


Proceeding Paper

Rocket Engine Vacuum Nozzle 3D Printing: Manufacturing, Weight, and Cost Savings [†]

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[†] Presented at the 14th EASN International Conference on “Innovation in Aviation & Space towards sustainability today & tomorrow”, Thessaloniki, Greece, 8–11 October 2024.

Abstract: Metallic materials additive manufacturing is extremely challenging nowadays, while aircraft manufacturers are trying to adapt the newly developed technology to produce parts of complex geometry with minimum materials losses. Skyrora is a company focused on the production of several launch vehicles and rockets with the aim of becoming a commercial provider for access to space. One of the Skyrora goals is to develop innovative and long-term solutions for future growth, and, within the Horizon European project “MADE-3D”, aims to improve the rocket propulsion system of the launch vehicle Skyrora XL by exploiting multi-materials during the production phase by additive manufacturing. The main goal of the present investigation is to document the already existing production phases of the “conventional” Skyrora vacuum nozzle printed with Inconel 718 to provide a baseline in terms of weight, manufacturing cost, lead processing time and CO₂ equivalent emissions of the under-development multi-material demonstrator.

Keywords: additive manufacturing; 3D printing; ABC; inconel alloys; carbon footprint; rocket engine vacuum nozzle



Academic Editors: Spiros Pantelakis, Andreas Strohmayer and Nikolaos Michailidis

Published: 6 May 2025

Citation: Alexopoulos, N.D.;

Zeimpekis, V.; Vasileiou, E.;

Thomaidis, N.; Souxes, T.; Lazaridou,

I.; Lutsyk, M.; Vorobev, R.; Karakash,

E.; Karpovich, E.; et al. Rocket Engine

Vacuum Nozzle 3D Printing:

Manufacturing, Weight, and Cost

Savings. *Eng. Proc.* **2025**, *90*, 109.

<https://doi.org/10.3390/engproc2025090109>

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1. Introduction

Additive manufacturing (AM) or additive layer manufacturing is the industrial production name for three-dimensional (3D) printing and more specifically the process of creating an object by building it one layer at a time (i.e., the 3D printing technology in which objects are created by layering materials). AM has gained significant attention in recent years, as it allows unique opportunities for design flexibility and customization. In [1], the advantages and drawbacks of numerous 3D printing processes are discussed, presenting also the various application areas of each type of process, including the AM technology and the Directed Energy Deposition (DED) 3D printers, which are of great interest in the present study.

The important advantages of AM are presented as follows: (a) supply chain: AM reduces the necessity for an efficient design and the cost of supply chain [2,3]; (b) speed: if the prototype is the appropriate one, simply by sending the file to a 3D printer, the final

product can be produced [4]; (c) material requirements: AM technologies are utilizing only the amount of material required for the product, instead of removing unwanted material from an over-dimensioned solid block using conventional machining [5]; (d) less waste: 3D printing not only has lower material requirements, but also generates less waste, as only a small amount of the material used may need to be removed during the final machining of the manufactured product [6]; and finally (e) lower energy consumption and carbon footprint: many studies have shown that 3D printing technologies require lower energy and have lower CO₂ emissions than the traditional manufacturing approaches [7,8].

Due to the afore-mentioned numerous advantages of the AM technology and furthermore due to the fact that AM on metals parts is increasingly used nowadays in the aerospace sector [9], the objective of this article is to present the manufacturing processes, the derived cost estimation relationships and respective cost evaluation models, the life cycle assessment (LCA) and the carbon footprint emissions of the Skyrora vacuum nozzle metal part created by the DED AM technology. Details of all intermediate activities of the different processes are documented and discussed.

2. Background

2.1. Cost Estimation of Additive Manufactured Metallic Parts

Numerous researchers have created models for estimating the costs of additive manufacturing, employing a variety of methods. These methods encompass break-down [10], activity-based [11,12], parametric [13], operation-based, regression models and artificial neural networks [13]. According to the literature reviews in [14,15], the AM state-of-the-art cost analysis methods are (1) break-down and (2) Activity-Based Costing (ABC).

