The method also enabled organisations to assess or improve their corporate social performances towards the employees, and the productivity in respect to other sustainability dimensions (Chapter 4 and 7). The following recommendation is made for future research based on the social impact analysis:

1. The identification and translation of the qualitative measures of the **Consumers** (supply chain and end users) social impact into a qualitative weighted value capable of representing the corporate social performance towards the customers.
2. The identification and translation of the corporate social performance towards the **Local Community** into a measurable quantitative weighted value and its interdependency with the aspects of the other sustainability dimensions.
3. The identification and translation of the corporate social performance towards the **Society**–(national and global) into a weighted value that determines the organisation's social index towards the national and global society.
4. The identification and translation of corporate social performance towards the **Value chain actors-suppliers** (not including end-consumers) into a quantitative factor that indicates performance and able to determine its interdependency with the aspects of the other sustainability dimensions.

#### **8.2.2.1.** *The Final Concluding remark of this Thesis*

This chapter demonstrated that the research contained in this thesis had accomplished all the research objectives defined in section 3.2 of chapter 3. The chapter summarised the entire thesis by first discussing the research findings followed by itemising the research contributions and then the limitations of the research. In the conclusion part, the chapter demonstrated the success of the research by evaluating each of the research objectives against the research achievement. This was followed by a recommendation section for future research work.

Overall, this thesis has successfully demonstrated competent and efficient research skills and rigour both in the research plan, execution process, interpretation and presentation of the research findings and results. Also, it contributed to the sustainability knowledge through the development and refinement of the sustainability theories, concepts, frameworks and models. This research achieved its aim of developing a holistic integrated simulation-based impact analysis framework for sustainable manufacturing design and management by meeting all the set research objectives.

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# APPENDIX A

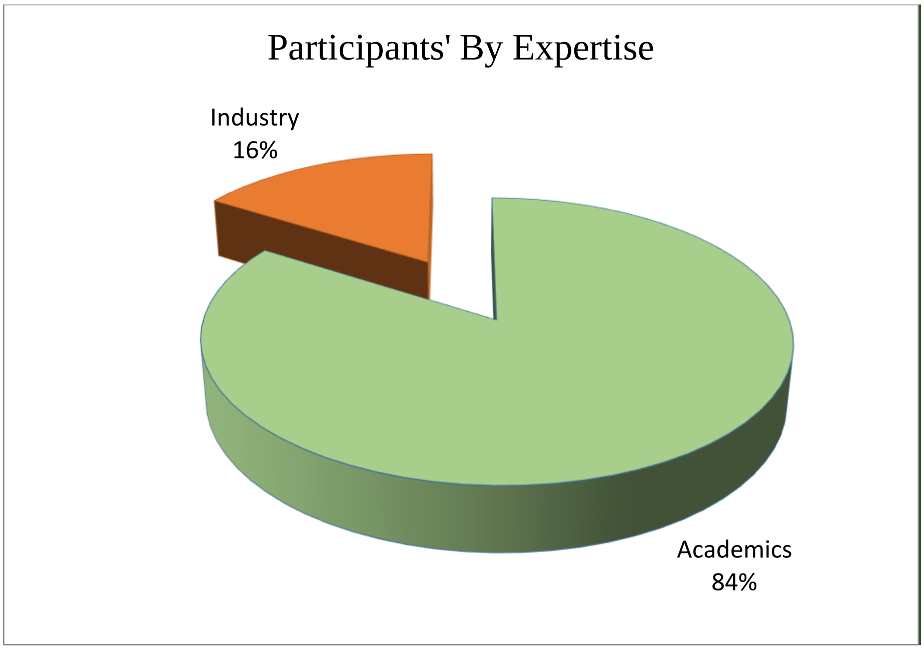
## DELPHI STUDY

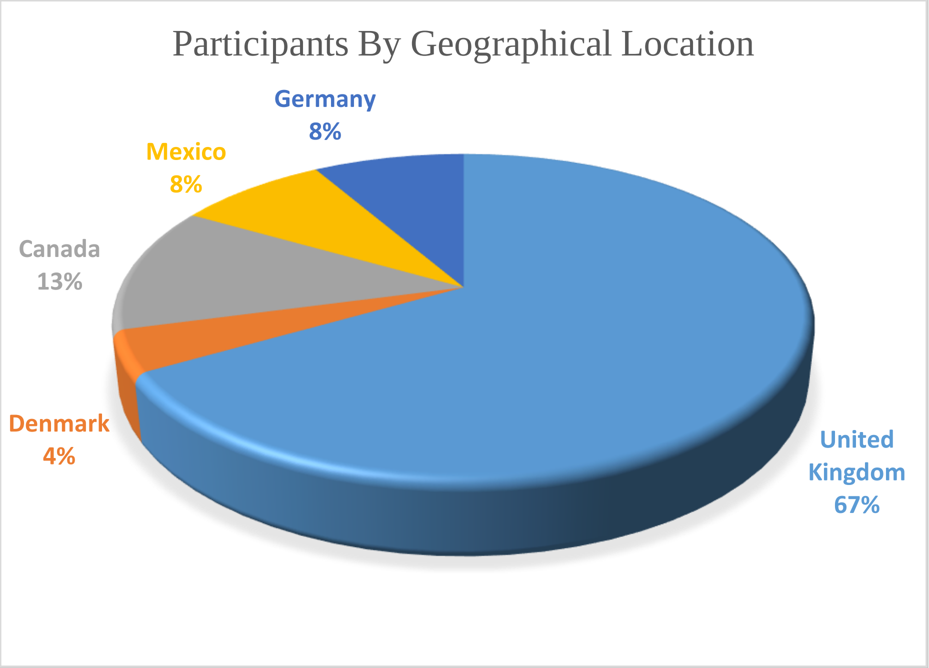
### Participants Profile and Geographical Location

