Holistic Simulation-Based Impact Analysis Framework for Sustainable Manufacturing

Mijoh A. Gbededo, Kapila Liyanage, Sabuj Mallik

***Abstract*—**The emerging approaches to sustainable manufacturing are considered to be solution-oriented with the aim of addressing the environmental, economic and social issues holistically. However, the analysis of the interdependencies amongst the three sustainability dimensions has not been fully captured in the literature. In a recent review of approaches to sustainable manufacturing, two categories of techniques are identified: 1) Sustainable Product Development (SPD), and 2) Sustainability Performance Assessment (SPA) techniques. The challenges of the approaches are not only related to the arguments and misconceptions of the relationships between the techniques and sustainable development but also to the inability to capture and integrate the three sustainability dimensions. This requires a clear definition of some of the approaches and a road-map to the development of a holistic approach that supports sustainability decision-making. In this context, eco-innovation, social impact assessment, and life cycle sustainability analysis play an important role. This paper deployed an integrative approach that enabled amalgamation of sustainable manufacturing approaches and the theories of reciprocity and motivation into a holistic simulation-based impact analysis framework. The findings in this research have the potential to guide sustainability analysts to capture the aspects of the three sustainability dimensions into an analytical model. Additionally, the research findings presented can aid the construction of a holistic simulation model of a sustainable manufacturing and support effective decision-making.

***Keywords*—**Life cycle sustainability analysis, sustainable manufacturing, sustainability performance assessment, sustainable product development.

I. INTRODUCTION

THE increasing awareness and challenges of sustainable consumption and production are leading many organisations to consciously limiting environmental and social degradation during economic development [1], [2]. The lack of life cycle thinking approach to the use of limited earth resources has been said to be a major global threat to existence [3], [4]. The implications of the activities involved in creating economic products are, however, not only restricted to the environmental impacts but also societal sustenance of the employees, local and global communities, customers, and suppliers [3], [5]-[7]. Various approaches as detailed in many sustainable manufacturing and related articles are aimed at providing a solution to these challenges [2], [8]. The product design engineers use a wide range of engineering methods and life cycle thinking approach to embed sustainability into the classical product design process [9]. Methods such as checklists, guidelines, MET matrix, and the environmental Life Cycle Assessment (eLCA) are often used for assessing the environmental performance of the processes [10]-[12]. Social life Cycle Assessment (S-LCA) and Life Cycle Costing (LCC) are also prevalent in the articles that concentrate on eco-design and eco-innovation [8], [12]. Similarly, the production engineers integrate sustainability approaches into the classical competitive manufacturing processes to model cleaner production, greener production, or lean-green manufacturing processes [13], [14]. These approaches incorporate strategies such as energy modelling, total quality management, and lean techniques to enhance waste reduction, resource optimization and efficiency of the processes. In addition, corporate social responsibility and costing tools such as activity-based-costing have been used respectively to ensure organizational ethical commitments and the economic soundness of the processes [5], [15].

A literature review has identified two major approaches to sustainable manufacturing which supports both the product design engineers and production engineers in development of a sustainable product: 1) SPD techniques and 2) SPA techniques [16]. The SPD techniques focus on resource conservation and environmental protection through waste reduction, use of alternate materials, optimisation, and elimination of toxic and harmful materials in developing products and processes [8]. The SPA techniques concentrate on ensuring the sustainability of the products and processes through quantitative performance assessments of the product lifecycle, and the processes involved in producing the products [17], [18].

The approaches to these two paradigms are, however, still segmented in the reviewed literature; that is, they have not been able to capture and analyse the interdependencies of the three sustainability dimensions [3]. Hence, they are unable to support effective decision-making [19]. Though various strategic methods for eco-design such as design-for-remanufacturing, design-for-recycling, and design-for-reuse [20] have been deployed with SPA tools, the challenges, however, are in combining the advantages of the approaches in a common framework to facilitate continuous effective sustainability decision-making [12]. In a previous research, a framework for optimising the advantages of the two paradigms has been developed and validated using a Delphi study, and the method for aligning the social impacts and the Herzberg two-factor theory of motivation has also been

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presented in line with the Delphi evaluation process [21]. This paper, therefore, outlines a theoretical framework for combining the two concepts into a holistic simulation-based impact analysis model. The aim is to enable sustainability practitioners to build a conceptual model which is able to capture both competitive and sustainability strategies and conduct an impact analysis of the three sustainability dimensions.