Lindermann et al. in [11] demonstrated why the ABC method is ideal for the cost analysis of AM metal component creation (when the AM refers to low volume parts, similar with the present case). To this end, the AM cost estimation model for metal parts was followed in the present investigation. ABC is a costing method that assigns overhead and indirect costs to related products and services, and has become a popular cost estimation method due to the poor results of the traditional costing systems [16]. The ABC model is composed of both the cost assignment view and the process view with activities as the intersection of these two views [17]. ABC analysis provides an understanding of how costs are driven by the demands for activities within a process and allows the identification of value- and non-value-added manufacturing operations, as well as how resources are consumed [18].

2.2. Carbon Footprint

In order to assess the impact of certain products on the environment (i.e., calculation of the emitted carbon footprint from cradle to grave of a product), a life cycle assessment (LCA) is the main instrument of choice. This standardized and scientifically based methodology increasingly forms the basis for development processes and marketing strategies related to environmental performance.

The last two decades have seen a flourishing of LCA studies exploring the environmental friendliness of various AM methods. For example, Lyons et al. in [19] presented a life cycle approach to the assessment of the global warming potential of knee implant production with conventional and additive manufacturing. Torres-Carrillo et al. in [20] provided a sustainability analysis of selective laser melting applied to the manufacturing of turbine blades of an aircraft engine and compared its environmental benefits to a more conventional process involving investment casting. The authors explored direct and indirect environmental implications of the two competitive manufacturing models, employing a rich array of impact categories, such as global warming, ozone layer depletion

and human toxicity potential. The environmental profile of contemporary AM technologies for lightweight components is also discussed in [21] considering flows and emissions over the entire life cycle of the components.

Recent research studies, e.g., by Peng et al. [22], have shown that laser additive manufacturing has an environmental impact roughly twice as high as traditional manufacturing for the same component. As a result, energy efficiency and emission reduction in additive manufacturing technology are crucial for the future, e.g., by Hopkins et al. [23]. Wang et al. [24] showed that investigating the carbon footprint linked to the additive manufacturing process is highly valuable. In conclusion, research on the carbon footprint of additively manufactured products is urgently needed.

3. Materials and Demonstrator Description

The Skyrora LEO rocket engine is equipped with a vacuum nozzle of a total length of 400 mm and a diameter of 400 mm in its outlet area (as seen in Figure 1a), which is a part of the launch vehicle Skyrora XL (a three-stage, light class launch vehicle intended to place payloads of a weight up to 315 kg into sun-synchronous orbit between a range of 500 km and 1000 km in altitude), used in the application area of aeronautics. Figure 1b shows a characteristic section of the upper part of the nozzle design.

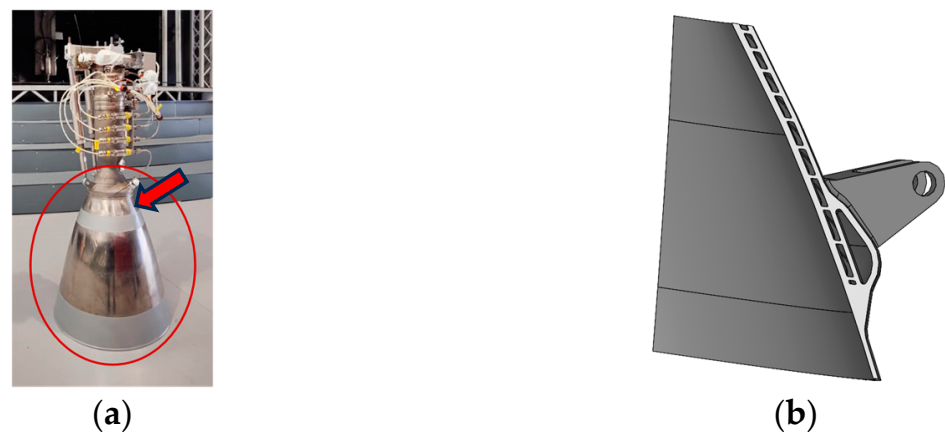


Figure 1. Schematic representation of the Skyrora vacuum nozzle: (a) assembled third stage of Skyrora XL without payload module equipped with vacuum nozzle (in the red circle), and (b) characteristic section of the upper part of the nozzle at the section marked with a red arrow in (a).

