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Evaluating LCA product families in an approach to determine baseline emissions within aerospace manufacturing.

Rylan Cox[a*], Roopa Sai Reddy Venkatapuram[a], Mohamed Afy-Shararah[a], Joseph L. Carter[b], James Artingstall[b], Konstantinos Salonitis[a]

[a] *Sustainable Manufacturing Systems Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield MK43 0AL, UK*
[b] *GKN Aerospace, Taurus Road, BS34 6FB, UK*

* Corresponding author. *E-mail address:* rylan.cox@cranfield.ac.uk

Abstract

This paper investigates a Life Cycle Assessment (LCA) based methodology to determine baseline emissions for an aerospace manufacturer. Aerospace manufacturing entails high complexity and low throughput of a vast array of components. Rather than establishing the environmental footprint through waste, electric, and gas data alone; an LCA cradle-to-gate approach extends to a product's raw material acquisition and shipment to provide a comprehensive set of environmental performance indicators. The approach combines several products that follow a similar manufacturing process and can be denoted as a product family. This paper discusses the ability that LCA product families must develop baseline emissions for products validated with a case study of an aerospace component. The methodology can be extended to other product families manufactured within the facility which when combined will accumulate to a site-wide environmental footprint. The paper further evaluates how this methodology can identify environmental hotspots at a process and product level. The aerospace component case study incorporates several manual and automated stages. This work aims to demonstrate the ease of determining baseline emissions using an LCA product family and enable aerospace manufacturing companies to adopt a similar approach to establishing environmental hotspots. This can drive strategic internal change for sustainable manufacturing aligning with company environmental, social, and financial frameworks.

Keywords: LCA; product families; environmental footprint; aerospace manufacture

1. Introduction

Aerospace is a significant emission-generating sector contributing 2% of the global energy-related CO_2 emissions [1]. Although over 99% of emissions are attributed to the use phase, manufacturing produces the remaining 1% [2]. However, as the industry transitions to greener fuel options, the emissions proportion will begin to shift to manufacturing, hence a change is needed now. The aerospace sector has committed to net zero emissions by 2050 in all areas inclusive of manufacturing [3]. Meanwhile, as environmental awareness has grown, customers are requesting suppliers to provide their products with environmental data. Therefore, the manufacturing industry must understand their products' carbon footprint and develop baseline emissions to drive improvement. Aerospace manufacture predominantly makes use of legacy, energy-intensive manufacturing equipment using virgin metals like aluminium or titanium. Further, energy data is usually collected at a high level for aerospace products with a fundamental lack of individual part monitoring throughout facilities. Coupled with a huge inventory of bespoke products, it becomes infeasibly time-consuming to equate every products

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emissions individually. Thus, simple, and transferable methodologies between different products are needed.

Conventionally, LCA is a widely accepted tool for sustainability assessments that identify the environmental and social impact of a product, service, or process [4]. LCA has been extensively utilised in comparing different manufacturing techniques and different materials but is a data and time-consuming method [5]. Limited studies demonstrate LCA's for entire processes or production lines within aerospace manufacturing. [6] discussed an LCA-based framework for assessing the environmental impact of aerospace aluminium components from a process perspective. Since LCA's have been introduced a growing interest and various adaptions have been made to estimate total baseline emissions [7].

The paper discusses an adaption of a cradle-to-gate LCA using a product family approach aiming to utilise a single LCA model that combines several products that follow a similar manufacturing process into a product family. This methodology can be repeated for several other product families to establish a complete site-wide baseline emission picture comprised of several products and processes. The case study selected is a product family of six components which contribute a substantial amount of the total emissions within an aerospace facility that manufactures over 1000 different products. The study aims to demonstrate how product families can be expanded onto other products by building several families leading to a total site-wide emissions image. Hence this approach can vastly improve the rate of establishing product emission. Further, the insight from the family LCA identifies environmental hot spots for products and processes within the family that can be targeted to help derive improvements. This methodology is a demonstration of how such an approach can be transferred across different manufacturing industries and processes.

