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Eco-social sustainability assessment of manufacturing systems: an LCA-based framework

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Abstract

In this paper, model-based sustainability assessment framework with social impact considerations is developed. The framework integrates the stochastic, nonlinear, and complex interrelationships that characterize most manufacturing systems, and incorporates their impact in the sustainability assessment module. The framework consists of three models that run successively, namely: stochastic discrete-event simulation (DES) model, environmental lifecycle assessment (LCA) and social LCA models. To test and validate the model, and to demonstrate its applicability and usefulness in industrial settings, a case study on the environmental and social impacts associated with the manufacturing of an aerospace component is carried out. Results revealed that integrating the stochastic behaviour of production systems can unveil production issues that are likely to arise at the strategic level and affect the sustainability performance, while not being instantly perceptible. Social LCA indicated that, although input data suffered from quality issues, there is a potential higher risk associated with overseas upstream supply chains. This risk can, however, be potentially mitigated through technology-based enhanced traceability and transparency of upstream supply chains, or even the localization of upstream activities, where possible.

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1. Introduction

The manufacturing sector, with a total share of an estimated 54% of the world's delivered energy [1], is one of the world's most prominent contributors to global warming. In addition to the environmental impact caused by emissions, resource use and toxicants, the manufacturing sector's impact on the social pillar of sustainability, particularly when examined from a lifecycle perspective, is also a concern [2]. Sustainability assessment of the environmental pillar is much more mature than its social counterpart, with a series of ISO standards (ISO 14040 series) that provide detailed standardised guidelines for carrying out lifecycle assessment (LCA) studies to assess environmental impacts. As for the social pillar of sustainability,

which is concerned with the potential impacts (both positive and negative) and risks on varying stakeholders (e.g., local community, employment, labour rights etc...), the most widely adopted tool, social lifecycle assessment (SLCA), is considered to be underdeveloped, or even described as being 'at its infancy' [3,4]. As a result of this underdevelopment in social lifecycle assessment, and in addition to the more pronounced risk of subjectivity in SLCA modelling, outcomes of poorly conducted social SLCA studies can be misleading. This could be attributable to, in addition to the aforementioned characteristics of SLCA, the difficulty of accessing and quantifying social data, as well as concerns about integrity of the collected data. There exists, however, detailed guidelines for carrying out SLCA studies, such as the United Nations Environment

Program's "Guidelines for Social Life Cycle Assessment of Products and Organizations" [5], which is considered the most widely accepted social assessment methodology [6].

In this paper, an LCA-based sustainability assessment framework for the environmental and social sustainability assessment of the manufacturing sector is developed. The framework consists of a discrete-event simulation model that feeds the environmental LCA model with an additional stream of case-specific data, an environmental LCA model and a social LCA model that run in a successive manner. The framework is validated, to demonstrate its applicability and usefulness, on a case study on the manufacturing of a metallic component from the aerospace manufacturing sector. The main novelty of this paper is the integration of different modelling tools, particularly simulation modelling as a complementary source of case-specific data, that account for stochasticity, and assesses both environmental and social sustainability in a unified framework. Although the framework is tested on a case study from the aerospace sector, it is equally applicable to any other industrial setting, as the main manufacturing processes and interrelationships are integrated in the simulation model.

The rest of the paper is organised as follows: in the next section, the framework is presented and its governing mechanisms explained. In Section 3, a case study on the environmental and social sustainability assessment of an aerospace component is carried out. Finally, the last section concludes with a brief discussion on the main takeouts from this paper, limitations of the framework and possible future research direction.

2. Related work

Although the advancement in environmental sustainability assessment, particularly LCA-based approaches, are far more advanced than those of social sustainability, particularly social LCA, interest in social LCA has been steadily increasing in the recent years [7]. Several review papers on social LCA have materialized in the recent years. In [8], the authors analyzed the literature on social LCA. In their critical analysis of 190 social sustainability assessment papers, the authors proposed a timeline for the development of social LCA, where they suggest that social LCA is currently at the 'search for standardization' stage. In [3], the authors analysed sustainability assessment case studies that utilized social LCA. Although their analysis included 35 papers, the author concluded that a universal definition of social LCA is still missing. The authors suggested that this absence of a universal definition can be attributed to the absence of impact assessment methods, which are well established for the environmental counterpart. In another review paper, the authors in [9] review the literature on social sustainability assessment of the mining sector. This sector is very important as the environmental and social impacts of mining activities are present in all LCA-based studies with 'cradle' as their starting point (e.g., cradle-to-gate, cradle-to-grave etc...). The methodological choices and assumptions in LCA-based studies that start from the cradle often treat mining activities, sometimes combined with raw material production (i.e., activities that start from material extraction up until the material is ready for processing) and transportation, as black