The vacuum nozzle is entirely made of nickel-based alloy Inconel 718, since temperatures can reach up to 900 °C during service. Currently, the vacuum nozzle is manufactured by the DED 3D printing method using Skyprint 1 and Skyprint 2, an in-house developed 3D printer. Since the vacuum nozzle is joined to the other components of the third stage by means of thermal welding, the surrounding parts of the vacuum nozzle are also made of Inconel 718.

4. Description of the Manufacturing Processes

The manufacturing stages of the examined demonstrator are grouped into three sub-processes, described as follows, in order to examine each process more effectively, thus enabling the identification of activities that generate costs and calculate energy, material, labour and total manufacturing cost (as well as the carbon footprint). A graphical representation of the activities flow is given in Figure 2.

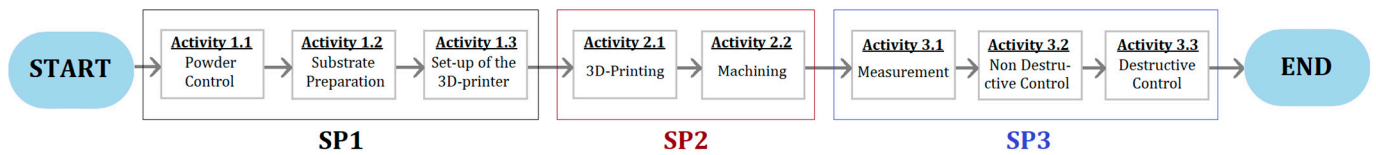


Figure 2. Schematic flow diagram of the manufacturing activities of the SKYRORA component.

4.1. Preparation (Sub-Process I)

This sub-process includes all the activities taking place before the main processing of the component. These activities intend to set-up and prepare the powder of the material Inconel 718 and the 3D printer, which are in turn needed for the main process activities (of 3D printing and machining). First, the incoming powders undergo a quality check (Activity 1.1) before being used for 3D printing. More specifically, the particle size distribution is assessed using an optical light microscope. The proportion of particles undersized ($<20\ \mu\text{m}$) and oversized ($>120\ \mu\text{m}$) should be less than 10%. Microscopic measurements are performed once for each new powder container before it is connected to the 3D printer. Additionally, the powder's humidity is measured with a hygrometer before commencing each new 3D printing job. The acceptable humidity level for the powder is below 5%. In Activity 1.2, the substrate's surface, on which the component will be additively built, is machined and thoroughly cleaned/degreased. More specifically, the required substrate for printing is prepared and cleaned by removing any contamination from the surface of the substrate (corrosion, rust, etc.) and cleaning the substrate using isopropyl alcohol and a rag. Rust may be removed using a wire brush, sandpaper, etc. Finally, in Activity 1.3, the substrate intended for powder deposition is installed in the 3D printer, and the powder containers are connected to the feeders. Calibration of the 3D printer (setting the zero-position of the substrate and nozzle) takes place, and specific build parameters (part geometry/deposition path, deposition rate, laser power, layer thickness, inert gas consumption, etc.) are established.

4.2. Main Process (Sub-Process II)

This sub-process includes all the necessary activities for the 3D printing and machining of the final component. More specifically, this sub-process consists of two operations. During the first Activity 2.1, the 3D printing takes place, using the DED additive manufacturing process in Skyprint 2, where the powder is deposited layer-by-layer and simultaneously fused via incremental laser melting to achieve the desired shape. This process step is the most time-consuming, but other auxiliary operations, such as powder control, substrate preparation, and separate machining, can be performed simultaneously by the labour force. In Activity 2.2, the component is separated from the substrate using a machining centre integrated into the 3D printer. Functional surfaces, such as the inner contour of the vacuum nozzle, are milled and ground. Drilling is performed for bolting surfaces to fix vacuum nozzle drivers.

4.3. Post Process (Sub-Process III)

After the successful completion of the printing process, it is necessary to evaluate the quality of the final component. To this end, in Activity 3.1, the printed part geometry is measured and compared to nominal dimensions, along with record measurements being held. The measurements occur in multiple locations to provide accurate overall measurements. Specifically, manual geometry measurements are conducted at eight (8) different control points to assess the component's geometry after machining. Subsequently, during Activity 3.2, ultrasonic measurements are carried out on the component using a portable measuring system, to ensure the absence of cracks and pores exceeding $20\ \mu\text{m}$ in

size. Finally, in Activity 3.3, where the destructive control takes place, control specimens for destructive tests are separated from the substrate. Tensile tests can be conducted on these specimens at an external lab.

