Sustainability Assessment of Aerospace Manufacturing: An LCA-Based Framework

Yousef Haddad(✉), Sandeep Jagtap, Emanuele Pagone, and Konstantinos Salonitis

Sustainable Manufacturing Systems Centre, School of Aerospace, Transport and Manufacturing,
Cranfield University, Cranfield MK43 0AL, UK
`yousef.haddad@cranfield.ac.uk`

Abstract. In this paper, a life cycle assessment (LCA)-based sustainability assessment framework is developed to estimate the environmental impact of production processes. The framework provides a methodical, context-independent, approach to carry out LCA studies. The framework sets guiding principles for products and key performance indicators (KPIs) selection and the associated data requirements in a reconfigurable manner that can be applied to any industrial setting. In order to validate and demonstrate the applicability of the framework, a cradle-to-gate case study pertaining to the manufacturing of a real aerospace metallic structural component is carried out. Results revealed that the complexity of aerospace components makes it difficult to improve the environmental impact from manufacturing operations as most of the impact comes from upstream activities that aerospace manufacturers, typically, have no control over, or access to.

Keywords: Sustainability assessment · Life cycle assessment · Aerospace manufacturing

1 Introduction

Interest in sustainability has been steadily gaining momentum over the last few decades. Indeed, in addition to the classical cost, time, quality and flexibility, sustainability is increasingly considered the fifth decision-making attribute in manufacturing systems [1]. Most governments have recently legislated laws to achieve Net-Zero emissions before the end of the century. The United Kingdom, for example, has set a goal to realize Net-Zero emissions by the year 2050. Achieving such a goal requires estimating the magnitude of GHG emissions from all sectors with a fair degree of certainty using scientific methods. In order to do so, it is important to measure GHG emissions not only at site levels (e.g., within the boundaries of a factory), but to take a life cycle perspective to understand the underlying emissions throughout a product's entire life cycle, from material extraction, up to disposal or recycling. In addition to GHG emissions, the sole focus of Net-Zero, there are other environmental concerns that merit similar efforts to mitigate. Such concerns include the availability of resources, emission of toxic and hazardous materials and land use, amongst many others. Apart from the environmental

H. Kohl et al. (Eds.): GCSM 2022, LNME, pp. 712–720, 2023.
https://doi.org/10.1007/978-3-031-28839-5_80

concerns, sustainability consists of two more pillars; social and economic. The intersection of these three pillars constitutes what is known as sustainability. An example of a plan with well-defined goals and a list of actions is portrayed in the United Nation's 17 Sustainable Development Goals, which cover all pillars of sustainability [2].

Life cycle assessment (LCA) is a widely used approach for sustainability assessment. It captures the impact that a product, service, or a process has on the environment [3] (or on the social or economic pillars, when life cycle costing or social LCA are used, respectively) during its entire life cycle (or specified boundaries). Within the aerospace manufacturing sector, which is the focus of this paper, most LCA studies are dedicated to the use phase of an aircraft, sidelining other life cycle phases, due to their (comparatively) significantly lower environmental impact. For example, one of the papers [4] that included the production phase of a commercial aircraft found that 99% of the environmental impact comes from the use phase. It further stated that wings and engine production accounted for 63% of the environmental impact of the corresponding components' production phase. In [5], the authors presented an approach for designing aerospace structural components with additive, instead of subtractive, manufacturing. In [6], the authors conducted an LCA study for the component designed in [5] and proposed a multi-criteria decision-making method to compare the two components (subtractive vs. additive manufacturing). A similar study was also conducted in [7], where the authors proposed the use of carbon fiber reinforced plastics. These two papers, i.e., [6, 7], accounted only for the component manufacturing process of the entire life cycle.

In this paper, an LCA-based sustainability assessment framework is developed to estimate the environmental impact of manufacturing processes. The framework is context-independent and is not confined to the aerospace manufacturing sector. A real case study on a metallic structural component from the UK aerospace manufacturing sector is performed to validate and demonstrate the framework's applicability. The rest of the paper is organised as follows: Sect. 2 presents the sustainability assessment framework. Section 3 presents the case study and discusses the numerical results. Finally, Sect. 4 discusses the concluding remarks.