| | Participants Area of Expertise | Current Function/Position | Country of Location | Website | Academics | Industry |
|---|---|---|---|---|---|---|
| *1* | Operations Management, Modelling & Simulation and Sustainable Manufacturing | Senior Lecturer | United Kingdom | www.derby.ac.uk | 1 | |
| *2* | Operations Management, Modelling & Simulation and Sustainable Manufacturing | Senior Lecturer | United Kingdom | www.surrey.ac.uk | 1 | |
| *3* | Supply Chain Management | Associate Professor | Denmark | www.business.aau.dk | 1 | |
| *4* | Remanufacturing | Reader (Associate Professor) | United Kingdom | www.strath.ac.uk | 1 | |
| *5* | Simulation, sustainable manufacturing, environmental | Prof Ops Mgt | United Kingdom | www.york.ac.uk | 1 | |
| *6* | Human Factors | Professor | Canada | www.ryerson.ca | 1 | |
| *7* | Sustainability | Sustainability Manager | United Kingdom | www.rolls-royce.com | | 1 |
| *8* | Operations Management | Head of Department for Academic Exchanges | Mexico | www.uaa.mx | 1 | |
| *9* | Project management, strategy management, operations | Senior Lecturer in Strategy and Operations | United Kingdom | www.uwe.ac.uk | 1 | |
| *10* | Supply Chain Management | Lecturer in Operations and Supply chain Management | United Kingdom | www.aston.ac.uk | 1 | |
| *11* | Sustainablity, change management | Co-founder and senior consultant at a sustainability and change management consultancy | Germany | www.sustainum-consulting.de | | 1 |
| *12* | Sustainable supply chain management | Lecturer | United Kingdom | www.surrey.ac.uk | 1 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| *13* | Digital Manufacturing | Professor | United Kingdom | www.strath.ac.uk | 1 | |
| *14* | Manufacturing Automation and Control | Head of Department | United Kingdom | www.bu.ac.uk | 1 | |
| *15* | sustainable product development | researcher | Germany | www.ioew.de | 1 | 1 |
| *16* | Operations Management, Business and Operational Excellence | Professor of Operations Management and Head of the Centre for Supply Chain Improvement | United Kingdom | www.derby.ac.uk | 1 | |
| *17* | Sustainable Manufacturing | University Lecturer | United Kingdom | www.lboro.ac.uk | 1 | |
| *18* | materials and manufacturing | lecturer | United Kingdom | www.derby.ac.uk | 1 | |
| *19* | Industrial Engineering | Operations Manager / Post-Doctoral Researcher | Canada | www.ryerson.ca | 1 | |
| *20* | Information systems and decision analysis | Professor | Canada | www.ryerson.ca | 1 | |
| *21* | industrial sustainability | Lecturer | United Kingdom | www.exeter.ac.uk | 1 | |
| *22* | Simulation | Professor | United Kingdom | www.shu.ac.uk | 1 | |
| *23* | Operations and Innovation | Senior Lecturer | United Kingdom | www.stir.ac.uk | 1 | |
| *24* | Environmental Engeneering | Environment & Energy Corporate Manager | Mexico | www.nissan.com.mx | | 1 |
| | | | | ***Total*** | **21** | **4** |

APPENDIX A


Participants' By Expertise
Industry
16%
Academics
84%


Participants By Geographical Location
Germany
8%
Mexico
8%
Canada
13%
Denmark
4%
United
Kingdom
67%

