

Simulation Aided Life Cycle Sustainability Assessment Framework for Manufacturing Design and Management

Mijoh A. Gbededo, Kapila Liyanage, Ilias Oraifige

Abstract—Decision making for sustainable manufacturing design and management requires critical considerations due to the complexity and partly conflicting issues of economic, social and environmental factors. Although there are tools capable of assessing the combination of one or two of the sustainability factors, the frameworks have not adequately integrated all the three factors. Case study and review of existing simulation applications also shows the approach lacks integration of the sustainability factors. In this paper we discussed the development of a simulation based framework for support of a holistic assessment of sustainable manufacturing design and management. To achieve this, a strategic approach is introduced to investigate the strengths and weaknesses of the existing decision supporting tools. Investigation reveals that Discrete Event Simulation (DES) can serve as a rock base for other Life Cycle Analysis frameworks. Simio-DES application optimizes systems for both economic and competitive advantage, Granta CES EduPack and SimaPro collate data for Material Flow Analysis and environmental Life Cycle Assessment, while social and stakeholders' analysis is supported by Analytical Hierarchy Process, a Multi-Criteria Decision Analysis method. Such a common and integrated framework creates a platform for companies to build a computer simulation model of a real system and assess the impact of alternative solutions before implementing a chosen solution.

Keywords—Discrete event simulation, life cycle sustainability analysis, manufacturing, sustainability.

I. INTRODUCTION

THE global society is becoming more conscious of the degrading environment and the resulting global warming, rising sea levels, and uncontrollable disasters, including the recent heat-wave in India [1]-[3]. Thus; stricter regulations and policies are driving many industries into eco-efficient or eco-innovation [4]-[6]. The global challenge today however, has been posited to be environmental, social and economic [7], [8]; For example; the main cause of global warming has been attributed to the over consumption of energy and materials such as coal, fossil oil, water and natural gases [9]. The greenhouse effect, for instance, which is due to emissions of gases caused by industries and human activity, has resulted into a temperature rise by over 0.6 degrees in the last 10 years [5]. Most of these contributions to an unsustainable environment occur during a company's supply chain and distribution of products and services to the consumer [9]. Few industries have resorted to the use of tools such as eco-

efficient and eco-innovation to transform from unsustainable development to one of sustainable development [10]. Business decision making and strategy formulation are anchored on either of these tools for products or services Life Cycle Assessment (LCA), and in response to international regulations, such as ISO 14040.

Strategic decision making for effective manufacturing development thus becomes a more complex task [11], with additional multiple criteria and variables to be considered simultaneously in order to achieve both competitive and sustainable development. Widok and Wohlgemuth [12] defined 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 economical capital on the one hand, and/or reduce the degradation of this capital on the other". In 1987, the United Nations General Assembly defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." In 2005, it also quoted and agreed amongst many researchers that the three main components of sustainable development are economic development, social development and environmental protection [8], [12]-[14]. There are however various assessment tools adopted by industries to assess the impacts of each of this sustainable aspects, such as Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA) and Environment Life Cycle Assessment (ELCA) [15]. Many researchers have proposed the use of LCA in parallel with performance optimization tools, such as lean manufacturing, value stream mapping, simulation, Activity Based Costing, and Decision Making Trial and Evaluation Laboratory [16], [17]. According to [8], the main world challenge is the integration of the economic, environmental and social features of the life cycle of a product. The author further stated that many companies claim activity towards sustainability at the strategic and operational levels, however, it appears that the frameworks used to support these activities are out of balance, being economically oriented and do not effectively account for environmental or acknowledge the social issues [1], [12], [18]. There is, therefore, a need for a robust sustainability evaluation process that enhances effective decision making.

In the past decades, simulation has provided solutions to many challenges of high cost of experimenting with real life situation. It provides opportunity for testing different approaches and varying indicator compositions to enhance

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process flow and achieve potential desired measure before a real life application [12], [19].

