Descriptive Framework for Simulation-aided Sustainability Decision-making: A Delphi Study

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Abstract

Making an effective sustainability decision at every stage of a product life cycle is key to achieving a holistic sustainable product development. The extant literature highlights the challenges and lack of effective tools for determining the impact of manufacturing processes on the environmental, economic and social dimensions, as well as the interdependence of the outcome of one dimension on the other. This research paper identifies methodologies, tools, and approaches that can be integrated into a single descriptive framework to enable both assessment and analysis of the aspects of the three sustainability dimensions. The paper also details the development of the framework using inductive methods and conceptual synthesis of key sustainability approaches and a Delphi study involving panels of international researchers and practitioners in the field of sustainable manufacturing. The framework can provide a platform for both practitioners and sustainability analysts to build impact analysis models that will support effective sustainability decision-making. It will also enable a clear perspective of the required elements, processes and indicators that need to be considered in sustainable manufacturing design and assessments.

Keywords: Decision-making; Delphi; Sustainable manufacturing; framework validation; LCSA.

1. Introduction

The integration of sustainability considerations into processes has become increasingly important for organisations' strategic commitments (Afgan, 2010; Haapala *et al.*, 2011; Aguado *et al.*, 2013; Gremyr *et al.*, 2014). This is due to the prevailing challenges of resource constraints, diminishing natural resources, regulations, and increasing market potentials for green and sustainable products (Aguado *et al.*, 2013; Bhanot *et al.*, 2015; Paju *et al.*, 2010; Rowley and Slack, 2007). In this context, sustainability considerations refer to the impacts on the three sustainability dimensions: environmental, social and economic as related to a manufacturing product, process or system (Haapala *et al.*, 2011). Assessing and managing these impacts is vital to sustainable manufacturing and effective sustainability decision-making.

The ISO 14040 framework for Life Cycle Assessment (LCA), provides a four-component guideline for assessing environmental impacts across a product life cycle. Though this framework has been criticised for its overwhelming procedures for data collection and environmental centric, the principles of the framework remain credible for determining the impacts on the economic and social dimensions as in the Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) respectively.

A product life cycle is a sequence of processing stages from cradle through to the end of life of the product. The stages include raw materials extraction, material production, transportation, product manufacture, product use, and end of life choices (Arena *et al.*, 2013). Each of the processing stages is a collection of activities that consume resources (natural, human and financial) and generate both positive and negative outputs that impact the three sustainability dimensions. Thus, the assessment of the impacts of the processes at each life cycle stage is important to effective sustainability decision-making. Independently, there are impact assessment techniques such as the environmental impact analysis, social impact analysis, and cost-benefit analysis that enable a separate analysis of each of the three dimensions (Körner, 2006; Heilala *et al.*, 2008; Paju *et al.*, 2010; Haapala, *et al.*, 2011). These techniques, however, do not consider possible consequence resulting from the impacts of one aspect of sustainability on the other (Bhanot et al., 2015).

The launch of Life Cycle Sustainability Assessment (LSCA) framework (United Nations Environmental Program (UNEP), 2011; Valdivia et al., 2013; Zamagni et al., 2013) establishes the importance of consequential analysis of the three sustainability dimensions throughout a product life cycle. LSCA framework draws attention to unintended consequences due to ineffective sustainability decisions and calls for contributions from all fields of study to discuss and develop a holistic approach to sustainability subject. Many authors have discussed and suggested different approaches; a recent literature review of the trend towards this holistic sustainability approach reveals that the current approaches are still segmented and do not often consider the interdependence of one sustainability aspect on the other (Gbededo et al., 2018).

In this paper, we present a validated descriptive simulation-based framework that can be used to integrate and analyse the interdependence of the aspects of the three sustainability dimensions and support effective sustainability decision-making. The initial descriptive framework was developed through the synthesis of a systematic literature review and a deductive analysis of the existing approaches to sustainable manufacturing as detailed in Gbededo et al. (2018). This is then evolved through a Delphi process that involved 24 seasoned researchers and practitioners in the field of sustainable manufacturing and related fields. A consensus was reached based on four testing criteria and two rounds of the study. This demonstrates a unified perspective of the sustainability experts and suggests the applicability of the framework for sustainable manufacturing design. The framework can be applied at any stage of a product life cycle or processes within the stage to drive effective sustainability decision-making. Then the next sessions of this study cover the framework development background, methodology and Delphi processes and validation of the framework.