APPENDIX A

# APPENDIX B

# SOCIAL IMPACT COEFFICIENT

Data Collection Model for Workers' Stakeholder Impact Category (Ref: GRI 400)

| GRI Code | **Impact Subcategories** | **Values** | | **Values** | **Total** |
|---|---|---|---|---|---|
| 401-1 | **401-1- EMPLOYMENT** | | | | |
| | Number of Male employees in the organisation | | Number of Female employees in the organisation | | **0.00** |
| | Number of Male employee hired in the reporting year | | Number of Female employee hired in the reporting year | | **0.00** |
| | Male employee hired (Age Less than 30) | | Female employee hired (Age less than 30) | | **0.00** |
| | Male employee hired (Age 30-50) | | Female employee hired (Age 30-50) | | **0.00** |
| | Male employee hired (Age Over 50) | | Female employee hired (Age Over 50) | | **0.00** |
| | Number of Male in the assessing production line | | Number of Female in the assessing production line | | **0.00** |
| | | | | | |
| | Number of Male employee who left in the reporting year | | Number of Female employee who left in the reporting year | | **0.00** |
| | Male employee left (Age Less than 30) | | Female employee left (Age Less than 30) | | **0.00** |
| | Male employee left (Age 30-50) | | Female employee left (Age 30-50) | | **0.00** |
| | Male employee left (Age over 50) | | Female employee left (Age over 50) | | **0.00** |
| | | | | | |
| | Previous available working hours available to the organisation | | Current available working hours | | **0.00** |
| | | | | | |
| | | | | | |
| | **401-3 PARENTAL LEAVE** | | | | |
| | Total number of Male employees that were entitled to parental leave | | Total number of Female employees that were entitled to parental leave | | **0.00** |