2. Methodology

2.1. Case study

A UK-based aerospace manufacturing company that produces structural metallic parts is used to demonstrate product family LCA's as a methodology for building up site emission profiles. The case study uses a single class of undisclosed products, due to confidentiality, and is designed to demonstrate the transferability to other product families to build a site-wide product portfolio. A detailed summary of a product family LCA approach can be found in [8]. In a company that manufactures over 1000 different products the components in the selected family have the highest production throughput and predicted highest site-wide environmental footprint. The product is an aluminium alloy with a high buy-to-fly ratio, therefore, has a significant environmental impact from the manufacturing perspective.

Initially, mapping of the manufacturing process was carried out through site visits and discussions where environmental-related data such as energy and material use, and waste generation helped identify preliminary environmental hotspots. The aluminium is virgin grade source from three different locations, followed by three-stage machining, two surface treatments, and painting as depicted in Fig. 1.

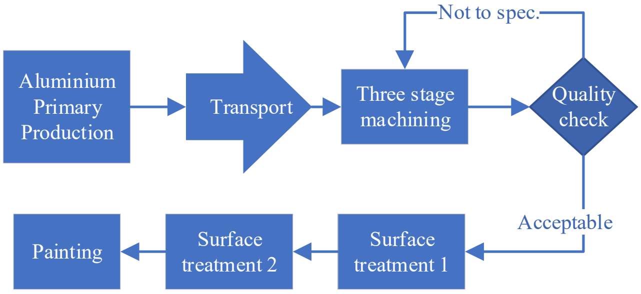

Fig. 1. Process flow diagram for the products

Data is collected for each part within each manufacturing task as per the flow chart to build a product family LCA. Data collection for a facility that manufactures over 1000 parts in combination with tracking material life cycle would be time-intensive and financially burdening for any company [6]. Product families aim to alleviate some of the burden by combining several different parts which can be categorised into one as each part follows the same manufacturing route with slight geometric or manufacturing time differences. Further, the ability of product families not only builds up a facility-wide emissions map quicker but helps to identify which of the products have the highest environmental impact within different families. Products were placed in families by matching the same materials and that follow a similar manufacturing route, i.e., aluminium with machining, surface treatment and painting only. If a product has more or different manufacturing stages or uses a different material, it cannot be included in the family. As annual energy and material consumption is recorded the ratio between total yearly usage and the family usage identifies the family's contribution to the overall environmental impact. LCA is a well-known tool for evaluating environmental impact over other site-wide sustainable assessments including value-stream mapping, energy audits, carbon accounting through the greenhouse gas protocols at all scopes and buy-to-fly ratios, hence was selected for this case study [6], [9], [10]. Compared with conventional product LCA's, product families only differ in the data collection and processing stages. In certain cases, data collection must be done on a part-by-part basis such as machining as geometric configuration varies between all parts. Batch processes such as surface treatment or heat treatment, distribute energy, waste, and materials as a function of time as a ratio of the total manufacturing throughput at the level that data is collected, either daily, monthly, or yearly.

2.2. Data collection

The upstream data for raw material production inclusive of mining and material processing to a billet was imported using different LCA databases [11], [12]. Billet transportation is accounted for from the three different sources within the LCA. Billet shipment was conducted through international marine shipping followed by road; ferry and road; or road only in the case of the UK as a source. To enable a Life Cycle Inventory (LCI), electrical, water and gas consumptions were obtained for each manufacturing stage or estimated. Similar to the study by [13] and the methodology set about in ISO 14955-2:2018 [14], partial in-depth data collection following the CO_2PE! framework was conducted for all the manufacturing stages, in which energy and material consumption were monitored through different sensors, meters or procurement to collect operation data for the products within the family, time data was particularly collected for each process through the consumption data as this was collected over a known period. However, the present study failed to include the emissions that may have been generated through reactions, evaporation, or essential-non-value-adding processes. For machining, electricity consumption was provided monthly between 2019 and 2020 along with electrical and material removal data for each product within the family at each stage. Other manufacturing stages in Fig 1 lacked the same level of data granularity in comparison. Between, October 2022 and June 2023 gas, electrical and water consumption data was provided for surface treatment 1 and October 2019 – June 2023 for surface treatment 2 and painting. The manufacturer could not quantify product level data for surface treatment and painting and was therefore assumed similar for all products which was deemed suitable considering the batch process, visual observations and discussions with manufacturing operators. Manual processes deburring, masking, key dimension measurement and demasking were excluded within the LCA. One manufacturing stage was subcontracted offsite which could not be controlled by the manufacturer and was left out of the LCA. Although it would have an impact on the final part's environmental impact by increasing the total GWP the study's focus was to demonstrate LCA product families as a fast-track route for a single facility and identify manufacturing environmental hotspots. To account for the high level of data for painting, surface treatment and flaw detection assumptions were defined with the manufacturer:

- Electrical and water consumption remained constant throughout the year with seasonal fluctuations in gas consumption averaged throughout the year.
- 70% of the energy consumption (gas and electric) in surface treatment 2 was specifically used for surface treatment only, and 30% for painting, deduced from the operation time of surface treatment compared with painting and drying equipment throughout the year.
- 30% of the surface treatment monthly energy consumption was allocated to the product family based upon the number of other orders and products manufactured in-house.
- 30 products are made per day as per yearly shipment demand over 5 years.
- Painting energy consumption within the facility is exclusive to the product family as it is the only part manufactured that requires painting.
- An average of 28 products are painted daily with a 16:12 product split between the two painting lines with products 1 and 2 sent to line 1 and products 3, 4, 5, and 6 to line 2 due to product sizes.
- Painting energy consumption between the two lines is split 43:57, due to the amount of time one of the lines is in operation and the number of products the different lines can serve.
- Flaw detection energy consumption (water, electric and gas) was equal to 15% of the energy consumption of surface treatment 1. Same system but a different chemical.

These assumptions lead to electric, gas and water consumption for each product displayed in **Tables A1.1** and **A1.2.** Although consumption data was formulated to a product-product level and product family overall, the outcome GWP may deviate away from the true value. With the transition to digitalisation, this can be mitigated by manually probing through clip-on sensors or simulating manufacturing tasks to determine energy or water consumption data to improve the overall LCA accuracy, further uncertainty analysis can be conducted.

2.3. Life Cycle Assessment

The LCA goal was to determine the cradle-to-gate environmental impact for the product family and develop baseline emissions within the aerospace site. The system boundary is inclusive of raw material mining, electrolytically processing of aluminium billets, and shipping from three supplier locations. The functional unit was the environmental impact of a single product manufactured within the company plant. LCA software SimaPro 9 was used and an LCA was developed for each product to incorporate all various machining consumptions that build up a product family LCA.LCI included the collection of transportation distances, energy consumption and material loss to become inputs for the LCA. Although the database within SimaPro9 (EcoInvent 20) contained most of the process stages, surface treatments, non-destructive testing and painting were manually input into the model. The production stage was fixed at assembly only, with disposal and waste outside the project scope. Although generated swarf, lubricant and water waste are recycled or cleaned in-house the data for this was not available.

Life Cycle Impact Assessment (LCIA) used midpoint impact categories related to ReCiPe 2016 to assess the product's carbon footprint within the family. A sensitivity analysis was conducted on the LCIA to assess the key parameters that impact the product’s carbon footprint and to enable insight into the manufacturing process’s emissions impact through a one-factor-at-a-time approach (OFAT). Energy consumption was varied by 5 and 10% to identify the overall model impact.

3. Results and Discussion

3.1. Life Cycle Assessment

Each product within the family has its own global warming potential (GWP) due to varying geometry and processing requirements as Fig. 2. Primary production is identified as the major contributor to the carbon footprint which correlates with previous aerospace component studies [6], [15]. Therefore, manufacturing must identify ways to increase recycled aluminium into the product and minimise the buy-to-fly ratio to dramatically improve carbon footprints within this product family. If virgin material in the family were to be replaced with 100% recycled material, it would reduce primary production emissions by up to 35% [16]. Additionally, the material factory is sourced from three global locations. As expected, the greater the distance from the source to the company the higher the overall contributing emissions, this only becomes beneficial if the upstream emissions from an aluminium supplier are lower than a closer supplier or if the supplier uses sustainable transportation. The type of transport had a significant impact as the national sources of material relied on Heavy Goods Vehicles (HGVs), whereas international shipment used both ferries and HGVs. It was concluded that nationally sourced material produces up to ten times or three times less emissions than shipment from the USA or mainland Europe respectively. Removing transportation and primary production meant manufacturing emissions for the product family ranged between 12-30% of the total GWP.