5. Cost Estimation and Carbon Footprint Calculation Boundaries

In this section, the methodology used for the economic evaluation of the Skyrora component manufacturing processes is presented. All equations used for the calculation of total production cost are described in detail, while all equation element units of measurement are defined in each subsection. The total manufacturing cost per sub-process consists of energy consumption, material and labour cost as well as the depreciation of used fixed asset.

In order to calculate the total manufacturing cost for the examined vacuum nozzle demonstrator, the following assumptions were made:

- (a) Depreciation can be claimed by the economic owner of the industrial product on a straight-line basis over the useful life of the equipment for a period of 5 to 20 years; in the present work, the depreciation period of each machine was given by Skyrora.
- (b) Based on the installed capacity of Skyrora equipment, the annual production rate of 21 components is considered (APR = 21 pcs/year).
- (c) A serial production for the manufacturing of components is followed. This means that all activities of manufacturing process will run in series, since their operation is dependent. In a follow-up investigation by the authors, the effect of manufacturing such components when being manufactured with parallel activities may be assessed. Additionally, it is important to mention that the operating time of equipment, as well as the working times of employees, were defined with direct observation and timing of the cycle work.

The assessment of the environmental impact of the examined vacuum nozzle demonstrator was performed according to the ISO standards. The objective was to extend the analysis over all stages of the life cycle of the examined industrial parts, from the acquisition of raw materials to the manufacturing and post-treatment of end-use products. The end-of-life scenario was not treated due to difficulties in the recycling of the rocket engine.

The Skyrora vacuum nozzle upper part is exclusively made of Inconel 718, a metallic superalloy that is extremely common in the aerospace industry. A gate-to-gate assessment of the environmental impact of this part was performed, as can be schematically seen in Figure 3. Pertinent to this analysis is the carbon footprint of the electricity consumed during the manufacturing process. To this end, the fact that the Skyrora's manufacturing site is exclusively powered by Great Britain's grid was conjectured (and not, e.g., through a bilateral power purchase agreement). As a basis for the calculation of the equivalent CO₂ emission rate, the 2021 generation mix was taken, readily available from software 'LCA for Experts' from Sphera[®] Chicago, IL, USA.

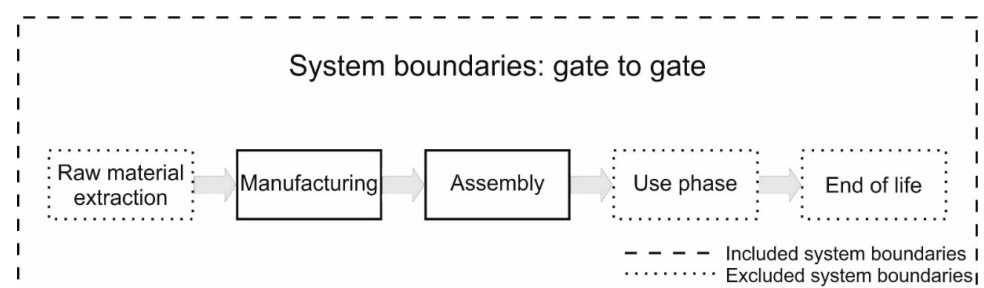


Figure 3. System boundaries of the investigated life cycle assessment (LCA) of the Skyrora vacuum nozzle.

6. Results

6.1. Cost Analysis Results

By performing the afore-described methodology, the (total) production cost (hereafter PC) (per unit) and the total final cost (hereafter TFC) (per unit) of the examined demonstrator were calculated as equal to the following:

$$PC = 1299.36 \text{ [no units]}$$

$$TFC = 1598.51 \text{ [no units]}$$

To this end, by denoting the material (M) and manufacturing overhead costs, along with the overhead costs of Research and Development (R&D), Transportation (TR), Profit (PR) and Selling, General and Administrative (SG&A) as “O” (overheads), a graphical representation of the final total cost and of the individual sub-process costs of the Skyrora demonstrator is plotted in Figure 4.