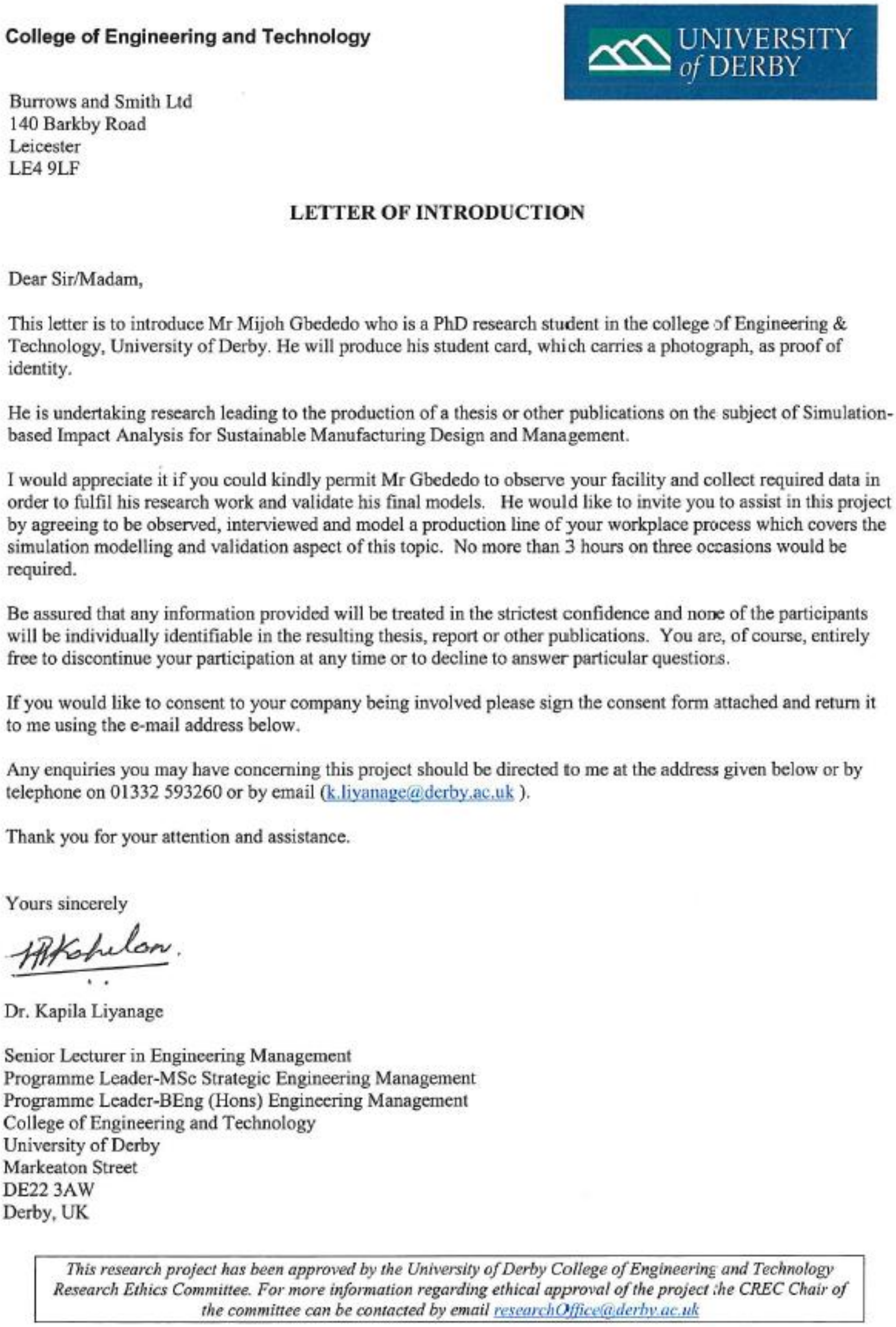
| | | | | | |
|---|---|---|---|---|---|
| 401-3 | Total number of Male employees that took parental leave | | Total number of Female employees that took parental leave | | **0.00** |
| | Total number of Male employees that returned to work after parental leave | | Total number of Female employees that returned to work after parental leave | | **0.00** |
| | Total number of Male employees still employed 12 months after returned to work from parental leave | | Total number of Female employees still employed 12 months after returned to work from parental leave | | **0.00** |
| | | | | | |
| 404 | **TRAINING AND EDUCATION** | | | | |
| 404-1 | **Average Hour of Training** | | | | |
| | Number of Male employee who undertook training in the reporting year | | Number of Female employee who undertook training in the reporting year | | **0.00** |
| | Hours of training undertook by Male employee in the reporting year | | Hours of training undertook by Female employee in the reporting year | | **0.00** |
| | | | | | |
| | **405-1 DIVERSITY AND EQUAL OPPORTUNITY** | | | | |
| 405-1 | **Diversity in Governance** | | | | |
| | Number of Male employees in the Governance Body | | Number of Female employees in the Governance body | | **0.00** |
| | Male representative that are (Age Less than 30) | | Female representative that are (Age Less than 30) | | **0.00** |
| | Male representative that are (Age 30-50) | | Female representative that are (Age 30-50) | | **0.00** |
| | Male representative that are (Age over 50) | | Female representative that are (Age over 50) | | **0.00** |
| | | | | | |
| 405-2 | **EQUALITY OF BASIC SALARY** | | | | |
| | Basic Salary of Male Workers | | Basic Salary of Female Workers | | **0.00** |
| | | | | | |
| 412-2 | **HUMAN RIGHTS ASSESSMENT** | | | | |
| | Number of employees working in operations that required procedures and human right protection | | Number of employees trained on human rights policies or procedures that are relevant to the operations | | **0.00** |
| | | | Hours devoted to training on human rights policies or procedures that are relevant to the operations | | **0.00** |
| | | | | | |
| | **INVESTMENT ON HUMAN RESOURCES** | | | | |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  | Number of male employee entitle to life insurance |  | Number of female employee entitle to life insurance |  | **0.00** |
|  | Number of male employee entitle to health care; |  | Number of female employee entitle to health care; |  | **0.00** |
|  | Number of male employee entitle to disability and invalidity coverage; |  | Number of female employee entitle to disability and invalidity coverage; |  | **0.00** |
|  | Number of male employee entitle to parental leave; |  | Number of female employee entitle to parental leave; |  | **0.00** |
|  | Number of male employee entitle to retirement provision; |  | Number of female employee entitle to retirement provision; |  | **0.00** |
|  | Number of male employee entitle to stock ownership; |  | Number of female employee entitle to stock ownership; |  | **0.00** |
|  |  |  |  |  |  |
| **LABOUR & MANAGEMENT RELATION** |  |  |  |  |  |
|  | Notice period in weeks before major changes in organisation |  | Are there provisions for consultation and negotiation? (1=Yes; 0=No) |  | **0** |
|  |  |  |  |  |  |
|  |  |  |  |  |  |
| **OCCUPATIONAL HEALTH AND SAFETY MANAGEMENT** |  |  |  |  |  |
|  | Respect for the right of workers |  |  |  |  |
|  | Number of executives members at formal joint H&S meetings |  | Number of workers representatives at formal joint H&S meetings |  | **0.00** |
|  |  |  |  |  |  |
|  | **INCIDENTS REPORTED** |  |  |  |  |
|  | **Number of incidents reported in the reporting year** |  |  |  | **0.00** |
|  |  |  |  |  |  |
|  | **NON-DISCRIMINATION** |  |  |  |  |
|  |  |  | Number of incidents of discrimination |  |  |
|  |  |  | Is the procedure for dealing with discrimination in place? (Yes =1; No =0) |  | **-** |
|  |  |  |  |  |  |
|  | **FREEDOM OF ASSOCIATION AND COLLECTIVE BARGAINING** |  |  |  |  |