In the next section, this paper discussed the relationship between eco-innovation and sustainable development, followed by Section III which covers the approaches to sustainable manufacturing and life cycle sustainability analysis. Section IV details the sustainability impact analysis framework, and Section V presents the framework for conceptual modelling of integrated simulation-based sustainability impact analysis. Section VI describes how to capture the social impacts and calculate the social impact coefficient, and Section VII summarises the study and conclude.

II. Eco-Innovation and Sustainable Development

The term eco-innovation has been used by many organisations to describe contributions towards sustainable development whilst improving the business competitive advantage [8]. There are, however, some misconceptions in the definition of eco-innovation as related to other "natural" innovations and sustainable development. The OECD [8], states

> "eco-innovation is an innovation that results in a reduction of environmental impact, no matter whether or not that effect is intended".

This definition often places eco-innovation and classical innovation in the same category in sustainable development. "Natural" innovations whose primary focus are not environmental protection may sometimes result in environmental gains [22]. However, a focus on competitiveness and environmental-friendliness will always distinguish an eco-innovation from other classical innovations. According to [22],

> "the relevant criterion for determining whether an innovation is an eco-innovation is that its use is less environmentally harmful than the use of relevant alternatives".

Thus, eco-innovation is a planned and intended approach to product or process development with the aim to reduce environmental impacts while sustaining the business competitive position. Sustainable development, however, as defined in the Brundtland report [5] termed "*our common future*" focuses on the environmental protection, economic development, and the social development. Hence, the main challenge with eco-innovation is the segmented approach to the three sustainability dimensions [12].

According to [8], the main interest of eco-innovation is on competitiveness and sustainability of the manufacturing process. To achieve this goal, eco-innovation focuses on change, redesign or modification of products, processes, and organisational systems such as technology, policy, and services [12]. For example, to extend a product's lifecycle, modularity and other remanufacturing techniques are deployed in eco-design [9], [23], [24]. Other approaches include the change of product materials to eliminate toxic materials or to enhance reuse and recyclability of the product. Similarly, eco-innovation targets the redesign of production processes to enhance waste reduction, quality, and energy efficiency [25]-[28]. In lean-green manufacturing and cleaner production, eco-innovations techniques are deployed to improve the competitiveness and sustainability performances [29], [30]. Thus, according to [8], eco-innovation has a three-dimensional approach to competitive sustainable manufacturing and can best be understood and analysed according to these dimensions: 1) The "TARGETS" such as process, product or technology that required amendment due to a perceived or real negative impacts on the environment. 2) The "MECHANISMS" such as redesign, modification, and change to be deployed to implement the required amendment on the "target". 3) The "IMPACTS" such as energy consumption, toxicity, and resource conservation which the outcome of the amendment will have on the environment. Fig. 1 depicts the relationship amongst the eco-innovation three-dimensional approaches.

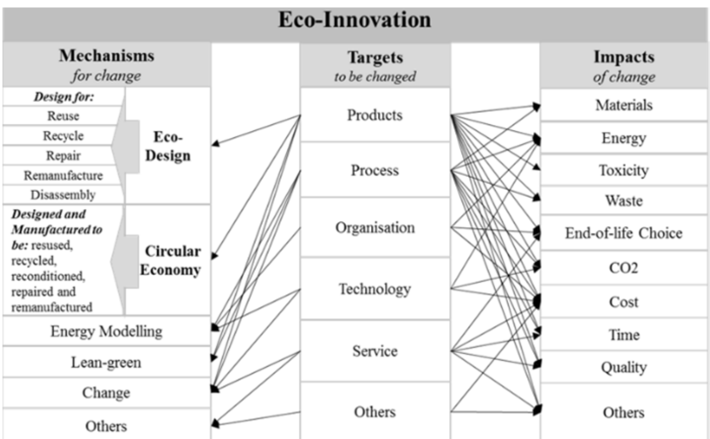

Fig. 1 Eco-innovation three dimensional approach [16]