DES has been used in manufacturing for the optimization of processes and resource usage. In recent years, we experienced various efforts of developers to use DES to achieve sustainable manufacturing. The application of DES-LCA or DES with Material Flow Analysis, as in MILAN software [19], promises to resolve environmental and economic factors, leaving behind consideration for social factors. This issue is common with many other integrated simulation software due to the difficulty to adequately incorporate all the three sustainability factors, most especially, the social aspects into software [19], [20]. The social indicators are however relatively vast and interdependent on other sustainable factors, thus resulting in ineffective sustainability decision making despite effective assessment of other indicators. According to [14], there is need for further innovative research and development in the area of Life Cycle Sustainability Assessment (LCSA) to address corporate policy and decision making. LCSA is a proposed integrated framework by researchers to balance and enable assessment and trade-off of the three factors for an effective sustainability decision-making process [12], [14]. It has been posited that the main challenge of designing and managing a sustainable manufacturing system is the complexity of interdependent factors and variables to be handled simultaneously [18], [20]. This research therefore proposed a simulation aided decision-making analytical tool for holistic assessment of sustainable manufacturing design and management. The tool will enhance DES-LCA by incorporating MCDA for analyses of stakeholders' and other social interests to enable integrated decision making support method for sustainable manufacturing design and management. As this research is still a work in progress, this paper does not aim to present a conclusive approach or methodology; rather, it presents a progressive step towards the development of a holistic analytical LCSA tool.

II. LCA AND LCSA

The concept of the life cycle approach to products and services design and its relevance towards achieving a sustainable production and consumption is widely discussed by many researchers. There are currently many frameworks, methodologies, methods, models, and tools that are now available and supported by various policies and regulations for sustainability assessment [14]. The sustainability factors (Economic, Social and Environment) are however, being addressed separately under three subject areas: LCC, SLCA and ELCA [15], [21]. The latter, which is hereafter referred to as LCA, is the most widely discussed [22] with the perspective of some authors that it also incorporates analysis that addresses economic and social sustainability, while some researchers argued that there is need to develop an integrated LCA system in order to confront sustainability issues [22]-[26]. LCA provides the elements to assess the environmental impacts (waste and emission) of a product throughout its lifespan. 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 [27]. According to [24], there are other LCA methods for example, "ecologically based LCA (Eco-LCA) which assesses ecosystems, such as water, minerals, and carbon sequestration. The 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 the 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 optimization [25]. Conversely, the challenges with the use of LCA are the difficulty to capture and measure the environmental aspects across a product life cycle, the unavailability of life cycle data of a product under design, and the lack of standardized weighting methods [14], [27], [38]. Groover [28] viewed this challenge under the manufacturing process as a complex supply chain infrastructure that 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 and interpreted to equivalent high level factors termed Environmental Impact. Environmental Impact Assessment (EIA) tools such as Ecotax, Ecovalue08, Eco-Indicator95, Eco-Indicator99, ReCiPe 2008 [29], LC-Impact, LIME, and Impact 2002+ have been widely discussed and analysed. As in [30], 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 easily collate key performance indicators in order to assess its economic performances. However, assessment of environmental and social performances is an ongoing challenge. In the past, through industrial evolution and development, economic performances are in adversarial relationship to both the environment and society. Thus, by incorporating environmental and social factors into product design, while maintaining a competitive position with economic growth, requires a level of compromises and trade-offs. Halog and Manik [24] identified some indicators for SLCA 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.

In recent years, the subject of LCSA has emerged and the United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) (UNEP/SETAC 2011), under its Life Cycle Initiative, have published a framework to support the development of a holistic LCSA [14], [22], [31]. The framework provides the platform for scientists from various fields to discuss the sustainability subject with a holistic life cycle perspective. Though the initial idea to combine LCA, LCC, and SLCA methodologies into a framework was first postulated by

Klöpffer [32], 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 life span. Valdivia et al. [22] posited that it is possible to combine LCA, LCC and SLCA to develop a holistic sustainability evaluation tool however; the authors stressed that the results of the evaluation should not be add up, as portrayed in the classical discipline approach to the LCSA model, but rather be jointly analysed (Fig. 1). The field of analytical science or computation science thus becomes apparent in the development of LCSA. Valdivia et al. [22] further states that combining the three methodologies into LCSA have potential benefits that include cost and risk reduction, consistency in reporting, and effective engagement of the stakeholder. In the special review of [14], 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 literatures in respect to the development of appropriate tools for the LCSA framework. The authors noted that the enterprises' behaviour of "ability to act on" [33], Life Cycle Thinking (LCT), which is an inherent nature of Sustainability Science (SS) [26] and Sustainability Analysis [34], are vital contributions toward framing a holistic LCSA tool. Parent et al. [33] emphasized the importance of LCT, LCA and SLCA in sustainable development and observed that SLCA is scarcely discussed under Statistical Process Control (SPC), and that the social impact of products on consumers is hardly mentioned. Thus Corporate Social Responsibility (CSR) and their appropriate efforts to act on social and customers' demands are vital to sustainable development.