| | | | | | |
|---|---|---|---|---|---|
| | | | Number of incidents or risk of violation of workers' rights to exercise freedom of association or collective bargaining | | |
| | | | Policies of intention to support rights to exercise freedom of association and collective bargaining (Yes=1; No=0) | | - |
| | **CHILD LABOUR** | | | | |
| | Number of under-aged employees (Age<14/15) | | Number of young workers exposed to hazardous work.(Age<18) | | - |
| | | | Policies of agaist child labour is in place (Yes=1; No=0) | | - |
| | | | | | |
| | **FORCED OR COMPULSORY LABOUR** | | | | |
| | | | Number of incidents bond or slave labour | | |
| | | | Are there policies that eliminate all forms of forced or compulsory labour in place? (Yes=1; No=0) | | - |
| | | | | | |
| | **ON SITE AMENITIES** | | | | |
| | Number of free onsite amenities available to all staff | | Number of subsidised onsite amenities available to all staff | | **0.00** |
| | | | | | |
| | **Examples of Onsite Amenities** | | **List of Onsite Amenities on your site** | | |
| | Car Park | | | | |
| | Staff Canteen | | | | |
| | Gym / Sport Centre | | | | |
| | Cash Machine | | | | |
| | Barber's shop | | | | |
| | Yoga or Prayer room | | | | |
| | Ebikes | | | | |
| | Indoor games | | | | |

APPENDIX B

# APPENDIX C- Ethical Approval



**College of Engineering and Technology**

UNIVERSITY of DERBY

Burrows and Smith Ltd
140 Barkby Road
Leicester
LE4 9LF

**LETTER OF INTRODUCTION**

Dear Sir/Madam,

This letter is to introduce Mr Mijoh Gbededo who is a PhD research student in the college of Engineering & Technology, University of Derby. He will produce his student card, which carries a photograph, as proof of identity.

He is undertaking research leading to the production of a thesis or other publications on the subject of Simulation-based Impact Analysis for Sustainable Manufacturing Design and Management.

I would appreciate it if you could kindly permit Mr Gbededo to observe your facility and collect required data in order to fulfil his research work and validate his final models. He would like to invite you to assist in this project by agreeing to be observed, interviewed and model a production line of your workplace process which covers the simulation modelling and validation aspect of this topic. No more than 3 hours on three occasions would be required.

Be assured that any information provided will be treated in the strictest confidence and none of the participants will be individually identifiable in the resulting thesis, report or other publications. You are, of course, entirely free to discontinue your participation at any time or to decline to answer particular questions.

If you would like to consent to your company being involved please sign the consent form attached and return it to me using the e-mail address below.

Any enquiries you may have concerning this project should be directed to me at the address given below or by telephone on 01332 593260 or by email (k.liyanage@derby.ac.uk ).

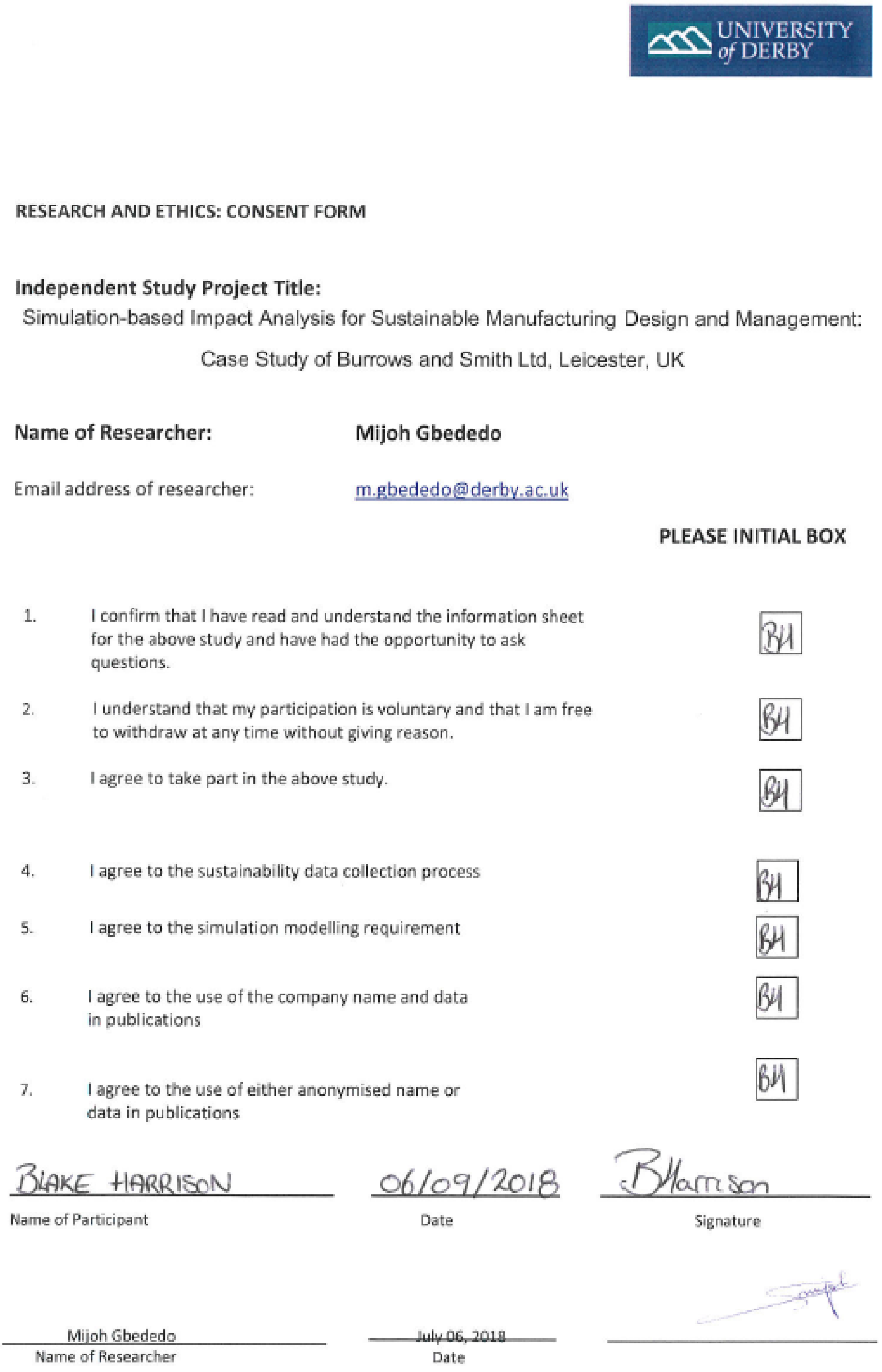
Thank you for your attention and assistance.