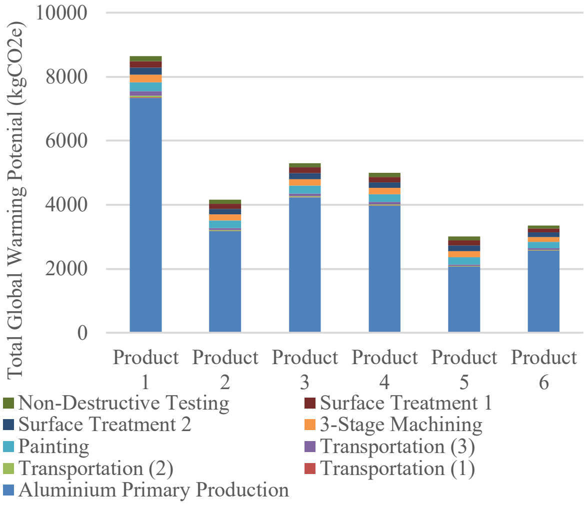

Fig. 2. Different products total CO$_2$ (eq) emissions for each stage

Breaking down the manufacturing tasks from Fig. 1, matching them with the total GWP emissions in **Error! Reference source not found.** and the Life Cycle Impact Assessment (LCIA) results from **Error! Reference source not found.** finds a similar emissions distribution for each product. Furthermore, it identified manufacturing tasks hotspots to enable targeted areas for improvement to achieve net zero goals. Painting and surface treatment 2 are the largest contributors at 26.4 and 21.3% followed by the three-stage machining at 19.2% GWP total. The trend is similar for all products with contributions for painting. surface treatment 2 and machining ranging from 25 – 28%, 19 – 21% and 21% respectively regardless of product size. The painting phase operated alongside several natural gas boilers was the reason for its significant proportion to the environmental impact. Paint drying using gas-fuelled along with a system which held the ovens on continuously whilst both sides of each product were painted individually extended the drying duration creating a significant non-value-adding asset. Surface Treatment 2 uses legacy technology within the facility with low energy efficiency in comparison to modern surface treatment processes. Similarly, to painting, multiple gas boilers are used to maintain tank temperatures rather than a single boiler unit or heat pump which can control all treatment tanks. Furthermore, one of the main chemicals used within the process is a known carcinogenic and has a major impact on the overall environmental assessment, hence a higher human carcinogenic score ratio is attributed to surface treatment 2 [17]. For the machining stages, phase three was the significant contributor to the environmental impact as it has a slower material removal rate and therefore higher energy consumption per unit removed.

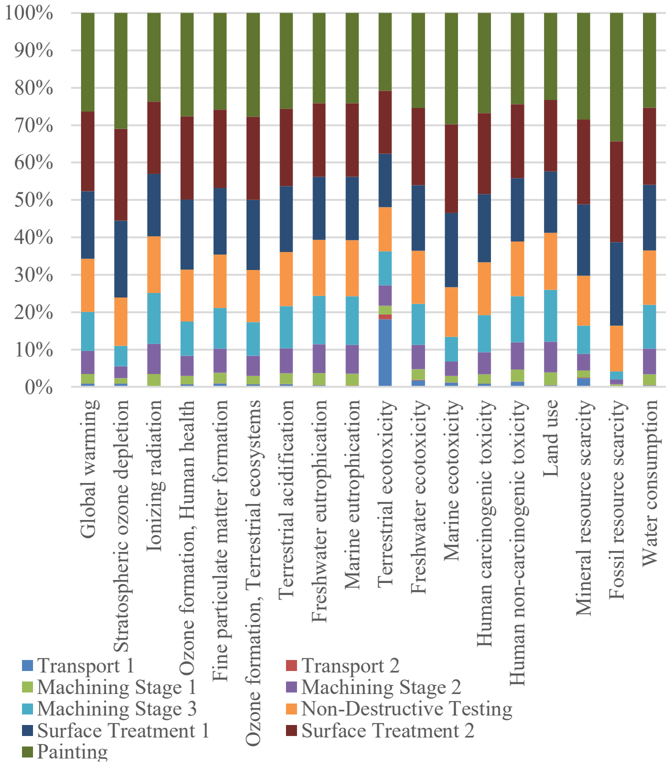

Fig. 3. LCA of product 4

Product 1 exhibited the highest manufacturing environmental footprint (1096 kg $CO2_e$) with the least from product 6 (707.2 kg $CO2_e$). However, when showing the emissions as a function of part mass the trend reverses with part 1 having the lowest kgCO2 (eq)/ kg of part and part 5 the highest as in **Error! Reference source not found.**.