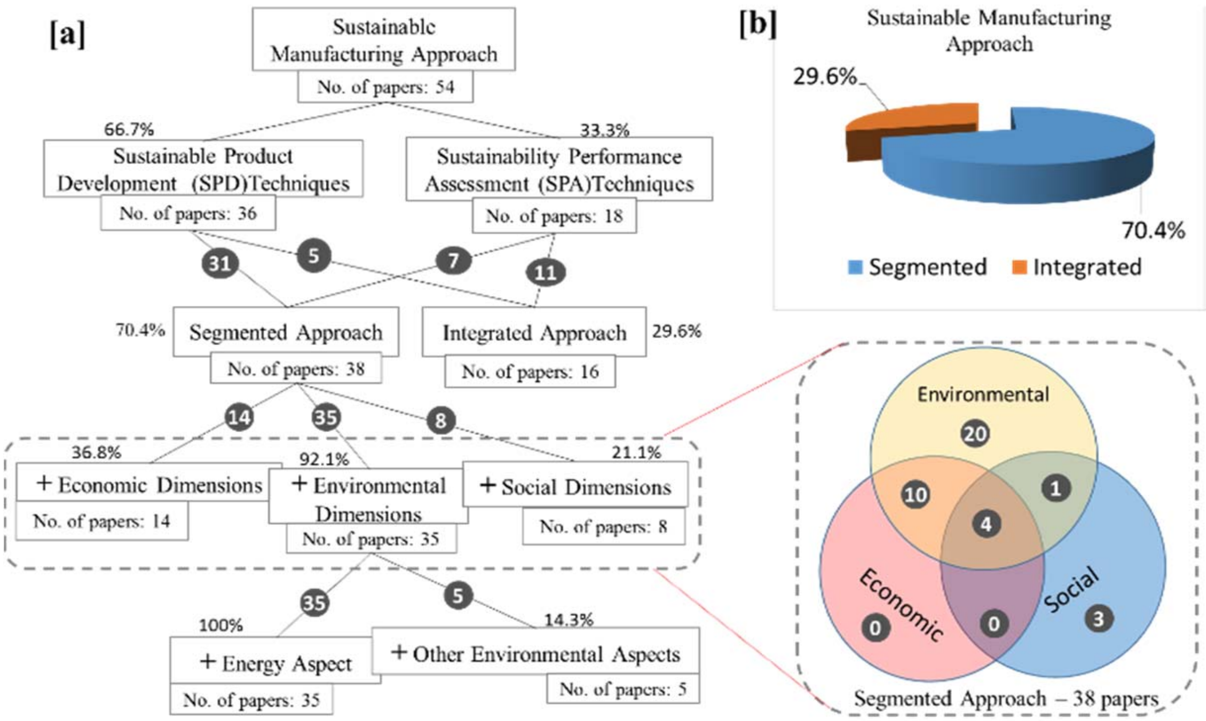

Fig. 2 Classification of sustainable manufacturing approaches [16]

III. Life Cycle Sustainability Analysis (LCSA) and Sustainable Manufacturing Approaches

The concept of Life Cycle Sustainability Analysis (LCSA) was launched to holistically address the objectives of sustainable development [5], [31]. The three pillars of the sustainable development which are environment, economy and society have been central to both the academics, practitioners and policymakers in addressing the sustainability issues [31]. The LCSA concept was launched by the life cycle initiative partnership of the United Nations Environment Programme (UNEP) and Society for Environmental Toxicology and Chemistry (SETAC) to encompass the three sustainability dimensions through life cycle thinking and interdependence analysis [31], [32]. The initiative supports some of the existing initiatives such as the ISO 14040 series for eLCA principles and framework [33], ISO 26000 social responsibility guidance standard for S-LCA [34], and ISO 15686-5:2017 buildings and constructed assets for Life Cycle Costing (LCC) [35]. Since the launch of LSCA initiative in 2011, various discussions, approaches, and applications have been recorded in many articles to support the LCSA methods. However, the challenge of integrating the three sustainability dimensions in sustainable manufacturing are still prevalent in the discussions [36], [37]. Whilst some authors focus on the importance of holistic approach to the three sustainability dimensions (integrated approach), others still concentrate on the segmented approaches that focus on one or two of the three dimensions. One of the major issues highlighted in the current articles is the challenge of integrating the social aspects with other sustainability factors in an analytical framework [36].