2. The Framework Development Background

2.1.Approaches to Sustainable Manufacturing and Sustainability Analysis

A systematic literature review of approaches to sustainable manufacturing design identified two major techniques: Sustainable Product Development (SPD) and Sustainability Performance Assessment (SPA) (Gbededo et al., 2018). The approaches deployed in these techniques are either segmented or integrated as summarised in Table 1.

Some of the authors discussed the Life Cycle Sustainability Analysis (LCSA) and suggested approaches that 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 et al., 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 LCA 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 (Abidi et al., 2015; Bhanot et al., 2015; Cannata et al., 2009; Gamage and De Silva, 2015; Paju et al., 2010; Seow et al., 2013). An approach such as Embodied Product Energy (EPE) attempted to address the environmental impacts of the entire system of an organisation (Rahimifard et al., 2010; Seow et al., 2013).

An evaluation of the approaches and techniques has revealed a lack of a holistic approach that integrates and considers the interdependence of the three sustainability dimensions, especially in a dynamic manufacturing environment. Thus, it 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 interdependence in a dynamic environment. In this regard, the focus is on the impact analysis at a product life cycle stage rather than the entire product life cycle. The life cycle 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 life cycle to drive effective sustainability decision-making.

Table 1 Summary of approaches to sustainable manufacturing design (see Gbededo et al., 2018 for a more detailed table).

Tools/Framework	Authors	Techniques	Approach
Eco-Design	Östlin et al. (2009); Abramovici and Lindner (2011); Hatcher et al. (2011); Bakker et al. (2014)	SPD	Segmented
Robust Design Methodology (RDM)	Gremyr et al. (2014)	SPD	Segmented
Simulation, Energy Modelling, Monitoring & Evaluation: Energy Efficiency	Abidi et al. (2015); Bhanot et al. (2015); Paju et al. (2010); Gamage and De Silva (2015); Afgan (2010); Cannata et al. (2009); Seow et al. (2013); Rahimifard et al. (2010)	SPD	Segmented
Materials Substitution & Composite Materials	Aguado et al. (2013); Crabbè et al. (2013)	SPD	Segmented
LCSA = LCA + LCC + S-LCA	Kloepffer (2008)	SPA	Integrated
LSCA = LCA + SA	Heijungs et al. (2010)	SPA	Integrated
Energy Technology System	(Afgan, 2010)	SPD	Integrated
LCSA= LCA+LCC+S-LCA	Klöpffer and Ciroth (2011)	SPA	Integrated
LCSA= LCA+LCC+S-LCA	Schau et al. (2012)	SPA	Integrated
SS and SA for development of a holistic LCA	Sala et al. (2013)	SPA	Integrated
LCSA= LCA+LCC+S-LCA	Valdivia et al. (2013)	SPA	Integrated
Transformation of environmental innovation into Lean System	Aguado et al. (2013)	SPD	Integrated
3P evaluation grids to analyse study cases	Crabbè et al. (2013)	SPD	Integrated
Network Analysis using graph theory	Bhanot et al. (2015)	SPD	Integrated

2.2. The Classical Delphi Technique

The term Delphi is synonymous with consulting for good judgment on matters; it has its origin from Greek mythology and practices of consulting oracles to predict the future. This concept, however, has evolved over time to the classical methods for forecasting especially in the application areas where scientific laws have not been established or where the outcome of results are more likely to be influenced by dominant personalities (Keeney et al., 2011). The classical Delphi method uses the anonymity of participants and depends on individual statistical prediction rather than a face-to-face group prediction (Chang et al., 2010; Keeney et al., 2011). This kind of technique was first applied in the 1950s by RAND Corporation in predicting the possibilities and counteractions for an enemy attack at the beginning of the cold war (Hardy et al., 2004; Keeney et al., 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; Chang et al., 2010; Holsapple and Joshi, 2002; Keeney et al., 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 the 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. The agreed consensus level found in the literature is different for various research and covered a range between 50% and 80% (Ahmad and Wong, 2019). Some depend on the diffusion of the field of study, while some depend on the stability of the rounds of study or are left for the readers to make the decision (Powell, 2003). A consensus level of 75% (Chang et al., 2010), is deemed appropriate for a diverse and multi-field study environment such as in the sustainability field and once the group of experts has come to an agreement that reaches this percentage on the position of a statement, a 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 administered to a selected group of experts (Chang et al., 2010; Keeney et al., 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. A 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 et al. (2011), this could be repeated until a diminishing return point is reached.