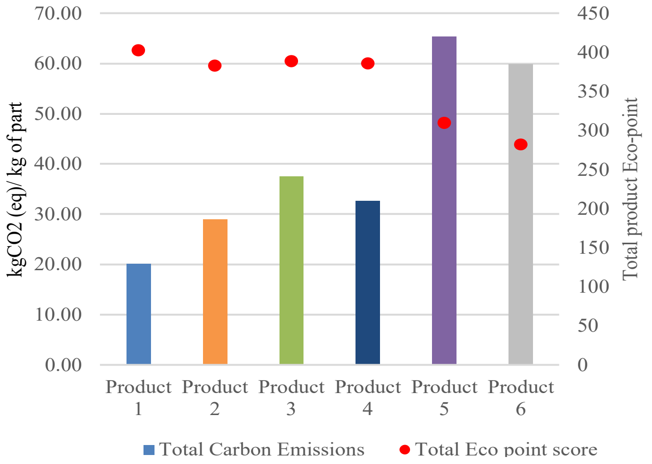

Fig. 4. kgCO$_2$ (eq)/ kg of part for each product left axis bar chart and total Eco point score right axis (dots).

Although the ratio of each manufacturing stage emissions remains constant across each part and the percentage of material removal (final mass 8 – 12% of the original mass), the initial to final material mass doesn't correlate to the total energy input into the system. Hence, lighter parts require a similar energy input as the larger parts but a lower final mass, hence having a higher kgCO2 (eq)/kg. Although tother processes such as surface treatment and painting are high emissions-based processes, from a product-to-product perspective the emissions remain constant. The reason is, that surface treatment and painting stages heat the same amount of open non-value-adding volume for each part, and the part size is insignificant compared to the non-value-adding volume. This highlights the process that varies each product's environmental impact within the family is machining, yet cumulatively, painting and surface treatment and primary production are more impactful. major and primary material extraction alone. One of the limitations of this study is some of the chemicals used in surface treatments were not accounted nor known how much was transferred to the part, as the data was not available.

3.1. LCA product families

Product family is usually an approach to exploit financial improvements in processes through economies of scale [18]. This study uses product families to evaluate environmental impact through an LCA of products that collectively follow a similar manufacturing path, rather than reconstructing a new LCA for every single product. The product family manufacturing GWP contributes 5434.32 kg CO_2 (eq) alone. Including primary production (23366.24 kg CO_2 (eq)) and transportation (676.87 kg CO_2 (eq)), this rises to 29477.43 kg CO_2 (eq). Primary production of aluminium is the most significant contributor to GWP. Depending on the company's scope for tacking emissions will decide how important recycling aluminium or keeping a closed loop with the supplier is. However, manufacturing contributes a total of 18.4% of the total product emissions. These results act as a starting point for total baseline emissions in the facility. As [19] and this study identified. the approach allows the repeated use of the same model with different data sets from the family and becomes a transferable methodology for other families. This streamlines LCA's as only one model is required with different input values of energy and water consumption, material usage and time.