box. Therefore, the findings of [9] can provide valuable guidance and insights into modelling upstream LCA-based activities.

In several occasions, social LCA has been combined with environmental LCA in a unified framework. In [10], the authors combine environmental and social LCA along with lifecycle costing (LCC) in a unified framework in a comprehensive sustainability assessment study of recycled plastic. In their findings, the authors of [10] identify burden shift in recycling plastics that has an adverse impact on the social pillar of sustainability. They, however, conclude that more improved and focused social databases must be developed first in order to draw firm conclusions with regards to the social risks associated with recycling activities. In [11], the authors combine environmental and social LCA in their sustainability assessment study of light emitting diodes (LED) lighting. In this paper (i.e., [11]), the authors drew interconnections between social and environmental LCA, and they recommend employing these two LCA-based tools together whenever conducting a sustainability assessment study.

3. Sustainability assessment framework

The framework starts first by modelling the production system, or by defining different production scenarios, which are then modelled in the stochastic discrete-event simulation model over several replications. These scenarios, which are defined by the user, can reflect current as-is, and potential what-if, production settings. These what-if scenarios can be part of sensitivity analysis experiments, where the values of key parameters are changed, and the outcome is observed, to establish an understanding of the impact that the change in these parameters can pose on the system's performance. The change in these parameters can reflect, amongst many others, an anticipated growth in production rate, an expected growth in the share of clean energy in the grid mix, or machines' depreciation, represented in longer breakdown times and more adverse environmental impact due to the consumption of resources needed to repair the equipment. From the perspective of this paper, future process changes can be assessed which may have an effect on factory emissions or the workforce and therefore have a social impact.

The role that the simulation model plays in the framework is a complementing one. To explain more, lifecycle inventory (LCI) data, both from primary and secondary sources, provide either average values, or values at certain operating conditions at a snapshot in time. Therefore, complementing LCI data with stochastic simulation outcomes can add an extra level of validity, within the intended domain of the study, to the LCA input data. This enhanced validity comes from the inclusion of the impacts of disruptions, and other stochastic and dynamic events, such as rejection and rework after inspection, energy consumption of machinery at varying stages of their operation (e.g., setup, changeover, idle etc...) and variation in materials and other resources, amongst others. In addition, the information revealed from the simulation model, particularly when the modelled system is yet to be founded, can lead to decisions that would indirectly impact the sustainability performance. An example of which is if, when the production system is modelled under stochastic conditions, a bottleneck is identified before a certain process, the solution might be to add

an extra resource (e.g., worker or additional equipment), which might in turn affect the environmental, social and economic profiles of the manufacturing institute.

Since the simulation model is stochastic, performance metrics obtained from a single simulation run are hardly reflective of the day-to-day operations of the modelled system. In order to supply the environmental LCA model with more representative input data, several replications, each with different random seed, are run, and then their mean values are fed into the LCA model. The confidence interval method is employed in the framework to determine the minimum number of simulation replications that are required to produce statistically significant outputs [12]. Once the minimum number of simulation replication has been determined, and the mean of the outcome of these replications is calculated, the framework checks whether all scenarios, if any, have been modelled or not. If all scenarios have been run, then the values generated from the simulation model are fed as supporting data to complement LCI. If not, then the process of running simulation replications is repeated as explained earlier as depicted in Fig. 1 below.

It should be noted that, in the context of this study, the simulation model supports the environmental LCI, and does not supply the social counterpart with input data. This is because social data are typically more difficult to quantify, prone to subjectivity and does not conform well to the discrete-event simulation modelling paradigm. Social-related data can, however, be modelled through different simulation paradigms (i.e., system dynamics and agent-based modelling) that can capture the subtle interrelationships and the complexity of social systems (e.g., through causal loops in system dynamics). Integrating any of these simulation modelling paradigms into the framework would, however, require hybrid modelling, which is outside the scope of this manuscript.

