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Additive manufacturing for an urban vehicle prototype: re-design and sustainability implications

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Abstract

Additive Manufacturing (AM), allowing the layer-by-layer fabrication of products characterized by a shape complexity unobtainable with conventional manufacturing routes, has been widely recognized as a disruptive technology enabling the transition to the Industry 4.0. In this context, the design of a Portable Assisted Mobile Device (PAMD) prototype was considered as a case study. The best practices of the re-design for AM were applied to three of the main structural components, and the most sustainable manufacturing approach between AM processes and the conventional ones was identified with respect to cumulative energy demand, carbon dioxide emissions and costs. The paper aims to promote the debate concerning the correlation between design choices, process selection and sustainable product development.

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Keywords: Portable Assisted Mobile Device (PAMD); Design for Additive Manufacturing; Energy efficiency; Cost assessment.

1. Introduction

Urban vehicles have been identified as an alternative and sustainable transport mode that could help to reduce traffic congestion and improve air quality in urban areas [1, 2]. This mobility mode can be considered as a fast link between private residences and public transport systems, or as a substitute for rapid transfers [3, 4]. The size and weight of urban vehicles have to be restricted to allow for easy transportation, and the energy demand for the propulsion is given by electrical power instead of internal combustion engines [2, 5]. The new design challenges could be supported by Additive Manufacturing (AM), which allows the production of mass-customized parts with advantageous performance-to-mass ratios. However, AM techniques, beside requiring an accurate design (or re-design) of the components, might need resources higher than those of the manufacturing processes which are traditionally applied. In this context, this research analyzes the correlation between the design choices regarding an urban vehicle prototype and the resulting manufacturing scenarios, with the aim of evaluating their environmental and economic implications. The case study and the re-design for AM procedures are described in Section 2, together with the LCA-based methodology for the impact assessment of the different manufacturing approaches. The results are presented and discussed in Section 3. The main conclusions and the future research outlooks are summarized in Section 4.

2. Materials and methods

The case study refers to a so-called ‘last-mile’ vehicle, i.e., a vehicle suitable for small journeys in urban areas. The design of such Portable Assisted Mobile Device (PAMD) prototype rose from a challenge proposed within the framework of an international Personal Urban Mobility Access (PUMA) project. This competition imposed, among other requirements, the use of recyclable materials and limitations on weight and costs. The project team opted for a hub-less wheel vehicle (shown in Figure 1*a*), and focused the attention on the AM technology, since it was proved to face

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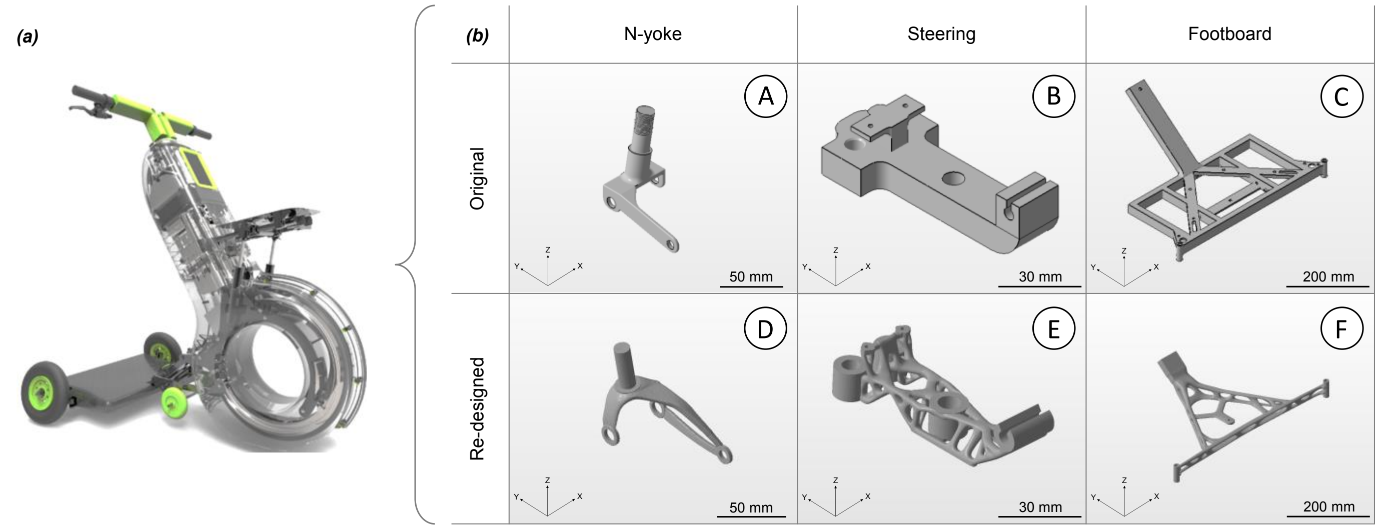

Fig. 1. Urban vehicle prototype (*a*) and components assumed as case studies (*b*).

the challenge requirements by allowing an optimized light-weight design.