The methodology is not limited to environmental LCA's and can be adjusted to social LCAs or into a decision-making framework to incorporate other KPIs such as time, cost, quality, and flexibility, [20]. Although this method minimises LCA model development time, the data-intensive nature cannot be bypassed. Combining this approach with real-time data monitoring using machine-level energy and water sensors and the emergence of Industry 4.0 (I4.0) technologies such as digital twins can reduce data collection bottlenecks. Overall, this case study has successfully demonstrated the unique ability of product families incorporation into LCA models to provide environmental impact at both product and process levels. It enabled a fast-track LCAs-based route to building plant-level emissions within aerospace manufacturing. One limitation of the case study is the bespoke nature of aerospace components in comparison to automotive and food or beverage sectors where there is limited part variation and high volume. In these cases, the product family approach can extend to many more products and build up a site-wide portfolio much faster than an aerospace company with thousands of parts bespoke parts with low volume. This case study was fortunate there were several products in the family, whereas many aerospace products will be manufactured so infrequently and may limit the usability of this approach when families contain only one part. Consideration should be taken when using this approach to evaluate the most time-considerate method to conduct an LCA on a product or if that product will have a significant facility-wide environmental impact. Continuing this work with other product families in the facility will build a portfolio comprised of several families, that when combined can provide product-level environmental analysis and process-level views of emissions. Expanding with sensitivity analysis can provide further insight into process hotspots to reach the net zero goals.

3.2. Sensitivity Analysis

Sensitivity analysis was used to extend the identification of process hotspots and prioritise their improvement by introducing a level of sensitivity at ±5 and 10% ranges. For all products, sensitivity impacted GWP from painting the most. Machining influence is dependent on the amount of material removed which is consistent across products. Surface treatment did not provide a major variation to the GWP.

Table 1. Sensitivity analysis for surface treatment, machining, and painting.

Process	Variation	GWP (kg CO2 eq)
Three Stage Machining	0%	176.24
	5%	185.05
	-5%	167.43
	10%	193.87
	-10%	158.62
Surface Treatment 1	0%	195.94
	5%	197.45
	-5%	194.42
	10%	198.97
	-10%	192.91
Painting	0%	242.21
	5%	244.52
	-5%	239.89
	10%	246.84
	-10%	237.58

4. Conclusion

The paper discusses process based LCAs with product families to determine baseline emissions in aerospace manufacturing. The product family manufacturing emissions totalled 5434 kg CO_2 (eq), with a total family GWP of 29477 kg CO_2 (eq) including material production and transportation. The LCA identified that painting, surface treatment phase 2 and machining were the hotspots in the family. Through sensitivity analysis, it was confirmed that environmental improvement to the painting process needed attention after being identified as the main environmental hotspot. The methodology becomes transferable to other products that can be placed into a family. This paper has demonstrated the flexibility and simplicity of product family LCAs to build a site-wide product and process emission portfolio for environmental impacts. A complete portfolio can enable suppliers to provide customers with environmental metrics and enable data-driven environmental improvements to their manufacturing lines.

Introducing I4.0 technologies and live data collection can alleviate the time pressures of data and enable continuous carbon accounting profiles of each product, family, process, and plant. Further, issues of high-level data as in this study can be resolved either through uncertainty analysis or live data collection. Moreover, the methodology for aerospace manufacture has only been evaluated in two case studies and needs further validation to confirm if a site-wide portfolio is possible or that the bespoke nature of aerospace product manufacture leads to families of one product alone negating the benefit of using product families as an approach. Finally, this approach has only been used to identify the environmental impact of the family but can be expanded for the social impacts in the same way as discussed within.

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Appendix A. Machining and energy data

A1. 1 Machining material loss and power consumption.

Product	Process	Material lost (%)	Electricity Consumption (kWh)
1	Machining 1	35%	99.12
	Machining 2	70%	106.05
	Machining 3	50%	142.29
4	Machining 1	36%	70
	Machining 2	56%	64.53
	Machining 3	55%	119.63
5	Machining 1	40%	79.44
	Machining 2	69%	76
	Machining 3	58%	126.67
6	Machining 1	39%	67.08
	Machining 2	70%	88.32
	Machining 3	50%	106.68
2	Machining 1	35%	80
	Machining 2	54%	81.25
	Machining 3	71%	120
3	Machining 1	35%	55.72
	Machining 2	72%	68.33
	Machining 3	67%	82.5

A1. 2 Energy and water consumption of product 4 at different stages

	Consumption		
Process	Electric (kWh)	Gas (kWh)	Water (m^3)
Quality check	7.55	10.48	0.045
Surface treatment 1	21.89	158.42	0.31
Surface treatment 2	50.34	69.89	0.3
Paint line 1	77.3	107.32	13.2
Paint line 2	76.85	106.7	-

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Cox, Rylan

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