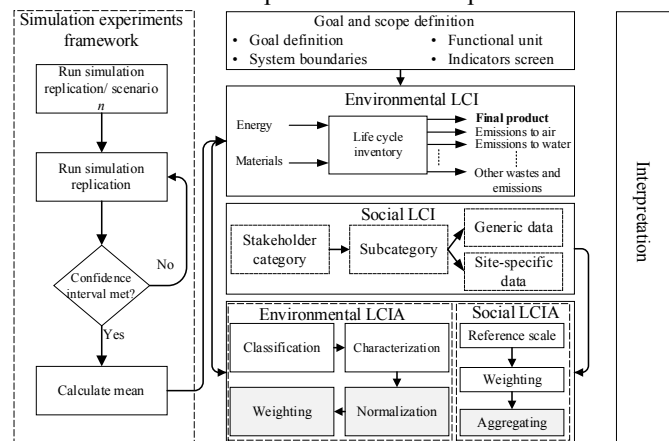


Fig. 1. Sustainability assessment framework

As for the sustainability assessment module of the framework, the steps for LCA (i.e., goal and scope definition, lifecycle inventory, lifecycle impact assessment, and interpretation) apply to both the environmental and social dimensions of the sustainability assessment. For the goal and scope definition, the outcome of this phase is the same for both the environmental and the social dimensions of the assessment (i.e., definition of the functional unit, determining the system boundary etc...). In the LCI phase, data related to both the environmental and social aspects are collected. Sources that can be used for data collection are public sources which

encompass contemporary literature, specialised databases (e.g., ecoinvent, the United States Life Cycle Inventory database (USLCI) for environmental-related data, and Social Hotspot Database (SHDB) for social-related data, amongst others), and primary data. These primary data are often company-specific and are obtained directly from the manufacturing company (e.g., utility bills, gas sensors readings to measure CO₂e levels, surveys about employees' satisfaction etc...). To ensure that the quality of the data collected is at an acceptable level of accuracy and representativeness of the reference situation, a pedigree matrix, which includes five quality aspects (namely: reliability, completeness, temporal, geographical and technological representativeness [13]), is built at this stage. The data in the pedigree matrix are then scored on a scale (e.g., from 1 to 5) [14]. In the social LCI phase, reference scales are set at this stage. Reference scales pertaining to social LCA are explained next.

In the lifecycle impact assessment phase (LCIA), the environmental assessment follows the steps specified by ISO standards 14042 standards [15] where the impact pathways method is employed. As for the impact assessment of social sustainability, the reference scale approach, provided by the United Nations' Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 [5] was followed. In the reference scale approach, social hotspots or *potential* social assessment performance are obtained through benchmarking impact indicators [5]. Examples of reference scales can be found in Table 1.

Table 1 Reference scale in social LCA, adapted from [16]

Scale level	Description
+2	Ideal performance
+1	Beyond compliance performance
0	Compliance with local laws
1	Non-compliant but improving
2	No data, or non-compliant

The shaded boxes in Fig. 1 represent the lifecycle impact assessment (LCIA) steps that are optional. These steps, although much debate revolves around them, are considered in the framework. In the weighting step in social LCIA, the relative importance of each indicator is established. It should be noted that weighting the indicators comes at the risk of subjectivity. It is, however, used here as it enables a more accurate representation, and protects against distortion of the results after the aggregation step. Aggregation, in the context of social LCIA, is the consolidation of outcomes into one score, which improves the understanding and assessment of the final outcome. In aggregation, low scores indicate negative impacts, while higher scores indicate a positive one. The weighting and aggregation processes are described in detail in [5].

In the final stage of the framework (i.e., interpretation), the results are analysed within the intended domain of application. In the interpretation phase, which is revisited recursively throughout all phases of LCA modelling, the decision-maker might recommend a change in the modelling assumptions, methodological choices, or further analysis of certain processes, amongst others.