2 LCA-Based Sustainability Assessment Framework

The sustainability assessment framework, depicted in Fig. 1 below, applies to a wide array of industrial settings and consists of three stages: identification, analysis, and LCA. In the first (identification) stage, relevant key performance indicators (KPIs) are identified. These KPIs are used in this stage to identify the hotspots that contribute the most to the environmental performance. Such KPIs can be related to waste reduction, energy efficiency, hazardous materials reduction or any other KPI in line with the goal of the industrial setting of framework application. It is worth noting here that these KPIs, identified at the initial stage of the sustainability assessment framework, differ from those determined throughout the LCA, which will be explained later. After identifying the KPIs, the candidate component(s), which are the basis of the LCA study, will be identified. It is important to note that most LCA studies are conducted on a component/product or a service because of the data-intensive nature of such studies. It is therefore difficult to conduct an LCA study on an entire production system that produces various components/product as this will entail tracing each of these components/products' life cycles from material extraction up to the end-of-life. Nevertheless, for entire sites or systems sustainability assessment, other well-established approaches such as carbon accounting, based on Green House Gas Protocol (GHGP), or energy audits exist. The candidate component for sustainability assessment can be based on any number of criteria such as energy intensity of production, buy-to-fly ratio (i.e., the ratio between the mass of the input material used to produce a component to the mass of the final product), the complexity of its supply chain, amongst many others.

The next stage in the sustainability assessment framework is the Analysis stage. The candidate component's corresponding supply chain is uncovered and mapped in this stage. In determining the candidate component's corresponding supply chain, similar to the life cycle inventory phase of the LCA that will be explained shortly, foreground and background data can be used. Foreground data are the data inputs that can be collected within the boundaries of the production system, typically physically collected. Background data, however, rely on multiple sources and often requires making many assumptions and simplification due to the occasional absence of data. In mapping the production processes, several modelling techniques can be used. Such techniques include value-stream mapping (VSM), a lean modelling tool used to visualize a production process and identify inputs and outputs of each process along with value-adding activities, discrete-event simulation, or any other mapping technique (e.g., Sankey diagrams to model energy inputs and waste streams of manufacturing processes). After the production process is mapped, values for the selected KPIs are assigned, either from foreground (i.e., physical data collection) or background, which could be obtained from specialized software databases (e.g., Granta EduPack, ecoinvent etc.), or from literature sources.

The final, and most data-intensive and lengthy stage, is the LCA stage. As this method is well-established and widely used, it will only be briefly explained. The interested reader can refer to [3] for a comprehensive and thorough guide on LCA. In short, the first step is to set the goal and scope of the LCA study. The goal (why is the LCA study being performed), the functional unit (a quantitative depiction of the *function* that the candidate component performs within the LCA study) and the scope (the processes within the corresponding candidate component's supply chain that are accounted for) are determined. Next, in the life cycle inventory (LCI) step, an inventory of all the inputs (material, energy, water etc.) and emissions (CO_2e, water, waste, etc.) is carried out. This step is time-consuming and requires the making of important methodological choices. Similar to the previous (Analysis) stage, foreground and background data inventory the candidate component's production processes. The next step is the life cycle impact assessment step (LCIA) where the impact of the output of the preceding (LCI) step is determined. There are many methodologies for carrying out the LCIA step (e.g., ReCiPe 2016, IMPACT 2002 +, TRACI etc.). LCIA itself consists of several steps, but they are out of the scope of this paper as they are already contained within the LCIA methodologies. The selection of the methodology can be determined based on the geographical location of the study, the selected KPIs or on whether the results are required at the midpoint or endpoint levels. For more details about LCIA, the interested reader can refer to [8]. Finally, in the interpretation stage, the results of the LCI and