2.2.1. The make-up of Delphi Panellist

The Delphi expert panel is made up of a group of "informed individuals" or specialists in a specific field or individuals with advanced knowledge related to the topic under consideration with the aim of seeking their opinion or judgement on the specific issue (Chang et al., 2010; Keeney et al., 2011; Powell, 2003). 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 ensure diversity of opinion and credible result of the process Chang et al. (2010). The process of defining who is an expert in a field could also create issues, thus often inclusion criteria are employed to create a clear boundary for experts' inclusion. The inclusion criteria may 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.

3. Methodology

A two-stage process to framework development as in Bacon and Fitzgerald (2001) and Holsapple and Joshi (2002) was adopted in this paper (Figure 1). The first stage deploys an inductive approach for the development of the initial descriptive framework of simulation-based sustainability 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; Gbededo *et al.*, 2018).

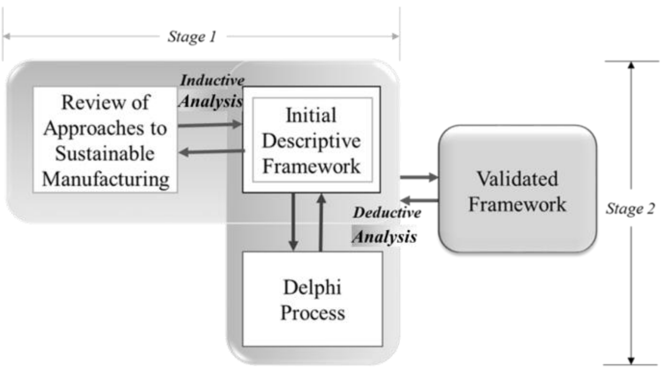


Figure 1. A two-stage approach to framework development, adapted from Holsapple and Joshi (2002)

The outcome of the systematic literature review of the approaches, methods and methodologies adopt in sustainable manufacturing is presented in Gbededo et al. (2018). Figure 2 shows the theoretical framework developed through an inductive analysis which was further evolved into a framework for conceptual modelling of integrated Simulation-based Sustainability Impact Analysis. The details of the development process can also be found in Gbededo et al. (2018).

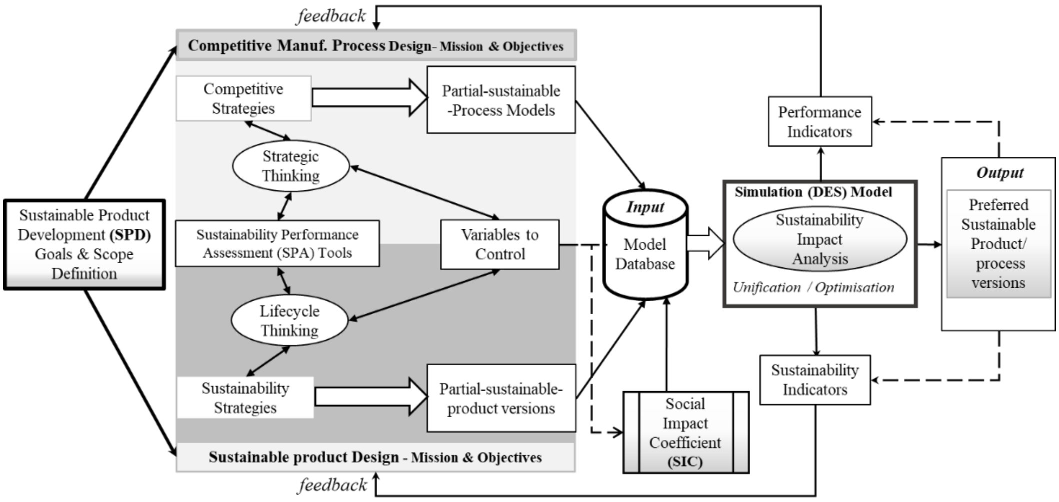


Figure 2. A theoretical framework for holistic simulation-based sustainability impact analysis.