Yours sincerely

Dr. Kapila Liyanage

Senior Lecturer in Engineering Management
Programme Leader-MSc Strategic Engineering Management
Programme Leader-BEng (Hons) Engineering Management
College of Engineering and Technology
University of Derby
Markeaton Street
DE22 3AW
Derby, UK

*This research project has been approved by the University of Derby College of Engineering and Technology Research Ethics Committee. For more information regarding ethical approval of the project the CREC Chair of the committee can be contacted by email researchOffice@derby.ac.uk*



UNIVERSITY of DERBY

RESEARCH AND ETHICS: CONSENT FORM

**Independent Study Project Title:**

Simulation-based Impact Analysis for Sustainable Manufacturing Design and Management: Case Study of Burrows and Smith Ltd, Leicester, UK

**Name of Researcher:** **Mijoh Gbededo**

Email address of researcher: m.gbededo@derby.ac.uk

**PLEASE INITIAL BOX**

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. BH
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving reason. BH
3. I agree to take part in the above study. BH
4. I agree to the sustainability data collection process BH
5. I agree to the simulation modelling requirement BH
6. I agree to the use of the company name and data in publications BH
7. I agree to the use of either anonymised name or data in publications BH

| | | |
|---|---|---|
| BLAKE HARRISON | 06/09/2018 | BHarrison |
| Name of Participant | Date | Signature |

| | | |
|---|---|---|
| Mijoh Gbededo | July 06, 2018 | |
| Name of Researcher | Date | |

APPENDIX C

UNIVERSITY *of* DERBY

**INFORMATION SHEET:**

**Modelling of Simulation-based Sustainability Impact Analysis**

## Title of Study:

Simulation-based Impact Analysis for Sustainable Manufacturing Design and Management

| **Principal Investigator** | **Researcher** |
|---|---|
| Dr Kapila Liyanage | Mr Mijoh Gbededo |

College of Engineering & Technology
University of Derby, Markeaton Street
DE22 3AW, Derby

## Background:

You are being invited to take part in a research study. Before you decide to participate in this study, it is important that you understand why the research is being done and what it will involve. Please take the time to read the following information carefully. Please ask the researcher if there is anything that is not clear or if you need more information.

## The purpose of this study is:

To collect sustainability data of a real manufacturing environment in order to model and validate a simulation-based impact analysis framework developed by the researcher