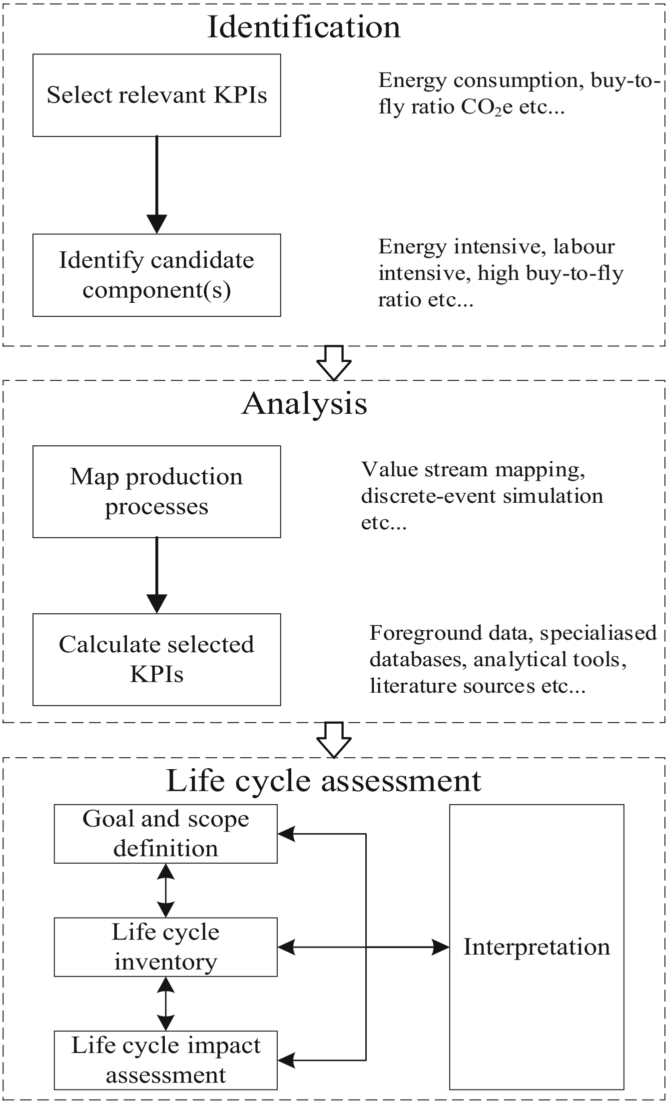

Fig. 1. The LCA-based sustainability assessment framework

LCIA are analysed, particularly with regards to the inherent uncertainty. To understand the impact of uncertainty on the results, sensitivity analysis is often used to uncover the impact that changes in the values of parameters (particularly those obtained from background data) can have on the study's outcome.

3 Industrial Case Study

In this section, a case study from the UK aerospace sector on a metallic structural component is carried out to demonstrate the applicability and usefulness of the sustainability assessment framework in the real world. The company is a Tier 1 aerospace components supplier that operates several factories worldwide. For confidentiality reasons, the name of the component will not be revealed, and the data presented in this section are normalised. In the Identification stage, the aerospace manufacturing company was concerned with the large amount of waste generated. Therefore, they chose buy-to-fly ratio to select the candidate component. The chosen component is a structural component made of aluminum alloy that the production company has identified as one of the most produced within their facility, and which also has a relatively high buy-to-fly ratio, which results in large amounts of waste.

The Analysis stage begins with mapping the production process of the chosen component. For this purpose, a simplified Sankey diagram has been chosen to model the production processes, material input, and waste streams, as in Fig. 2 below.

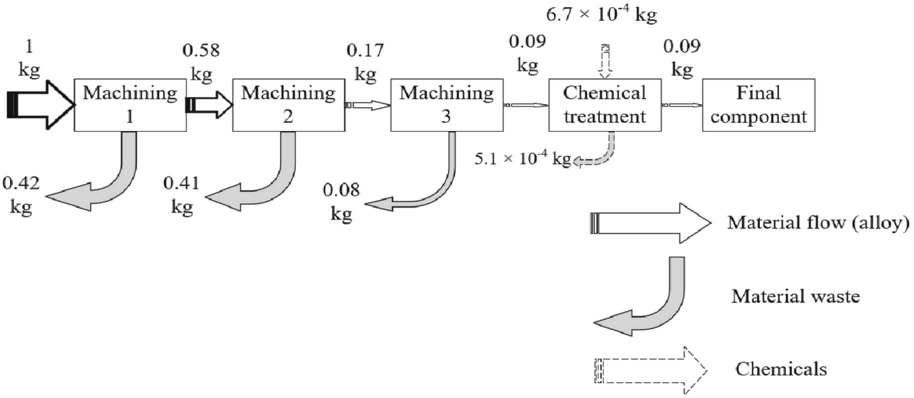

Fig. 2. The simplified production process of the chosen component

Figure 2 above depicts the gate-to-gate processes where the collection of foreground data was possible. For the upstream processes (i.e., material extraction, alloy production and transportation), these processes were taken as a black box, and their values were obtained from Granta EduPack 2021 R2 software. The box containing chemical treatment contains several (anodising) chemical treatment processes, but they have been combined in one box due to their very small amount.