This is then followed by the Delphi process stage used in a deductive approach to evaluate the theories, concepts and principles applied in the development of this 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.

According to Bacon and Fitzgerald (2001) and Holsapple and Joshi (2002) methodologies for framework development and validation, the first phase prior to the two-stage approach is to outline the boundary conditions and evaluation criteria as depicted in Figure 3. This phase provides a guide for defining the scope of the study, identifying relevant literature 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 which is often carried out before the beginning of stage 2 of the two-stage approach is to outline the criteria for selecting the panel of experts. This is then followed by defining the experts' employment process, the size of the experts' group, the consensus level, iterative rounds, mode of communication and the questionnaire for the Delphi study.

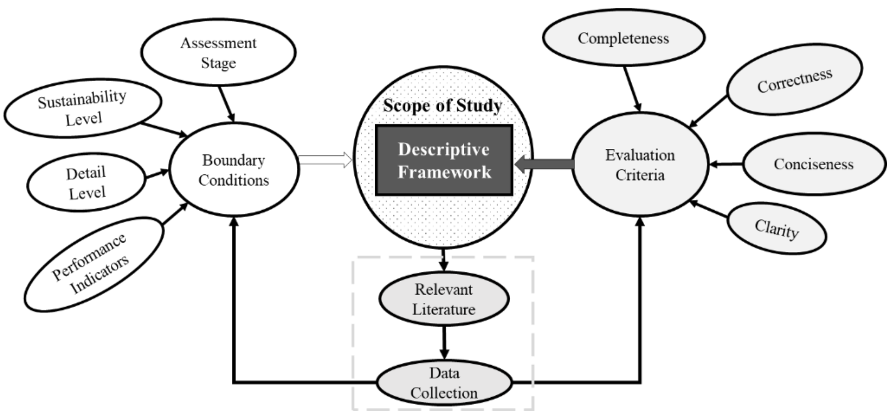


Figure 3. The outline of boundary conditions and evaluation criteria

3.1. *Stage 1- Initial Descriptive Framework Development Process*

The initial descriptive framework developed accounts for the result of the process of matching sustainability approaches, concepts, principles, ideas and 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 (Gbededo et al., 2018).

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 life cycle.
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:*** The 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 the 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.

3.2. Stage 2- Delphi Process for Framework Validation

The Delphi technique was adopted in stage 2 (refer to Figure 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. The approach provided the opportunity to gather the experts' perspectives and to revise the descriptive framework. The process was conducted in a two-rounds 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.

A heterogeneous purposive sampling as used by Holsapple and Joshi (2002) was adopted to recruit members into the Delphi panel; this was to ensure diversity in the panel of expert. 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 authors, 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 committed to participate in the study. The agreed 24 participants 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 academic. At the time of the study, each of the participants 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.

3.2.1. Data Collection

An internet-based survey instrument (Survey Monkey) was used to design and administer the questionnaire. 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. It is worth noting that the fifth option (Neither Agree nor Disagree) was not included in the Likert-scale in order to avoid indecisive outcome for the Delphi study. This aspect was critically considered during the participant selection process by ensuring experts and experienced researchers or practitioners in the field of sustainability were engaged in the study.

A web-link to the questionnaires was then generated from the survey 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 and (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.

4. The Descriptive Framework of Simulation-based Sustainability Impact Analysis

The principles of LCSA emphasised on the evaluation of all environmental, economic and social impacts of a product life cycle. The evaluation process addresses the impacts of manufactured products throughout their life cycle, analyses the interdependence of the three sustainability dimensions, 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 interdependence 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, 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.

The descriptive simulation-based framework in Figure 4 is a high-level diagram of the theoretical framework depicted in Figure 2. It 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.