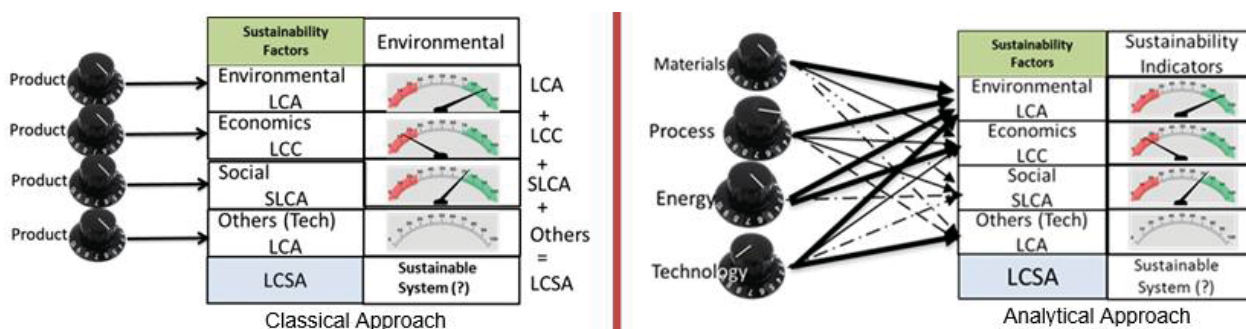


Fig. 1 Example of Classical versus Analytical Approach to LCSA

III. SS AND LCSA

In harmony with LCSA development, SS has also been posited as a holistic approach to achieving sustainability [26]. This method approaches sustainability development from cultural, historic and institutional perspectives. According to [26], its emergence compliments the inadequacies in classical disciplines and scientific approaches to the management of sustainability. The application of SS thus made it possible to "scientifically transcend reductionist analysis of classical science through a system thinking approach to address sustainability factors within a political and sustainability domain" [26]. One important 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 society, in order to design a holistic sustainability framework [14], [26]. Guinée, et al. [34] expressed the ideology of LCSA framework with a similar concept termed LCSA. This new framework better described the jointly analytical requirements of the combined LCA, LCC and SLCA methodologies. Sustainability Analysis is core to SS and is interchangeably used with Sustainability Assessment in some literatures [14], [33]. According to the observation of [26] 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 framework overcame this inadequacy through an integrated approach. Sala, et al. [26] also summarised the development of the sustainability analysis framework as characterised by a 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". This research aims to deploy the capabilities of both SS and LCSA (Analysis) with the view of a systemic and analytic approach to sustainability. This approach to sustainability is LCT based, which incorporates various sustainability assessment methodologies, methods and tools to analyse the interactions of sustainability factors and to evaluate their sustainability within a defined domain. Fig. 2 is the high-level view of the proposed analytical model. We aimed to disintegrate the various factors through cause and effect analysis and capture the life cycle inventories, in order to evaluate the sustainability indicators within the defined assessment boundary. Sala et al. [26] highlights key sustainability development principles as "Precautionary principle; Irreversibility, Regeneration, Substitutability, Critical Loads/carrying capacity, Holistic approach, Polluter pays, Future generations, Good governance (Subsidiarity, Proportionality and Public Participation)". While there is full consideration for all the principles, our research is in particular, aimed to incorporate the holistic approach and good governance into the proposed model. In

the introduction, it was mentioned how DES will provide the necessary platform for integration and analysis of the three sustainability factors. DES is the widely accepted tool for evaluating and improving systems behaviour; however, the existing commercially available DES does not include environmental and social factors in its modules. The authors of this study are still evaluating the strengths of Simio-DES software in providing the capability of incorporating

environmental and social factors; nevertheless, we have viewed our approach as a step forward towards achieving the analytical requirements for holistic sustainability development. MCDA is proposed for the analysis of various stakeholders' interest and to capture the social indicators, it will also provide the framework for interpreting the analysis results which involves value choices [14].