The production process depicted in Fig. 2, along with the upstream alloy production (black box), was modelled in SimaPro 9.2 software. The background data for the life cycle inventory step were retrieved from the ecoinvent 3 database [9], a specialist LCI database for production processes, has been utilised. As for the LCIA process, the ReCiPe 2016 methodology [10] has been chosen. ReCiPe 2016, one of the most widely used LCIA methodologies, has been chosen due to its geographical coverage that covers Europe, where the study takes place, as well as the rest of the world, in addition to including characterization factors for both midpoints and endpoints indicators. In this study, KPIs pertaining toabout midpoint indicators have been chosen due to the more detailed information about environmental impacts midpoint indicators provide and the lower uncertainty associated with the outcome [8].

Results for the midpoint indicators, depicted in Fig. 3 below, reveal that the upstream processes of the alloy production, accounted for as black box, contribute the most for nearly all indicators. It should be noted in Fig. 3 that two chemical treatment processes were represented instead of one aggregate process as in Fig. 2. This is because the *amount* of chemicals used in the manufacturing processes was very small (almost negligible) when compared to the amount of metals used. In contrast, the *impact* of these chemicals – on certain midpoint indicators – was noticeable.

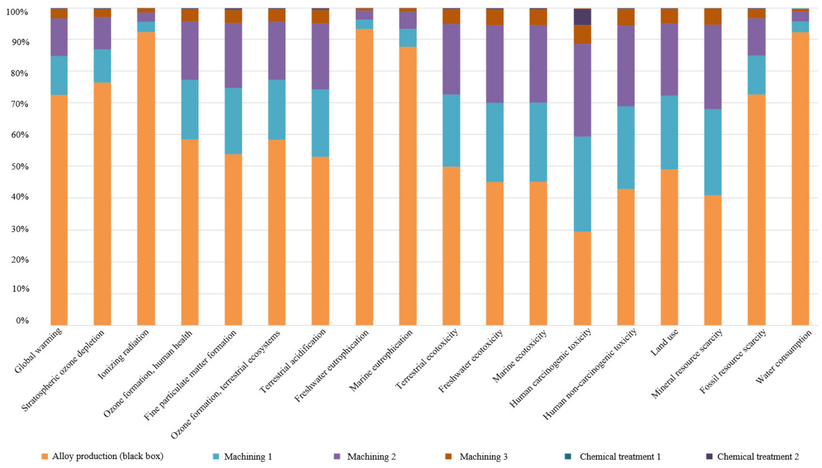

Fig. 3. LCIA results for the midpoint indicators

The near-domination of the alloy production on the overall cradle-to-gate processes of the candidate component can be attributed to several reasons. First, metal extraction occurs in disparate geographical areas around the world which, in addition to the highly polluting mining activities with the use of heavy equipment and energy and water-intensive processes [11] along with large amounts of waste and adverse changes to land use [12], also incurs long distances transportation. What also adds to the already considerable environmental impact of the early stages in the upstream activities of alloy production is that activities are often carried out in developing countries where the electricity mix is still highly reliant on coal due to its high energy density.

The above results have led the aerospace manufacturing company to intuitively realise that the majority of the environmental impact resulting from the manufacturing of the candidate components stems from elsewhere, and is, currently, difficult to mitigate. This fact is even further exacerbated when considering the environmental impact of the candidate component in its downstream life cycle (i.e., aircraft use phase and end-of-life solutions). Indeed, as discussed earlier in the Introduction section, it has been found that as much as 99% of a commercial aircraft's (Airbus 320) entire environmental impact comes from the use phase of the aircraft over a period of 20 years [4]. Therefore, to improve the environmental impact of aerospace manufacturing processes, aerospace manufacturers should have tight control and transparent access to information about all upstream processes to come up with solutions to mitigate the environmental impact. Another solution is to adopt alternative materials and manufacturing technologies in aerospace manufacturing. This solution, however, is challenging as the aerospace manufacturing industry is tightly controlled and is subject to stringent regulations that require lengthy approval processes. Regardless of the challenges of using alternative materials, there is an upward trend in these aspects, particularly with regards to the use of composites [13] and additive manufacturing technologies [14]. Although these new materials and manufacturing technologies seem promising, there is a risk that the environmental impact might from one life cycle phase to another. To explain more, although composites are lightweight and contribute considerably to mitigating the environmental impact of the use phase, some of this environmental burden is shifted from the use phase to the manufacturing phase. In this particular example, the overall environmental gains outweigh the shift in the burdens throughout the life cycle.