In the systematic review of sustainable manufacturing approaches towards LCSA [16], two major categories of approaches were identified as predominant among the reviewed authors from 2006 to 2015: 1) the approaches that focus on support for sustainability decision-making through process, system or product's SPA, and 2) those that focus on innovative design or continuous improvement of the processes, systems or products to support SPD, see Fig. 2 (a). The articles that focused on SPD deployed eco-innovation mechanisms such as eco-design, circular economy, and energy modelling [25], [38], [39] while SPA focused on approaches that support decision-making such as eLCA, checklists and guidelines [28], [40]. The result of the review indicated that most of the approaches in the two categories are segmented (70.4%) compared to those authors that focus on integrated approach (29.6%), see Fig. 2 (b). Further, in the analysis of the review, environmental aspects received the highest focus in sustainable manufacturing approaches (92.1%), while social aspects are least considered (21.1%) among the segmented approaches (see [16] for details and methodology adopted).

In view of the analysed articles, a gap in the research is clearly identified for a framework that supports the integration of the three sustainability dimensions [11], [16]. The integrated framework will enable the construction of a conceptual model that combines the three sustainability dimensions in a common framework. In the next section, we described a theoretical framework developed through an inductive analysis [16].

IV. Integrated Sustainability Impact Analysis Framework

The sustainable production environment is characterised by uncertainties due to the increasing changes in the consumption and production patterns, and a growing complexity of products, products modularity, diversity, and social issues [41]. These challenges expose the business to the risks of unintended consequences which can significantly damage the organisation's competitive position. The ability to effectively cope with this dynamic environment requires a holistic analytical tool that can support effective decision-making [41], [42]

The application of Discrete Event Simulation (DES) with sustainability methodologies to support decision-making is not a new concept in the operational level of manufacturing [43]. Many authors in the field of sustainable manufacturing have integrated sustainability methodologies into DES to support decision-making [44], [45]. This is due to DES functionalities which enable the modelling and analyses of a dynamic operation's environment [16]. The importance of combining the advantages of existing sustainable manufacturing approaches has also been emphasised [11], [32].

A. Theoretical Framework for Impact Analysis

The integrated sustainability impact analysis framework is aimed to optimise and experiment with combinations of the three sustainability dimensions in a DES analytical environment. The theoretical framework will provide the guidance for integrating sustainability into the product design and production process, and conducts the impact analysis of the three sustainability dimensions Fig. 3.

The defined SPD goals and scope sets a boundary for the competitive and sustainability objectives. In an iterative process with strategic thinking, "partial-sustainable-process models" are generated from the competitive strategies, SPA, and variables to be controlled. Similarly, by lifecycle thinking in an iterative process, "partial-sustainable-product versions" are generated from the sustainability strategies, SPA and the variables to be controlled. The parameters from the two axes are then modelled into the simulation input database. The challenge of capturing and converting qualitative social aspects of sustainability into a measurable quantitative unit has made many authors leave social aspects out of the analytical equation. In a predefined process, the Social Impact Coefficient (SIC) is calculated and modelled into the simulation input database. The SIC is synonymous with the labour productivity factor, and it is calculated from the identified social aspects in the defined variables to be controlled (see [21]).