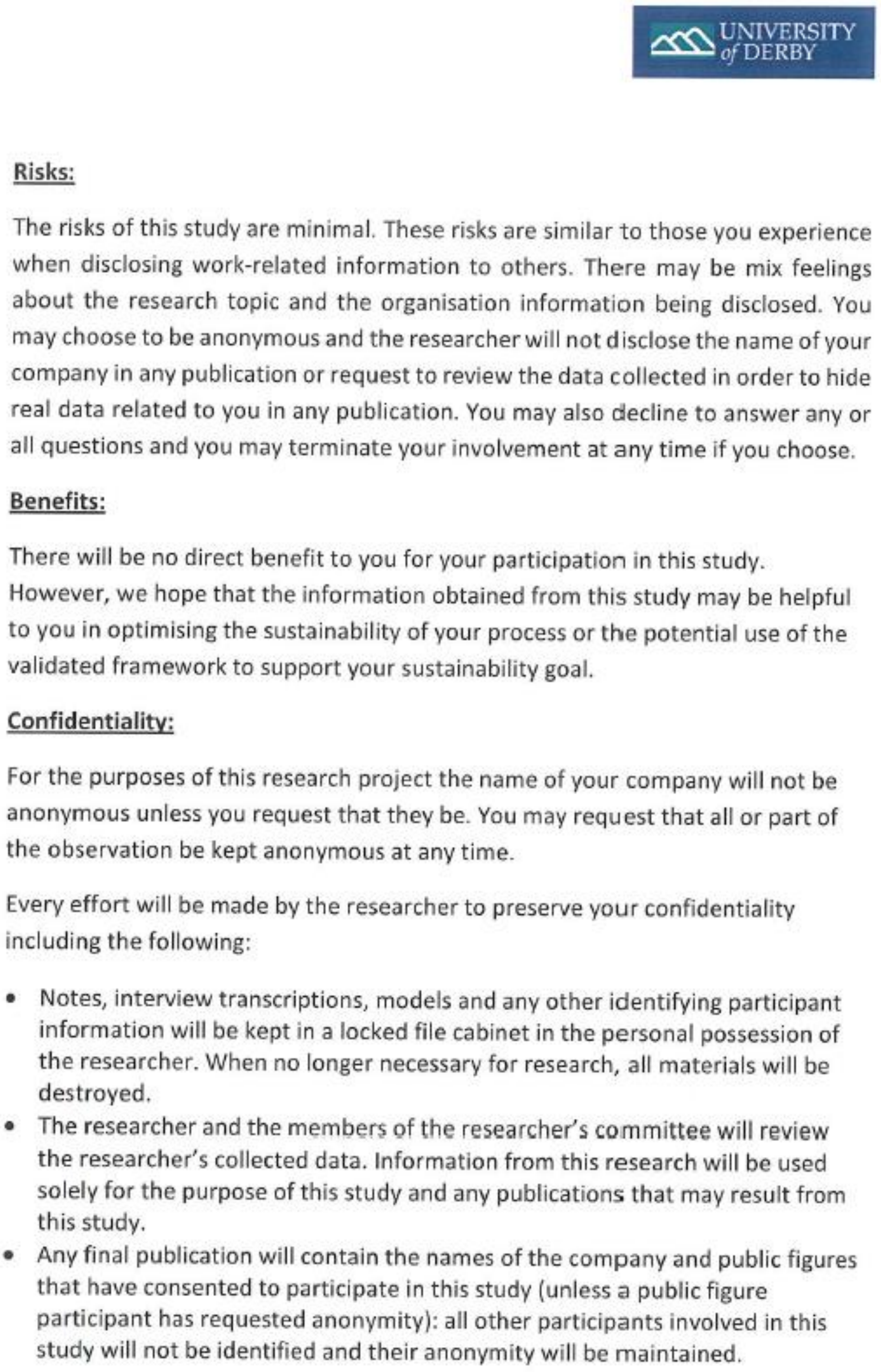
## Study Procedure:

Your expected time commitment for this study is 7 to 10 hours.

*Procedure:*

1. You will assist the research in the gathering of data related to a production line and the shop floor of your organisation.
2. You will assist the researcher by providing access to the environmental, economic and social data of the shop floor. (Note: the social data may extend to the manufacturing site since this cannot be separated)
3. You will assist the researcher in validating the theoretical data with the practical data.

APPENDIX C



**Risks:**

The risks of this study are minimal. These risks are similar to those you experience when disclosing work-related information to others. There may be mix feelings about the research topic and the organisation information being disclosed. You may choose to be anonymous and the researcher will not disclose the name of your company in any publication or request to review the data collected in order to hide real data related to you in any publication. You may also decline to answer any or all questions and you may terminate your involvement at any time if you choose.