4. Case study

4.1. Background

In order to test and validate the framework, and to demonstrate its applicability, a case study on a new aluminium aerospace component is carried out in this section. The modelled component has passed the design and testing stages, but is not yet fitted on aircrafts. The component, which will be

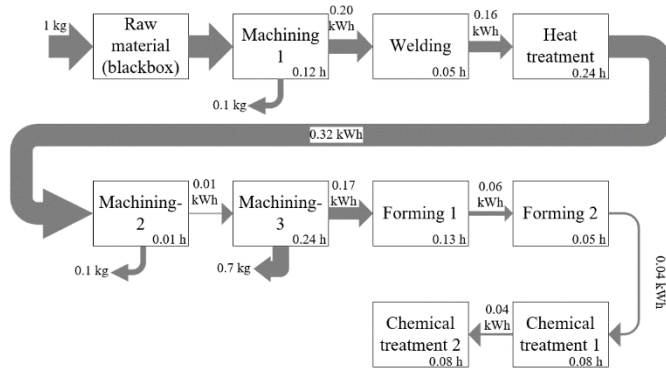


Fig. 2. High-level Sankey diagram of the production process

produced in the UK, is considerably more lightweight than the component it replaces, which would result in an improvement over the entire lifecycle of an aircraft. The environmental and potential social impacts associated with the widescale production of this component are still not yet fully established. Therefore, this section will carry out an environmental and social sustainability assessment to determine the impact associated with the manufacturing of this component. All numerical data will be normalised, and production processes names will be generalized, for confidentiality reasons. Fig. 2 below depicts a high-level view of the production processes of the component.

In Fig. 2 the major manufacturing processes required to manufacture the component are depicted. It should be noted, however, that the Sankey diagram in Fig. 2 does not include moving, loading, queues, and testing activities.

The first step in the framework is to build the simulation model. The simulation model, which is a stochastic discrete-event one, is built using AnyLogic 7.3.2 University Edition. A top-level view of the processes in the simulation model is presented in Fig. 3 below.

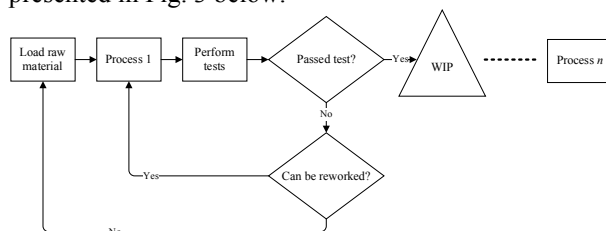


Fig. 3. High-level view of the processes within the simulation model

In the simulation model processes that appears in Fig. 3 above, in which the boxes represent aggregate processes, the raw material is first loaded into the first machine, then the material is processed in the first machine. After the stochastic production time has elapsed, the workpiece is subjected to a

series of tests, if it passes the tests (e.g., non-destructive scanning), then it is moved and kept as work-in-process (WIP) until the next machine is available. If it fails the test and the same piece can be reprocessed, then the production activity is repeated on the same workpiece. Otherwise, a new workpiece is loaded into the machine and processed. These steps are applied to all processes in the production plan of the component. The stochastic parameters in the simulation model include processing time, rejection rate, and material removed. The outputs of the simulation model include total energy consumed per each process, total material and resource consumption, total WIP time before each process, and machine utilisation.