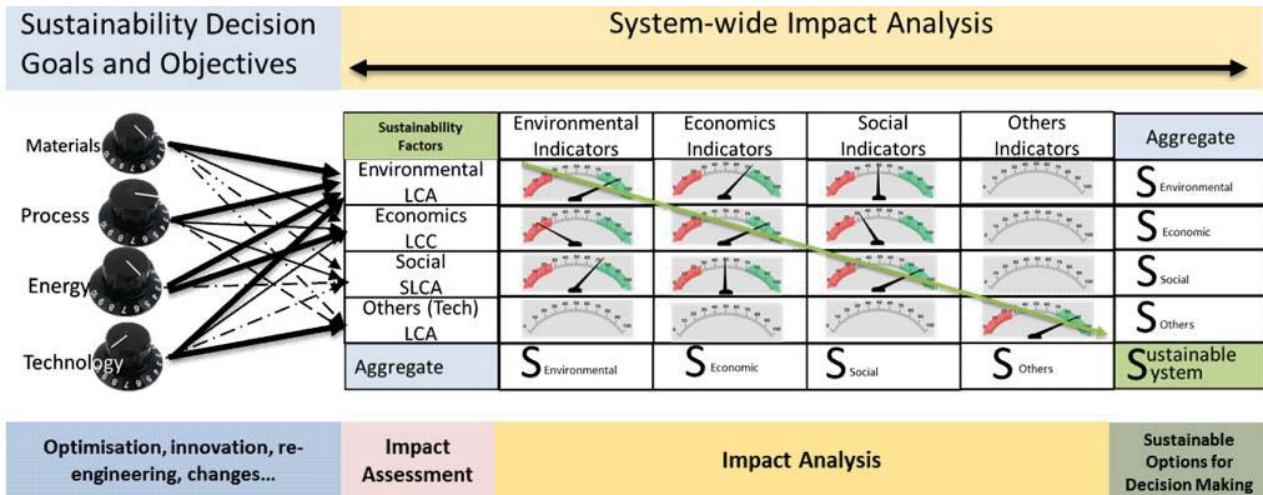


Fig. 2 Simulation-Based Conceptual Model for Life Cycle Sustainability Analysis (LCSA)

IV. SUSTAINABILITY ASSESSMENT SCOPE AND BOUNDARIES

The challenge of having large data, and or lack of necessary data and information that cut across a product life cycle, pose restriction in conducting an effective LCA. The system thinking approach to sustainability development involves understanding of the inter-dependences of the sustainability factors, the trade-off requirements amongst the sustainability pillars, and the occurrences of known or unknown desired or undesired consequences [14]. Guinée et al. [34] have posited the need for comparative analysis of the options to avoid unintended negative consequences and to proactively optimise positive impacts in the aid of achieving sustainability objectives. The scope of the life cycle of a product under assessment could sometimes span combination of geographical coverage, time frame, activities, connecting mechanism, and stakeholders or participating actors, thus making it complex to capture the required data. As in [14], the geographical scope of LCA can range from global to continental, country, regional, and down to the local scale.

In addition, within this scope, there may be geopolitical and regulatory implications to consider. The complexity of this challenge is partly addressed by well accepted boundary classification, such as "cradle to grave", "cradle to gate", "gate to gate", and "gate to grave". 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 [30]. The data identification and

collection process could be overwhelming and having inefficient data can cause a serious delay and restriction during development of a simulation model [39]. It is therefore necessary to define to what extent an assessment can look outside the assessment domain for a particular product or service under design.

Another interesting subject in the scope of sustainability development is: "What is to be sustained?" and "What is to be developed?" and the relationship between both [26]. The level of scale or scope is a function of the defined assessment boundaries since the perception of sustainability varies by geopolitical scale and time frame. Part of the challenge of the conflict in the performance evaluation of the sustainability factors are anchored on different perspectives of what the scope of the assessment is. According to [26], these differences in ideology are reflected in the various adopted weighting schemes in sustainability evaluation. The authors gave further examples of what is to be sustained under "Nature as: Earth, Biodiversity, Ecosystems; Life Support as: Ecosystem services and functions, Biotic and abiotic resources, Environment; and Communities as: Culture, Groups, and Places. Examples of what is to be developed under People as: Health, Life expectancy, Education, Equity, Equal Opportunity, Security, Safety, Well-being; Economy as: Employment, Decent work, Dignity of workforce, Desired consumption, Technology and transportation. Society as: Institutions, Social capital, States and regions". For this stage of the research, the authors proposed a strategic approach for the development of a simulation based impact analysis

framework that supports sustainable manufacturing decision making by defining and taking the following steps, Fig. 3.