4 Conclusion

In this paper, a context-independent LCA-based sustainability assessment framework for manufacturing processes is developed. The framework works as a decision-aid tool for identifying candidate components, and as an assessment tool to determine the environmental impact of the life cycle of the candidate component. The framework has been applied to a real case study in the aerospace sector for the production of a metallic structural component. Results from the case study revealed that most of the cradle-to-gate environmental impact comes from upstream processes (alloy production) that are outside the control of the aerospace manufacturing company. The main contribution of this work is twofold; first, the sustainability assessment framework, which brings LCA, a well-established structured methodology, into a wider set of guiding principles that facilitate the selection of candidate component(s) and relevant KPIs. The second contribution is the design of a real case study from the UK aerospace manufacturing sector where important remarks that can guide future decisions regarding improving the environmental profile were drawn, particularly with regards to the impact of upstream processes.

This research can be extended in several directions. First, and most obviously, although challenging and time-consuming, foreground detailed data regarding the upstream processes can be added to the LCA model. Such a detailed study would enable manufacturers to gain insight and control over upstream processes. It would also enable them to improve their environmental profile and ensure that the social aspects of sustainability, particularly far upstream in the supply chain, are handled fairly. Another possible research direction can be a comparative study comparing the current, as-is, production processes of the candidate component with future scenarios of alternative materials or manufacturing technologies such as those highlighted in the previous section.

References

1. Salonitis, K., Ball, P.: Energy efficient manufacturing from machine tools to manufacturing systems. In: Procedia CIRP, pp. 634–639 (2013)
2. Sustainable development goals. United Nations. https://sdgs.un.org/. Accessed 16 May 2022
3. Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (eds.) Life Cycle Assessment: Theory and Practice. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-56475-3
4. Howe, S., Kolios, A.J., Brennan, F.P.: Environmental life cycle assessment of commercial passenger jet airliners. Transp. Res. Part D **19**, 34–41 (2013)
5. Hodonou, C., Balazinski, M., Brochu, M., Mascle, C.: Material-design-process selection methodology for aircraft structural components: application to additive vs subtractive manufacturing processes. Int. J. Adv. Manuf. Technol. **103**(1–4), 1509–1517 (2019). https://doi.org/10.1007/s00170-019-03613-5
6. Hodonou, C., Kerbrat, O., Balazinski, M., Brochu, M.: Process selection charts based on economy and environment: subtractive or additive manufacturing to produce structural components of aircraft. Int. J. Interact. Des. Manuf. **14**, 861–873 (2020)
7. Witik, R.A., Gaille, F., Teuscher, R., Ringwald, H., Michaud, V., Månson, J.E.: Economic and environmental assessment of alternative production methods for composite aircraft components. J. Clean. Prod. **29–30**, 91–102 (2012)
8. Hauschild, M.Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., et al.: Identifying best existing practice for characterization modeling in life cycle impact assessment. Int. J. Life Cycle Assess. **18**, 683–697 (2013)
9. Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B.: The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. **21**(9), 1218–1230 (2016)
10. Huijbregts, M.A.J., et al.: ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. **22**(2), 138–147 (2016). https://doi.org/10.1007/s11367-016-1246-y
11. Hisan, S., Huda, N., Mahmud, M.A.P., Saidur, R.: A review on the impact of mining and mineral processing industries through life cycle assessment. J. Clean. Prod. **231**, 1200–1217 (2019)
12. Kosai, S., Yamasue, E.: Global warming potential and total material requirement in metal production: Identification of changes in environmental impact through metal substitution. Sci. Total Environ. **651**, 1764–1775 (2019)
13. Brunner AJ. Fracture mechanics of polymer composites in aerospace applications. Polymer Composites in the Aerospace Industry. Elsevier Ltd; 2020. pp. 195–252
14. Blakey-milner, B., Gradl, P., Snedden, G., Brooks, M., Pitot, J., Lopez, E., et al.: Materials & Design Metal additive manufacturing in aerospace : a review. Mater. Des. **209**, 1–33 (2021)

Sustainability assessment of aerospace manufacturing: an LCA-based framework

Haddad, Yousef

2023-04-26

Haddad Y, Jagtap S, Pagone E, Salonitis K. (2023) Sustainability assessment of aerospace manufacturing: an LCA-based framework. In: 18th Global Conference on Sustainable Manufacturing (GCSM 2022), Manufacturing Driving Circular Economy, 5-7 October 2022, Berlin, Germany. Lecture Notes in Mechanical Engineering, pp. 712-720

https://doi.org/10.1007/978-3-031-28839-5_80