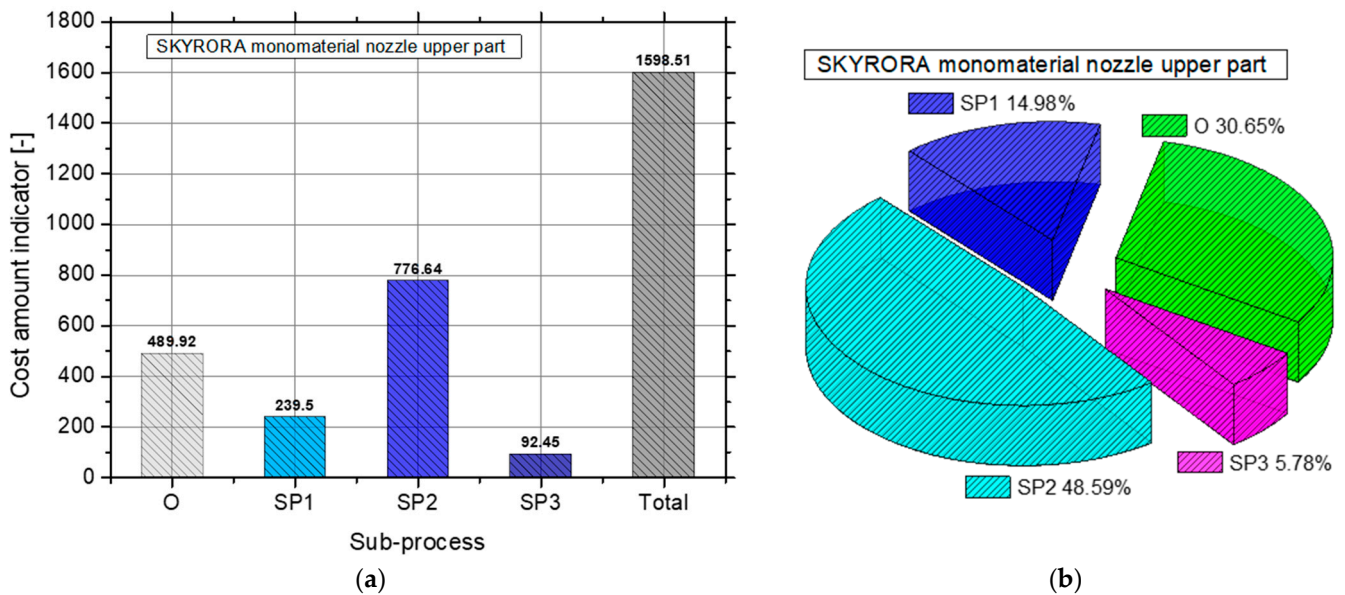


Figure 4. Individual sub-processes costs (a) in Cost Amount Indicator [no units]; (b) expressed in %.

As seen from Figure 4, the main phase SP2 (Sub-Process 2) includes all the necessary activities for the 3D printing and machining of the nozzle and consumes most of the resources (almost 49%) for the total manufacturing cost of the product. Finally, Figure 5 shows the cost analysis per different cost categories, as well as a graphical representation of the final total cost and of the individual category costs of the demonstrator.

Figure 5 indicates that the primary cost categories are not predominantly energy (E) or material (M) based; instead, depreciation (D) and overhead (O) costs significantly influence the total cost per unit (capital-intensive production process). As the output number of vacuum nozzles produced increases, the impact of these cost components is expected to diminish. Moreover, material (M) and labour (L) costs contribute minimally to the overall manufacturing costs associated with 3D printing technology, accounting for roughly 11% and 8% of the total costs, respectively. This is due to the nature of 3D printing, where material costs are largely confined to the purchase of powder feedstock.