As for the sustainability assessment module of the framework, a cradle-to-gate system boundary has been chosen to assess. The exclusion of the use and end-of-life phases is to attempt to put more emphasis on the often-overlooked upstream processes in aerospace-related sustainability studies. The functional unit selected for the study is the manufacturing of one individual unit of the selected component in a UK-based factory. For the LCI phase of the environmental LCA, the ecoinvent 3 [17] database, the contemporary literature, Granta EduPack software, and data provided directly by the UK supply chain that will manufacture the component were used. As for the social LCI phase, free publicly available databases from the World Bank [18] and the UK's Organisation for Economic Co-operation and Development (OECD) [19], as well as data collected from the contemporary literature were used. It should be noted here that there are specialised social LCI databases (e.g., social counterpart of the environmental ecoinvent) such as the social hotspot database (SHDB) [20]. For the social LCI and social impact assessment, country-level assessment instead of company-level was conducted. This choice was made to ensure the generalisability of the results, and the usefulness of dissemination. For the impact assessment phase, the environmental impact assessment was carried out using the ReCiPe 2016 [21] method due to its wide geographical coverage. The impact categories were evaluated at the midpoint level (i.e., environmental mechanisms) from a hierarchist cultural perspective (i.e., impact assessment is realised through current scientific evidence, and the potential future impact is determined from a risk-aware perspective) [22]. The social impact assessment was performed using the reference scale approach. The choice of the reference scale approach was dictated by the goal of carrying out a social LCA, which is to understand the potential social impact. If, however, the goal was to understand the consequences of the impact, then the impact pathway approach, which resembles in principle the environmental impact pathway, is preferred [5]. In the reference scale approach, the social impact of activities within the product system are assessed based on reference points [7], as explained in the previous section.

4.2. Results and discussion

In this section, the numerical results from implementing the case study in the framework are discussed. First, the production system that is involved in the manufacturing of the aerospace component is run with stochastic parameters in the simulation model. The number of required simulation replications that brought the confidence interval to 95% (i.e., the probability that there is a 95% chance that the *true mean* is bounded in the

confidence interval) was determined to be 20.

The output of the simulation then was used to feed the environmental LCA in the LCI part. The mean WIP values before each process, where WIP occurred in excess are depicted in Fig. 4 below.

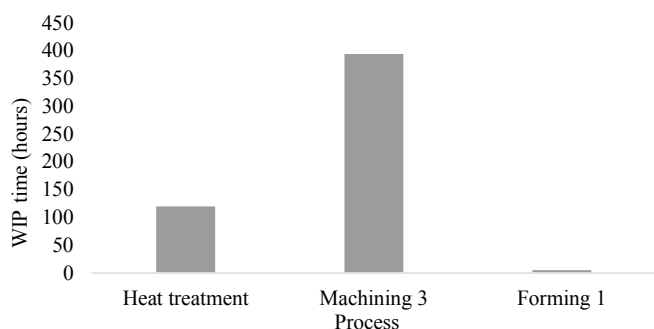


Fig. 4 Mean WIP time before processes

The outcome of the simulation model, for one year of operations, indicated that due to the stochastic processing times, which their impact on production is easily captured through simulation, long queues emerge before heat treatment and machining 3 processes. Therefore, an additional oven capacity and/ or an additional machining equipment might be needed to achieve efficient lean production. The addition of these equipment will, however, possibly adversely impact the sustainability performance (environmental and potentially social) of the production processes of the component. This adverse impact on particularly the environmental performance is not only due to the additional emissions and waste, but also due to the environmental impact associated with the production, maintenance, and transportation of these heavy machinery. This problem can, however, potentially be solved through the use of efficient scheduling algorithms, where the rich field of mathematical programming can efficiently allocate resources to tasks.

The environmental LCA was carried out using SimaPro 9 where the output of the simulation model, with regards to the used materials and consumables, and energy consumption, was added to the inputs and outputs of the processes. The normalised outcome of the midpoint categories and the processes contribution of the environmental LCA are depicted in Fig. 5. From the normalised midpoint indicator results, it can be noticed that marine and freshwater toxicity are the most widely affected indicators.

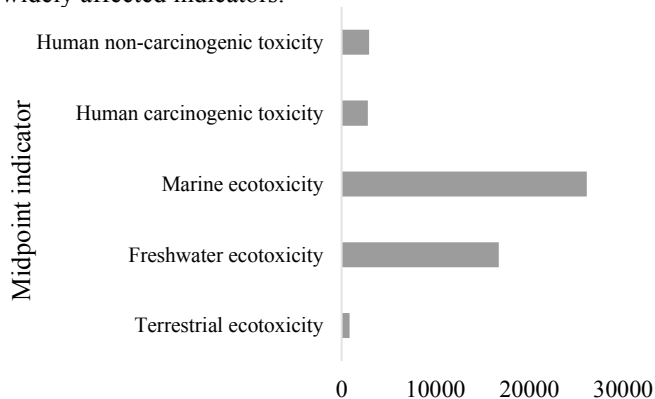


Fig. 5. Normalised midpoint indicators

Production of the aluminium alloy has been found to have the most significant environmental impact, with an approximately 75% share of all lifecycle stages. Upstream processes pertaining to material extraction and raw material production were modelled as blackbox due to difficulty in obtaining such upstream data. Indeed, the production of aluminium causes considerable environmental impacts as the processes (bauxite mining, alumina production and smelting, casting etc...) are energy and resource intensive [23].