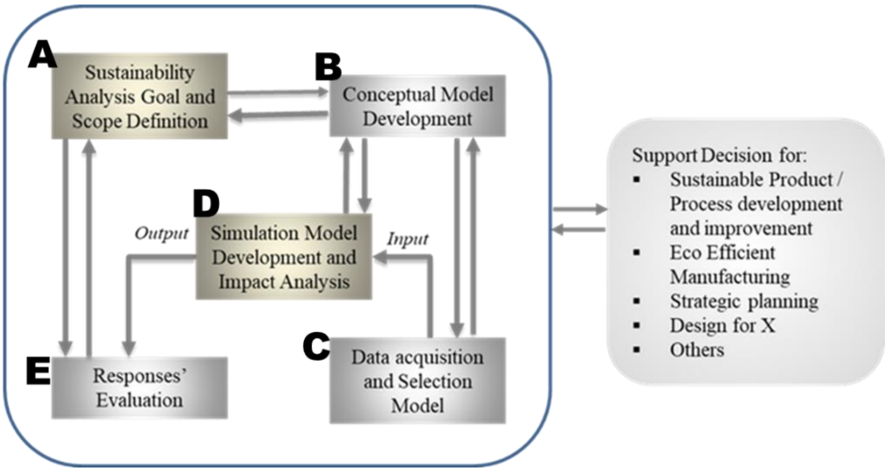


Figure 4. A framework for conceptual modelling of integrated Simulation-based Sustainability Impact Analysis

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, n.d.; Robinson, 2008a), 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 life cycle 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 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 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). 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, business process modelling, data modelling and system modelling.

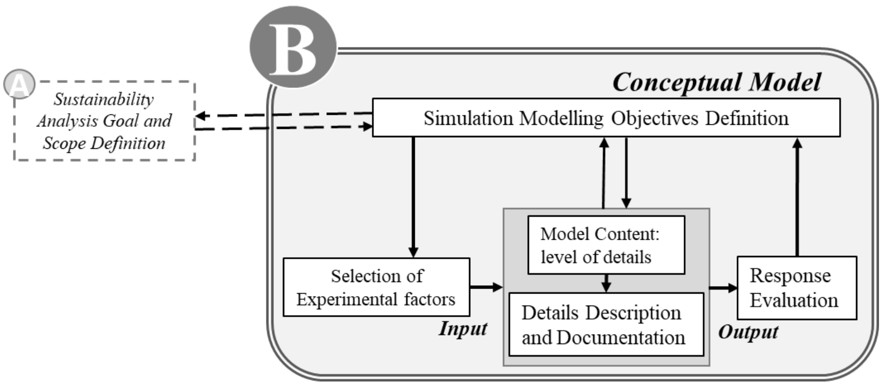


Figure 5 Conceptual model development process based on Robinson (2007)

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, 2008a). 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 the 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 more 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 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 6 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.

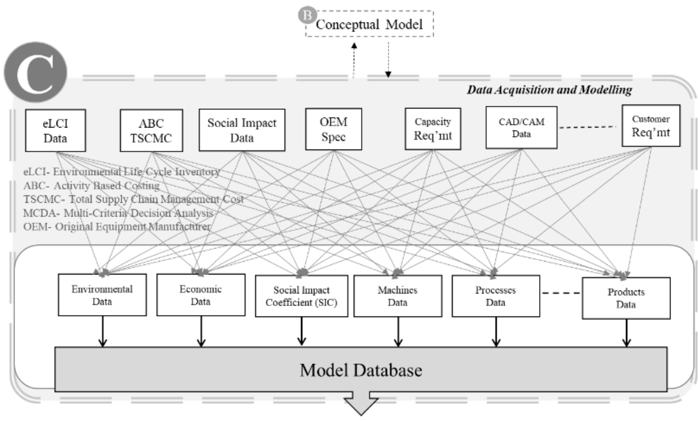


Figure 6 Data acquisition and selection model based on goals, scope, and objectives

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 an eco-innovation, direct observation of the systems and intelligent guesses.
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 for 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 7 which include:

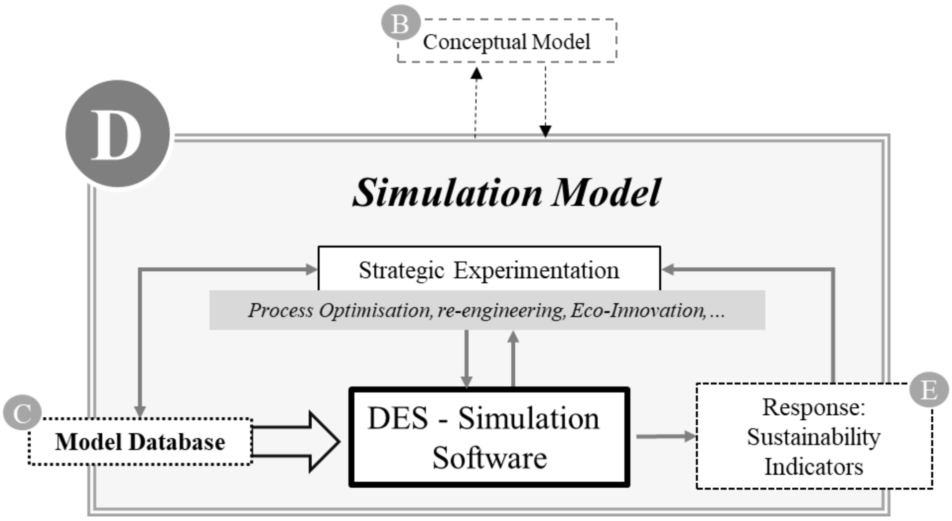


Figure 7. Development of computer simulation model and experimentation

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, 2008b). 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 8). The response evaluation is based on the following two factors:

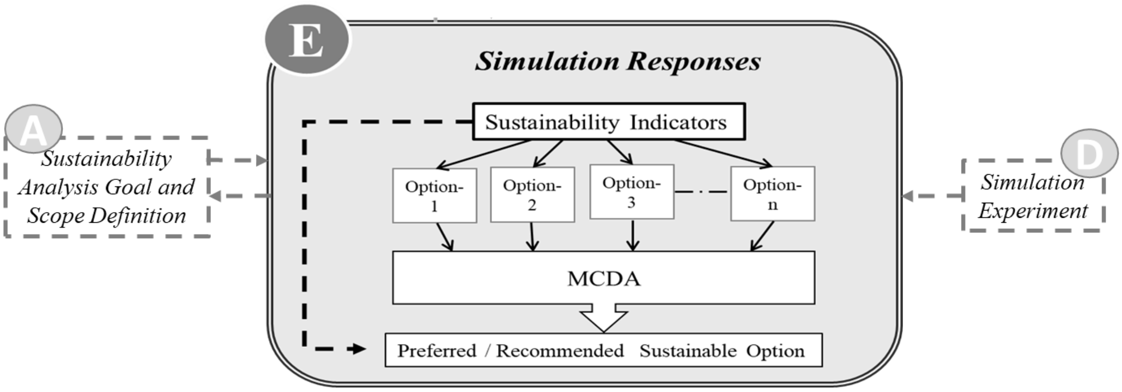


Figure 8. The response evaluation and the interpretation model

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, the 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 the 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 competing options of interest.

5. Findings and Discussion

At the beginning of the study, the activities' acceptable level for consensus was set to Aggregated Weights rated 3 or above and value of respondents equal or greater than 75% for each of the testing criterion (Chang et al., 2010).

The study design contained 42 questions and was organised to cover the four defined framework evaluation criteria. 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 2. The comments of the respondents in the open-ended questions were analysed based on the defined two categories: (1) suggestions relevance to the revision of the framework, and (2) comments viewed to be outside the boundaries of the study. However, few concerns were raised which are related to the motivational theories, principles and applications of the framework.

Table 2. 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%			

1. *Two of the participants expressed their concern about non-inclusiveness of the whole value chain of a product life cycle in a gate-to-gate assessment and another two were unclear what the gate-to-gate sustainability analysis stands for*. The participants' concerns are relevant for holistic product LCA, however, this approach has proven ineffective due to time, scope and challenges involved in the data collection. 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 for defining the scope of each stage of a product life cycle. The approach is appropriate for simulation modelling since it is not feasible to model the whole value chain of a product life cycle.

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 when assessing economic or social dimensions.*

These three statements were part of the questions explored during the Delphi study. The aim was to investigate if the improvement or optimisation of one of the dimensions, would have an impact on the other two and vice versa. The LCSA framework (United Nations Environmental Program (UNEP), 2011) emphasised on developing a framework that would increase the awareness of the decision-makers through a holistic analysis of the three sustainability dimensions. Hence, the need to examine some principles such as system thinking and life cycle thinking and how they are related. In a further investigation, the study explores if LCA methodology is effective in assessing the impact of a manufacturing process on each of the three sustainability dimensions. The result of this investigation supports the development of the descriptive framework.