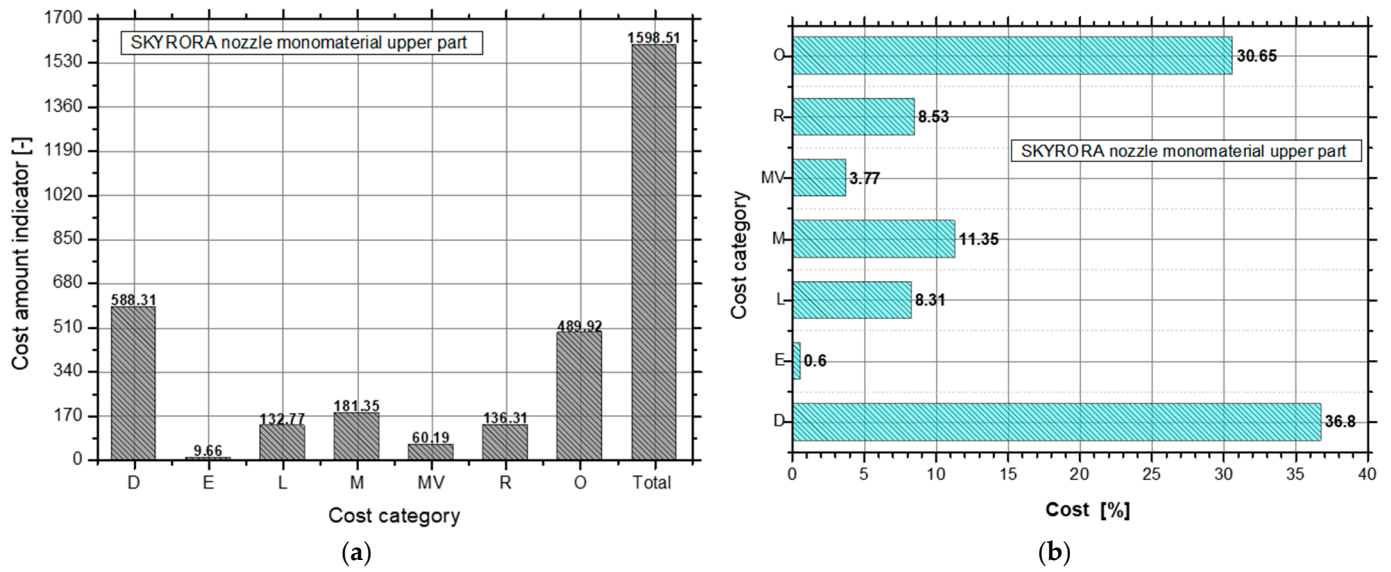


Figure 5. Different category costs (D = depreciation, E = energy, L = labour, MV = machine variable, O = overheads, R = rental cost, and M = material) (a) in Cost Amount Indicator [no units]; (b) expressed in %.

6.2. Carbon Footprint Results

Figure 6a shows the CO₂eq. emission shares per production stage of a single vacuum nozzle upper component. In line with the findings of previous displays, “3D Printing” is deemed the most pollutant production stage, emitting the equivalent of 21.6 kg of CO₂ in the atmosphere, a figure which is clearly associated with the energy intensive and the processing time of this activity. All other production stages have a considerably less significant carbon footprint that does not exceed 1.20 kg of CO₂eq.