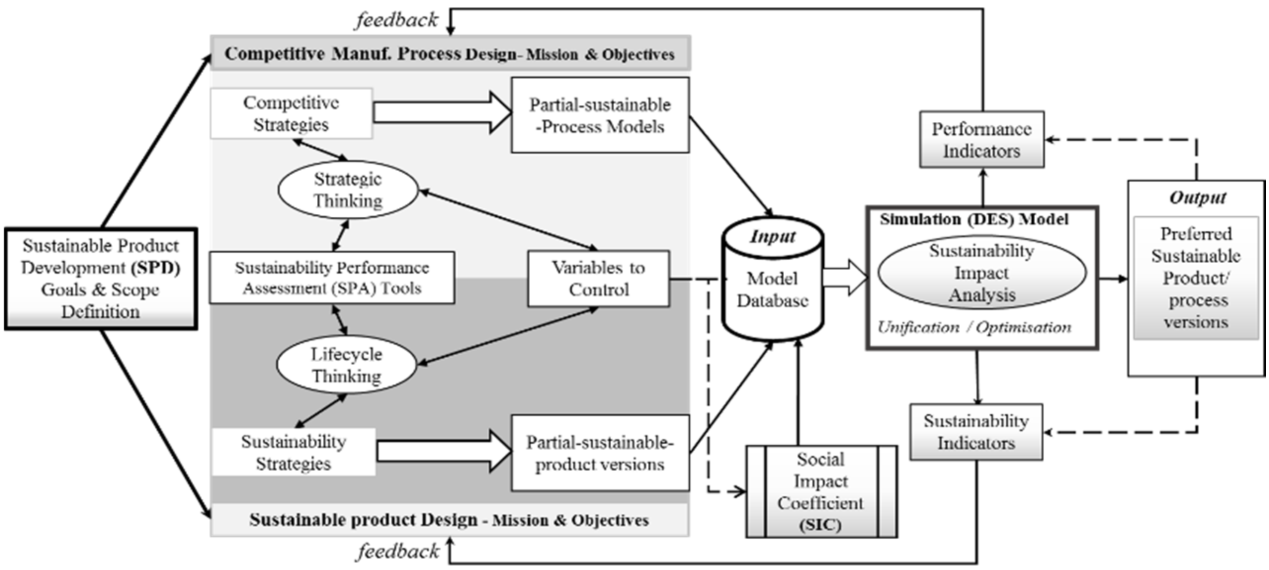

Fig. 3 The theoretical framework for holistic simulation-based sustainability impact analysis

V. Simulation-Based Sustainability Framework for Conceptual Modelling

In a Delphi study consisting of a mix of 24 academics and industry experts from the field of sustainable development, a series of survey questions were deployed to review the completeness, correctness, conciseness, and clarity of a developed descriptive holistic sustainability framework. The descriptive holistic simulation-based sustainability impact analysis framework is an amalgamation of sustainability tools and approaches, developed in the initial theoretical framework in Fig. 3. The framework deploys the principles of LCSA [31], and simulation conceptual modelling frameworks [46] as shown in Fig. 4.

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 descriptive 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 [46], [47].

The Delphi survey further explored the relationship between the social dimension of sustainability and the theory of motivation as related to workers' productivity. There was a consensus among the 24 experts after a two-round study that there is a relationship between social aspects and workers' motivation and productivity.

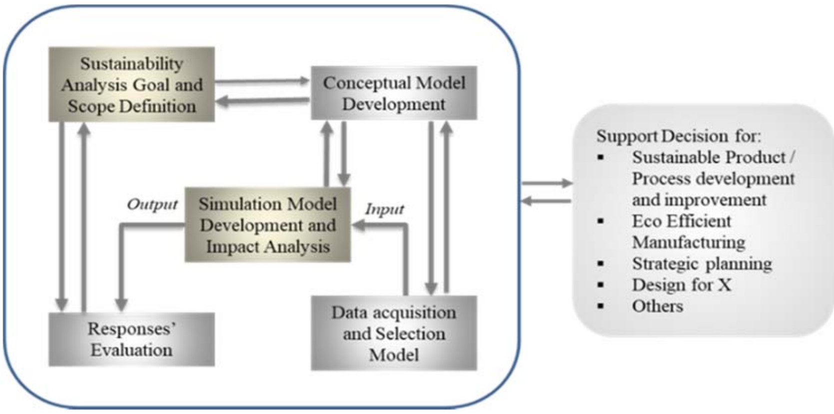

Fig. 4 A Framework for Conceptual Modelling of integrated Simulation-Based Sustainability Impact Analysis

VI. Social Impact Assessment (SIA) and Social Impact Coefficient (SIC)

Many reviewed articles and empirical studies have shown the economic benefits of integrating environmental aspects of sustainability into the product and production design processes. However, the integration of the social aspects and its benefits on the aspects of other sustainability dimensions have not been fully captured for analysis [21]. The terms such as eco-design, lean-green and clean productions are often used to describe the business commitments to environmental issues, whilst the concepts of corporate social responsibility are used separately to highlights the social commitments. The lack of clear integration and assessment of business social impacts and the interdependency with other sustainability dimensions exposes the business to the risk of ineffective sustainability decision [48].

The Social Impact Assessment (SIA) is a methodology that focuses on the social impacts occurring at a single processing or facility level [7], [21], [48], [49]. Unlike the S-LCA that assesses the social impacts of an entire product lifecycle, SIA focuses on a single stage of the product lifecycle such as a project site, roads, recycling sites, shops, and factories. Every social hotspot is identified with groups of social stakeholder categories and subcategories. According to the Global Reporting Initiative (GRI) [50] and [7], there are five major stakeholder categories: the workers, customers, suppliers, local communities, and national and global societies. Each of the categories is associated with impact subcategories which are of interest in social performance measurements.