3. *One respondent comments: "workers motivation depends on many factors and very difficult to associate with the social performance"*. 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 authors have discussed the alignment of the two social impact categories with the two-factor Herzberg theory of motivation in another publication (Gbededo and Liyanage, 2018).

4. *Another respondent states: "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."* The statement of the respondent is right, however, the descriptive framework understudy is built upon the analysis of literature in the manufacturing domain and the boundary within workers social stakeholders' category. 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."* The factors of motivational theories and social aspects are both qualitative and related. The alignment of their elements and performances enable the 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. *Another respondent states: "I doubt that sustainability can be dealt with only by using such models since the process seems to be socially under complex. How are values, trade-offs, etc. dealt with in this model? And in any case, a personal discussion is needed."* The challenge expressed by this respondent is prevalent in extant literature where most of the approaches to sustainability are segmented. 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, n.d.). 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."* We do not consider this statement to be true. An organisation's social performance will result in workers' satisfaction if the positive social aspects are deployed as described in section 4.4. Also, job satisfaction 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 Figure 4*. The double arrows in the framework represent an iterative process between the activities while the single arrows represent a flow of information.

5.1.The Result and Analysis of responses to the Delphi Study

The result of the first round in Table 2 shows that over 90% of the respondents 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 9 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 10 shows the graphical representation of the relative frequency distribution of the participants' response to each of the evaluation criteria. Comparing the respondents' view with the evaluation criteria, "Conciseness" and "Clarity" tests are considered to be highly successful compared to the "Completeness" and the "Correctness" tests. Figure 11 depicts the relative frequency distributions for the evaluation criteria.

Figure 9. Responses for each evaluation measures

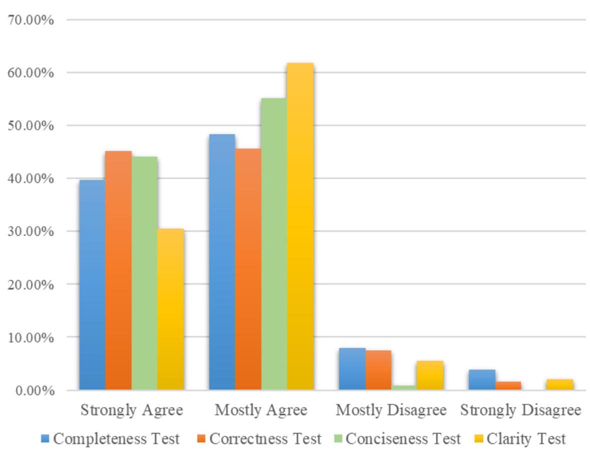
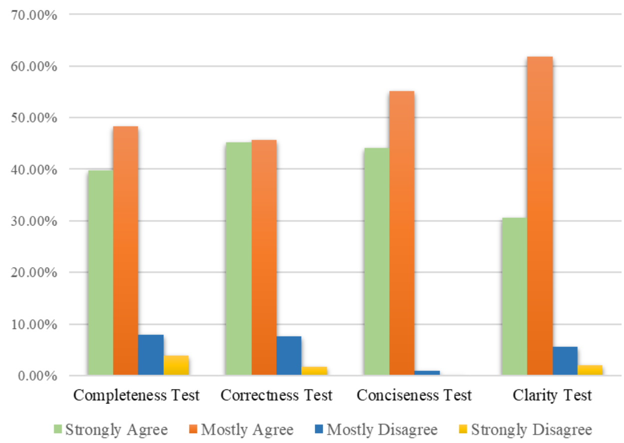