The first step in the social LCA is to identify the stakeholder categories that will be included in the analysis. The social assessment was performed on a country level, and included the cradle-to-gate activities of raw material production and manufacturing of the component. The production of the raw material was assumed to take place in Eastern Europe, while the production of the aircraft component takes place in the UK. Therefore, data were collected separately for the two aforementioned processes, and then combined. The next step is to develop a reference scale for each indicator in the social assessment. The indicators that were used in the SLCA include percentage of full-time employment, unemployment, employees receiving minimum wage, corruption perception index, child labour risk, access to drinking water, and economic growth rate. Then, a scale ranging from 1 – 4 is developed as explained in [24].

After determining all the indicators and their respective values, a pedigree matrix is constructed to establish the quality of the data that were collected. Then, in the social impact assessment phase, the reference scale is used to score the included indicators. It should be mentioned here that all indicators were assumed to have equal weight, as the goal in this research is to establish basic understanding of the social impact on all indicators. The next step is the aggregation of the reference scales into a single score as explained in [5,24]. The results from the aggregation are presented in Table 2 below.

Table 2 SLCIA scores of raw material production (RM) and component manufacturing (M)

Stakeholder group	Score (RM)	Score (M)	Minimum	Cut-off	Maximum
Local community	0.26	0.33	0.09	0.23	0.38
Value chain actor	0.05	0.06	0.02	0.04	0.06
Worker	0.18	0.31	0.09	0.23	0.38
Society	0.09	0.17	0.05	0.12	0.19

Results presented in Table 2 reveal that the overall social impact from the production of raw material is higher than that of the manufacturing of the component (in Table 2 the higher the score, the less impact is posed on the stakeholder groups). For the production of the raw materials, the worker and society groups are adversely affected by these processes as the score falls below the cut-off point, which is determined from the reference scale, and which marks the aggregate value that below which, the impact is considered adverse. The results for the production of the component, however, are all above the cut-off point, which indicate a favourable, or at least neutral,

impact on stakeholder groups. In order to observe the aggregate social impact, Table 3 depicts social impacts per processes, rather than per stakeholder group.

Table 3 Social life cycle impact assessment per lifecycle stage

Lifecycle stage	Score	Minimum	Cut-off	Maximum
Raw material production	0.59	0.25	0.65	1
Component manufacturing	0.88	0.25	0.65	1

It is important to reiterate that these results reflect country-level, not company-level, therefore, these results can significantly differ if this study was carried out from a narrower context. In conclusion of the results, it could be clearly noticed that the social impact is more pronounced in the raw material production stage than the component production, which might signal a need for closer monitoring of overseas suppliers, or in considering localised upstream supply chains, where possible.

5. Conclusion

In this paper, an LCA-based sustainability assessment framework, that accounts for the perceived impact of stochastic processes and the dynamic behaviour of manufacturing systems, with social considerations was developed. The main findings from the case study further validate the near-consensus in the extant literature on the usefulness of complementing LCA with tools that can capture, and reveal the impact, of the dynamic and stochastic behaviour of manufacturing systems. The other main finding, which is intuitive but needs much more thorough examination, is that social impact of upstream processes, when they are not under close monitoring and control of the focal point in the supply chain, might be at the risk of being more adversely affected than localised processes.

This research can be extended in a number of directions. First, the generalisability of the framework has to be further established by carrying out several other heterogeneous case studies. Another possible research direction is to compare the social impact of distributed localised production systems against centralised production systems that source materials from sprawling supply chains that span different continents. Finally, since it is not always possible to localise material sourcing, it is worthwhile to investigate the role that the Industry 4.0 toolset (e.g., blockchain to improve the traceability and transparency of upstream processes) can play in both the assessment and improvement of environmental and social sustainability.

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