According to Benoit et al. [7], the social hotspot is

> "unit processes that are within a sector and region that has high risks of negative impact or high opportunities for positive impact".

The positive social impacts present high opportunities to promote workers well-being and performance, while the negative social impacts are of high risks both to the worker's and business economic development [50]. In a review, the alignment of the positive and negative social impacts with the Herzberg two-factor theory was presented, see [21], [51]. In the review, the authors discussed the theory of reciprocity, social exchange principles and employees' productivity at work and argued the relationship between the social impacts and the theory of motivation according to Herzberg [51].

A. Social Impact Coefficient (SIC) β

The alignment of the positive and negative social impacts with the two-factor Herzberg theory enabled the calculation of the social impact coefficient (SIC) [21]. SIC is synonymous with the Productivity Factor (PF) which is a measure of workers' productivity. Total Factor Productivity (TFP), Multi-Factor Productivity (MFP), and Partial Factor Productivity (PFP) are examples of PF used by practitioners to explain and improve efficiency and productivity of manufacturing inputs, economic growth, and workers welfare [52], [53]. The SIC (β), determines the intensity of an employee motivation at work. In an ideal situation, an employee will work at 100% or ($\beta = 1$) of his/her capability when all the necessary tools and skills are provided. The SIC is calculated from the aggregation of the weights of the positive social impacts (γ) and negative social impacts (α) Fig. 5.

The calculation of SIC facilitated the integration of social aspects into the sustainability analytical equations. This will enable the practitioners to determine the impacts of social aspects on employee's productivity and the economic development. SIC has the highest coefficient of "1" and serves as a multiplier in a simulation model.

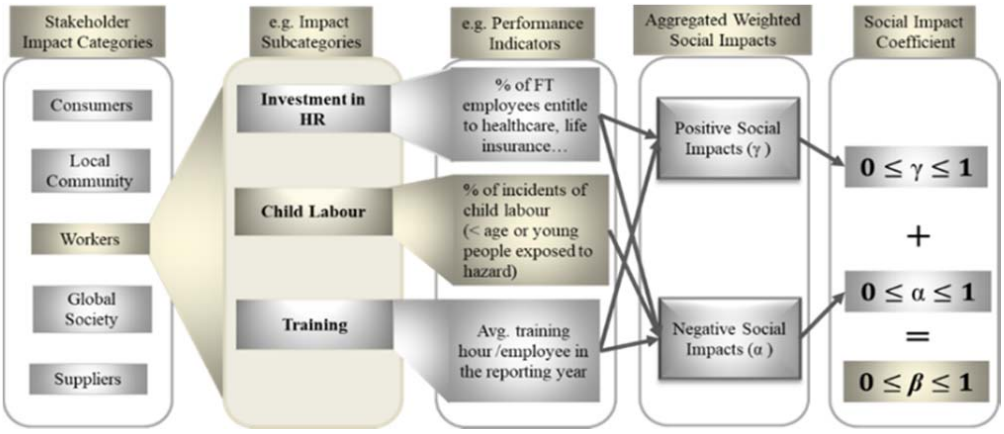

Fig. 5 Key components and process for calculating the social impact coefficient (β) [21]

VII. Summary and Conclusion

This paper discussed SPD and SPA as the two major approaches to sustainable manufacturing [16]. The misconception of eco-innovation which has been synonymous with sustainable development is also discussed, and the authors argued the importance of integration and interdependent analysis of the three sustainability dimensions.

Starting from the results of previous research, this paper discussed an integrative approach which would enable a holistic simulation-based sustainability impact analysis. The paper captured a process for calculating the social impact coefficient (SIC), a factor similar to Productivity Factor (PF) used by practitioners to explain and improve efficiency and productivity of manufacturing inputs, economic growth, and workers' welfare. The SIC is an aggregation of the weighted values of positive and negative workers' social impacts, the highest value attainable for a business SIC is "1" [21]. The result of the SIC and the framework for conceptual modelling will enable sustainability practitioners to build a conceptual model which is able to capture both competitive and sustainability strategies and conduct an interdependent analysis of the three sustainability dimensions.

It should be noted that this framework is still in its initial development stage and has been able to capture the workers' social stakeholders' category. The ability to capture other social stakeholder categories and integrate the factors in a holistic model is an area of future research. The empirical application of the SIC has not also been studied. However, the GRI [50], provides extensive formulas for calculating various social subcategories which played important roles in the calculations of the workers' SIC.

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