Figure 10. Responses for framework validation criteria test



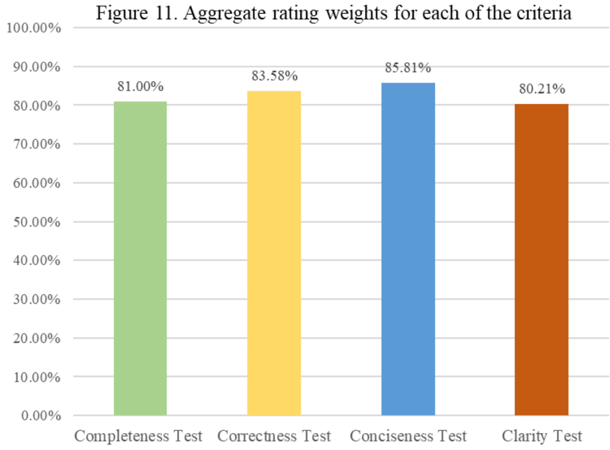


Figure 11. Aggregate rating weights for each of the criteria

In the follow-up to the aforementioned concerns and the result analysis of the first study, the summary of the results was sent to the participants in a 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 3 shows the weighted averages of the participants' responses to each of the major concerns.

Table 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 life cycle assessment can be the aggregation of all the sustainability assessments of all the stages of the product life cycle.”	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%		

The result of the second round shows 60% of the participants strongly agreed and 40% mostly agreed to the evaluation questions. This demonstrates consensus among the participants with no further objection to the hypothesis proposed under the study, hence, there was no need for the third round.

5.2.Research Implication and future direction

In the previous sections, the framework development background and process were discussed and two main research approaches to sustainable development were identified as SPD and SPA as highlighted in Table 1. Each of the methods deployed by these two techniques is either integrated or segmented and mostly considered under a static operations' environment. These approaches have received independent attention from the researchers at the product-level, system-level and process-level (Jayal et al., 2010; Parent et al., 2013). The theoretical framework developed integrates these two techniques in a simulation-based framework to support effective sustainability decision-making in a dynamic manufacturing process.

Although, we have already provided in section 4 the objectives of the LCSA and during the discussion of this research's results on how this framework can be used to capture, model and analyse the interdependence of the aspects of the three sustainability dimensions, there are still potential future research paths in the area of LCSA. While the simulation-based framework still needs to be tested in other process levels such as logistic and distribution stages, the system-level and product-level sustainability analyses are still at large. One research question based on the discussion of this research's results is:

> *How do we aggregate the results obtained from each stage of a product life cycle to support effective decision-making for a manufactured product?*

An aggregated result of the sustainability analysis of all the stages of a product life cycle will support LCSA principles and provide effective support for making a decision for a holistic product life cycle analysis.

6. Conclusion

This paper presented a methodical and detailed framework for developing an integrated simulation-aided decision-making model for sustainable manufacturing design and management. The application of the framework would enable conceptual modelling of an integrated simulation-based sustainability impact analysis that supports the decision for a sustainable product or process development and improvement, eco-efficient manufacturing process, and strategic sustainable manufacturing planning.

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

The fields of study covered in the development of the framework make it robust in addressing the LCSA objectives. However, some limitations were noted in the responses and comments of the participants which were addressed by the researchers. 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 researchers' assertions in the initial descriptive framework. Furthermore, the Delphi method enabled a constructive and systematic process that enhances the organisation of the group of experts both from the academics and industry to study and evaluate the framework based on four 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 key contribution of this research is the provision of a detailed framework for developing an integrated simulation-based impact analysis model for sustainable manufacturing design and management. However, the inherent limitation of simulation modelling makes the analysis of huge sustainability data or beyond a certain scope of a product life cycle stages almost practically impossible. Thus, limits the application of the framework to the gate-to-gate boundary or within a defined applicable scope. Also, the qualitative data of sustainability social aspects cannot be fed directly into the input of a simulation experiment, hence, such data have to be captured and aggregated into a quantitative factor such as Social Impact Coefficient (SIC) before coded into a simulation model. Although the framework is simplified enough for a sustainability analyst to understand and apply, the knowledge or expertise in simulation modelling required at the application stage.

In a follow-up paper, the researchers would present the results of the practical application of this framework in a real manufacturing environment where the performance and interdependence of energy consumption as an environmental aspect, employees' motivation as the social aspect and productivity as the economic aspect were analysed and optimised in a simulation model. Currently, this framework has only been tested and verified in a manufacturing gate-to-gate assessment level, hence, its practical application is still in the testing stage. Further research, contributions and feedback on the applicability of the framework at other gate-to-gate stages such as distribution and logistics stages would enable effective improvement and general application of the framework.

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