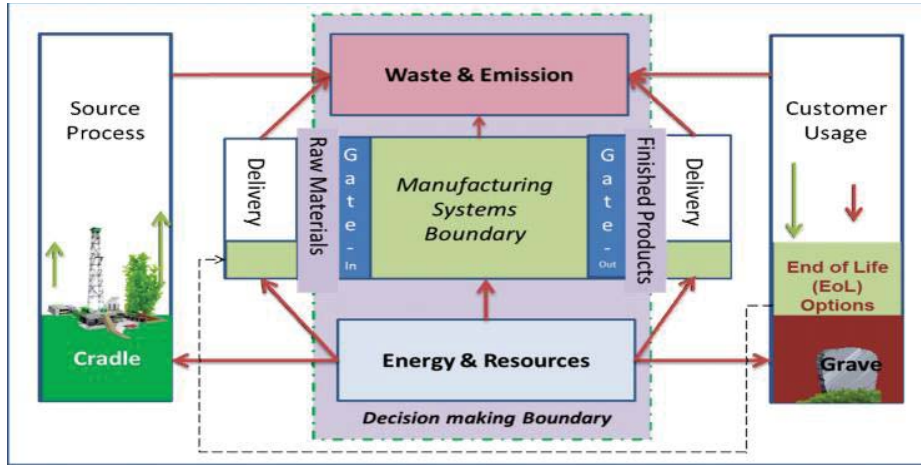


Fig. 3 Sustainable Manufacturing System Gate-to-Gate Boundary

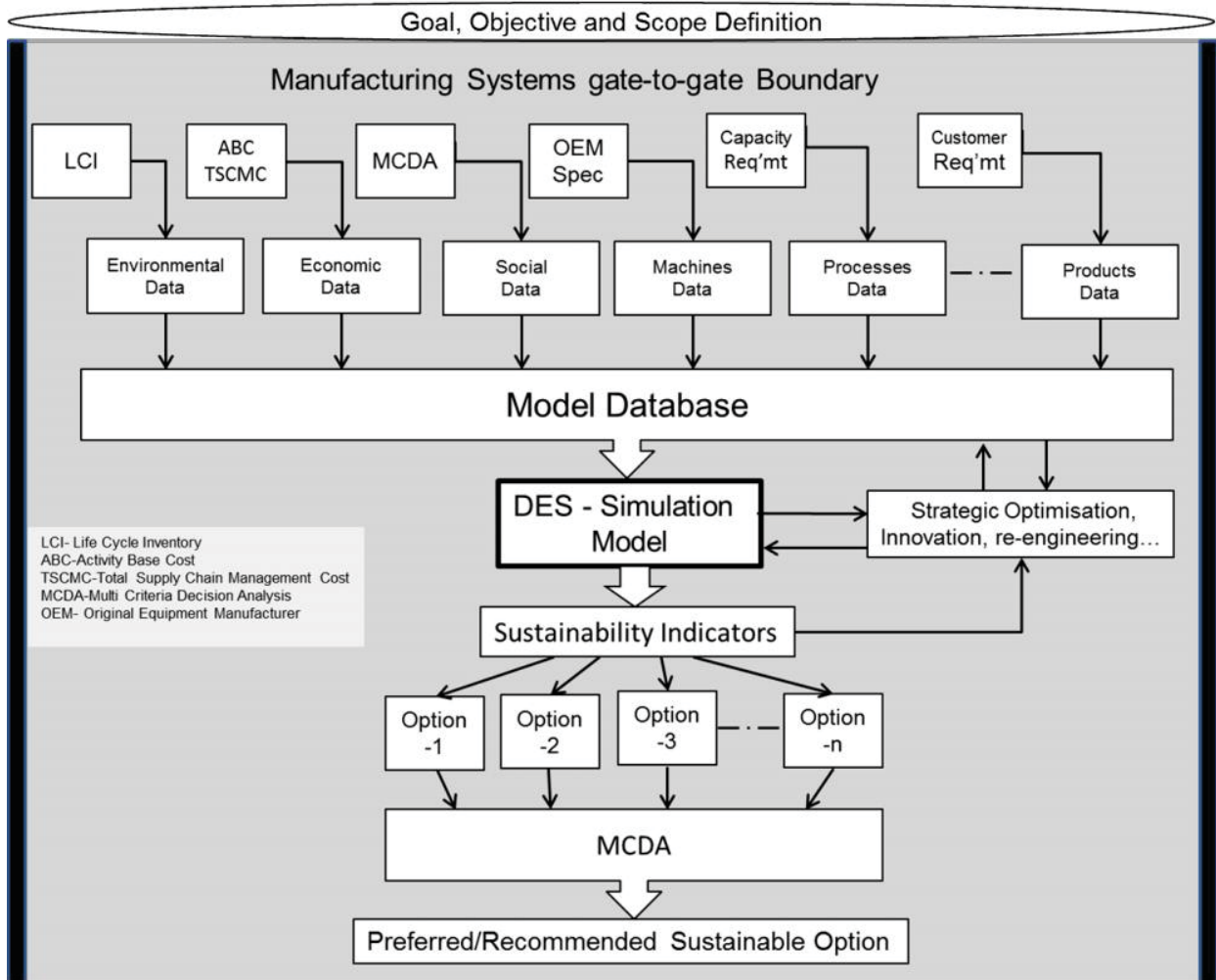


Fig. 4 Integrated Framework for Sustainability Analysis

V. PROPOSED FRAMEWORK FOR SUSTAINABILITY ANALYSIS

The Gate-to-Gate approach was mostly applied when there was no factual or literature information to study [35]; however, it has been repeatedly used recently in manufacturing process, to study the environmental impact of temperature change [25], [36]. Puettmann and Wilson [37] also used the gate-to-gate approach to conduct a study of life-cycle inventory for the production of glued-laminated timbers. Jacquemin et al. [25] in their review of application fields dealing with LCA, identified four researchers who used the gate-to-gate approach in the last decade. In this research, we adopted the gate-to-gate approach as shown in Fig. 3. The gate-to-gate boundary definition limits the scope of the decision and minimised the issues of LCA data. It is a progressive approach to achieve complete life cycle sustainability analysis of products or services. In future research, the authors aimed to progress from **gate-to-gate** to **cradle-to-gate**, **gate-to-grave** and **cradle-to-grave**. Cradle-to-grave will represent an all integrated analytical model that incorporates data from different stages of the product life cycle.

The definition of goal and scope is critical to conducting effective simulation-based sustainability analysis; it provides the necessary guide for collection and collation of modeling data. We are currently examining the strengths and weaknesses of various tools capable of capturing appropriate environmental, social and economic data of the product or service to be assessed. LCA application software, such as CES EduPack, SimaPro, Eco-Indicator99, Recipe and MCDA methods, are under review with the aim to evaluate their capabilities to capture the model data. The framework of the