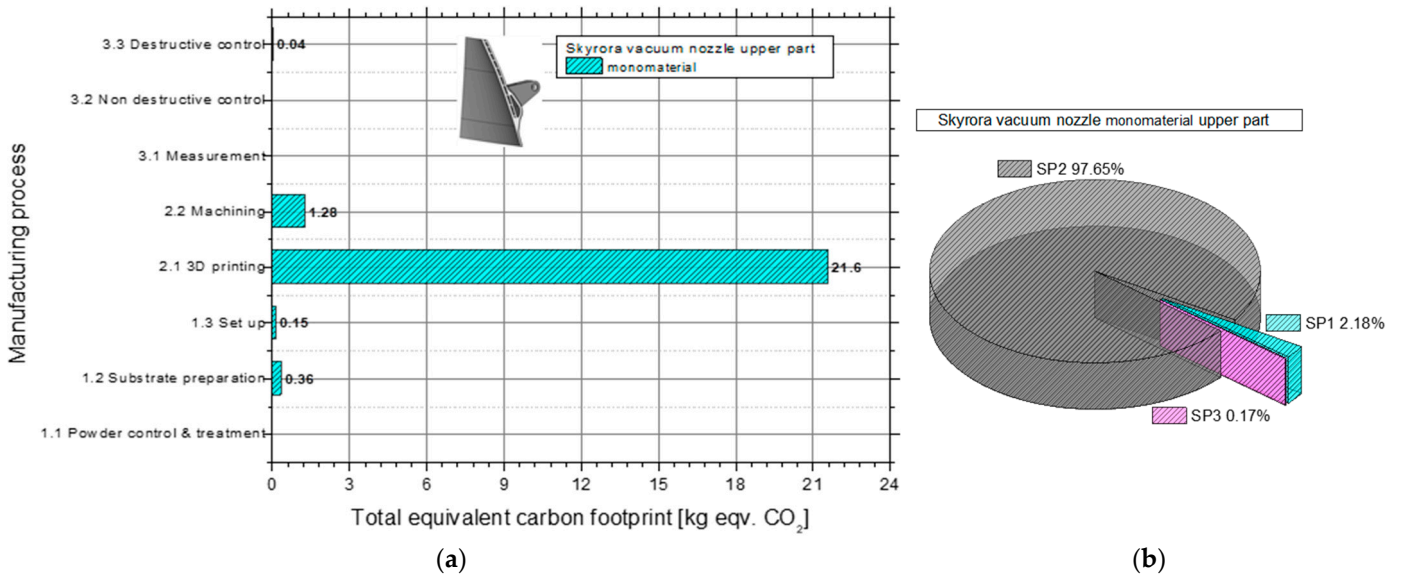


Figure 6. Total equivalent carbon footprint (gate to gate) of the Skyrora vacuum nozzle upper part per: (a) manufacturing process; (b) sub-process.

Furthermore, as Figure 6b shows, where the total equivalent carbon footprint per sub-process is plotted, sub-process 2 (including the “3D Printing” and the “Machining” stage) is the less environmentally friendly procedure. This sub-process alone is responsible for almost 98% of the total carbon emissions.

7. Further Considerations

Optimization of the nozzle could be performed in the near future, as not all the areas of the vacuum nozzle are exposed to temperatures above 450 °C, and therefore, the nickel-based superalloy can be replaced by the lower-density (two times lower) titanium alloys. Thus, future research could aim to efficiently perform multi-material design in the vacuum nozzle, by exploiting thin functional intermediate layers, through thermodynamic calculations between the Ni-based and Ti-based superalloys, and thus the multi-material 3D printing of the nozzle (within the MADE-3D project).

8. Conclusions

The manufacturing processes for producing the Skyrora vacuum nozzle with 3D printing technology was documented. The following conclusions could be drawn:

- (1) The main phase dedicated to the 3D printing of the nozzle consumes most of the resources (almost 49%) for the total manufacturing cost of the product.
- (2) The main category costs are depreciation and overheads that play a pivotal role in the total cost per unit. With the increase in the output number of vacuum nozzles to be manufactured, these contributions are expected to be decreased.
- (3) Material and labour costs play a small role on the total manufacturing cost of the 3D printing technology, contributing to 11.3% and 8.3% to the total cost, respectively. This can be attributed to the 3D printing technology, where the material purchase is restricted to the powder feedstock only.
- (4) The carbon footprint is exclusively emitted (almost 98% of the total) during the sub-process 2, where electric energy for the grid is needed for the main additive manufacturing phase. The other sub-processes emit minor emissions since minimal energy is consumed or minimal waste is generated during these phases.

Author Contributions: Conceptualization, N.D.A.; methodology, V.Z., E.V. and N.T.; software, I.L.; validation, E.K. (Evgeniy Karakash), E.K. (Elena Karpovich), M.L., O.G. and R.V.; resources, N.D.A.; writing—original draft preparation, T.S. and I.L.; writing—review and editing, N.D.A., V.Z. and E.V.; visualization, I.L.; supervision, N.D.A.; project administration, N.D.A.; funding acquisition, N.D.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by HORIZON Research and Innovation Actions, of the act HORIZON-CL4-2022-RESILIENCE-01 with Grant Agreement code 101091911.

Acknowledgments: The authors gratefully acknowledge the financial support of the HORIZON Research and Innovation Actions, European Health and Digital Executive Agency for the implementation of the project “MULTI-MATERIAL DESIGN USING 3D PRINTING” with the acronym “MADE-3D” of the act HORIZON-CL4-2022-RESILIENCE-01 with Grant Agreement code 101091911.

Conflicts of Interest: The authors declare no conflicts of interest.

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