**Benefits:**

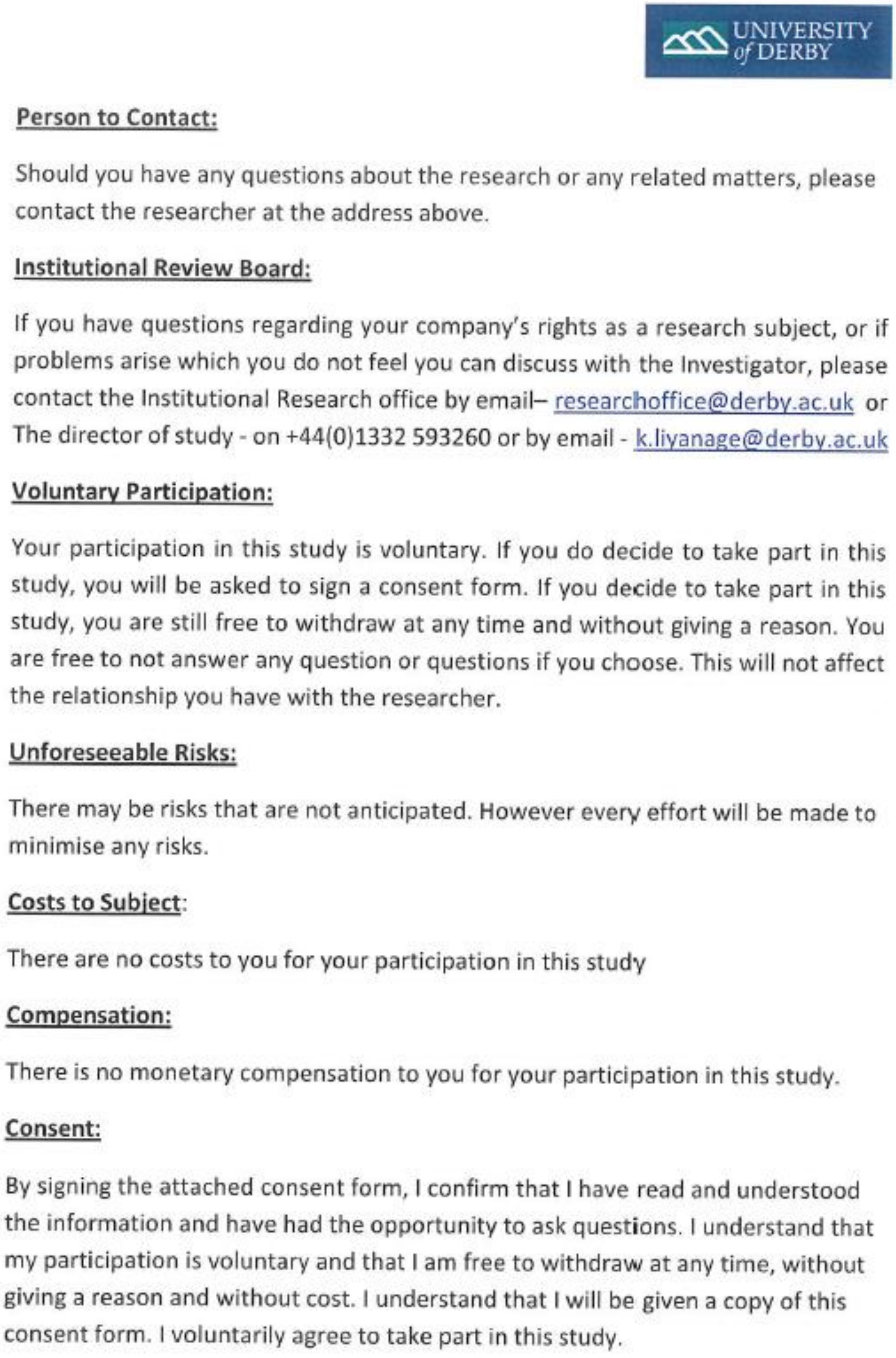
There will be no direct benefit to you for your participation in this study. However, we hope that the information obtained from this study may be helpful to you in optimising the sustainability of your process or the potential use of the validated framework to support your sustainability goal.

**Confidentiality:**

For the purposes of this research project the name of your company will not be anonymous unless you request that they be. You may request that all or part of the observation be kept anonymous at any time.

Every effort will be made by the researcher to preserve your confidentiality including the following:

- Notes, interview transcriptions, models and any other identifying participant information will be kept in a locked file cabinet in the personal possession of the researcher. When no longer necessary for research, all materials will be destroyed.
- The researcher and the members of the researcher's committee will review the researcher's collected data. Information from this research will be used solely for the purpose of this study and any publications that may result from this study.
- Any final publication will contain the names of the company and public figures that have consented to participate in this study (unless a public figure participant has requested anonymity): all other participants involved in this study will not be identified and their anonymity will be maintained.



UNIVERSITY of DERBY

**Person to Contact:**

Should you have any questions about the research or any related matters, please contact the researcher at the address above.

**Institutional Review Board:**

If you have questions regarding your company's rights as a research subject, or if problems arise which you do not feel you can discuss with the Investigator, please contact the Institutional Research office by email– researchoffice@derby.ac.uk or The director of study - on +44(0)1332 593260 or by email - k.liyanage@derby.ac.uk

**Voluntary Participation:**

Your participation in this study is voluntary. If you do decide to take part in this study, you will be asked to sign a consent form. If you decide to take part in this study, you are still free to withdraw at any time and without giving a reason. You are free to not answer any question or questions if you choose. This will not affect the relationship you have with the researcher.

**Unforeseeable Risks:**

There may be risks that are not anticipated. However every effort will be made to minimise any risks.

**Costs to Subject:**

There are no costs to you for your participation in this study

**Compensation:**

There is no monetary compensation to you for your participation in this study.

**Consent:**

By signing the attached consent form, I confirm that I have read and understood the information and have had the opportunity to ask questions. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason and without cost. I understand that I will be given a copy of this consent form. I voluntarily agree to take part in this study.