proposed procedure is depicted in Fig. 4. The DES-Simulation model provides the necessary links between the model database (known or captured data) and the sustainability indicators (the desired to know information). The sustainability indicators provide alternative sustainable options with measurable information about how sustainable combinations of input data are. The research aims to deploy Simio-DES software into the framework for integrated analysis with strategic optimization, innovation, substitution, and or process re-engineering. The result of the analysis will provide a combination of competitive and sustainable options that can support decision making.

VI. CONCLUSION

Sustainability development has evolved from inefficient LCA of individual sustainability factors into a holistic, integrated analytic Life Cycle Sustainability Analysis (LCSA) that requires contributions from various fields of discipline including analytical and computational science. This research reviewed different challenges including scope and boundary definitions, which often extend the data of a product life cycle beyond the understanding of the end consumer. This research has proposed a boundary strategy that could resolve the issues of unavailability of data that inhibits effective sustainability assessment. Furthermore, the approach is to combine DES

with multi-criteria decision analysis tool to analyse various input data from both competitive and sustainability aspects within a defined boundary. The findings of this research will serve as the basis for further work. It aims to model and gather discrete changes in the life cycle of a selected product and investigate the impact of the changes and the effects on decision making in a sustainable-oriented manufacturing design. The outcome of the analysis would underpin the development of a simulation aided decision-making tool for sustainability practitioners.

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