2.1. Re-design for Additive Manufacturing

Three small-to-medium parts of the assembly, namely (A) the N-yoke, (B) the steering servo, and (C) the footboard frame, were re-designed for AM (as highlighted in Figure 1*b*). The main objective of the design phase was to minimize the mass while ensuring the resistance to loads, including the human weight. The re-design was performed by combining Finite Element (FE) simulation, Topology Optimization (TO), and the application of Design Rules for L-PBF, in an iterative loop. The need for supports removal and finishing operations were also taken into account through a proper selection of the parts' orientation in the build volume. To explore all the possible configurations, the design space was assumed as the largest as possible, with the only constraint of avoiding interferences between neighbouring parts. The N-yoke was designed by considering both the steering load and the bump load deriving from a wheel that collides road irregularities. The angles that provide a working steering kinematic were kept as the original. The steering servo, instead, transmits the rotation from the handlebar to the front wheels of the vehicle and it is connected to several other kinematic components. In this case, the attention was focused on minimizing and simplifying the machining operations of mating surfaces, considering the notch effect at the same time. Finally, the footboard frame was designed with particular care for its connection with the central structure, integrating a tubular support to shift the location of the welded connection far from the area of maximum stress.

2.2. Manufacturing scenarios

Different design choices impose different manufacturing approaches, equipment and feedstock materials to be used. Therefore, some alternative manufacturing scenarios were hypothesised and evaluated in this research, according to Table 1. The scenarios #1 and #2 analyze the production of the components 'A' and 'B' (i.e., prior to the re-design) by means of a conventional milling approach starting either from a casting or a massive block-shaped workpiece. In such case, the kind and amounts of feedstock materials are expected to vary, with consequent effects on the raw material usage efficiency.

Table 1. Manufacturing approaches and assumed scenarios.

Scenario	Component	Manufacturing approach	Material
#1	A, B	Machining from casting	Al 356.0
#2	A, B	Machining from massive workpiece	Al 7075
#3	C	TIG welding + Machining	Al 6061
#4	D, E	L-PBF (EOS M290) + Machining	AlSi10Mg
#5	D, E, F	L-PBF (EOS M400-4) + Machining	AlSi10Mg

The scenario #3 concerns the component 'C', which can be produced by welding the pre-formed tubulars and then machining the holes and the mating surfaces. As for the AM-based approach, scenarios #4 and #5 refer to the integrated additive-subtractive manufacturing of the re-designed components identified as 'D', 'E' and 'F' in Figure 1*b*. Two L-PBF machines (namely, the EOS M290 and M400-4) were considered, and a finish machining operation was planned to guarantee the geometrical product specifications where needed. As far as the machines are assumed to operate at full capacity, 8 components 'D' and 14 components 'E' could be simultaneously manufactured in the M290 machine. These numbers increase to 18 and 30, respectively, when the M400-4 machine is used. Due to its dimensions, the footboard was producible with the M400-4 model only, in a single-part configuration.

2.3. Environmental and economic impact assessment

Recently-published models for the environmental and economic assessment of both the conventional and additive-based manufacturing approaches (please see the refs. [6, 7])

were specifically adapted to the case studies. Therefore, a cradle-to-gate LCA was carried out while assuming a single produced part (within a batch-size of 1000) as the functional unit. Three process metrics were addressed: the Cumulative Energy Demand (CED), the carbon dioxide emissions and the product costs. Feedstock material production, manufacturing and post-AM processes were the assessed bits of the product life. The use phase was left out of the boundaries of the research, whereas the benefits arising from the upstream flow of recycled material in the current supply were included by adopting the so-called ‘recycled content approach’ proposed in [8]. Figure 2 shows all the energy, consumables (e.g., tools, cutting fluids, gases), and material flows which affect both the conventional and the AM-based approaches. The emissions and waste streams are highlighted, together with the main cost drivers.

2.4. Data inventory

Following the path of the materials from the cradle to the exit gate of the production plant, waste streams occur during each unit process. Despite the chosen manufacturing approach, raw materials have to be obtained by means of primary as well as secondary material production routes. Then, pre-manufacturing processes are needed to allow for the proper feedstock material to be provided to the subsequent manufacturing process. Each pre-manufacturing process results in a specific material loss. The input/output material ratios were fixed to 1.21 for investment casting, 1.05 for workpiece forming, 1.06 for beam extrusion and 1.05 for powder atomization [9, 10]. Further, to achieve the final part, each scenario listed in Table 1 requires different amounts of feedstock materials, and different waste streams are due as a by-product of each manufacturing process. The material flows, labelled as defined in Figure 2, are given in Table 2 for the conventional manufacturing approaches. As far as the material flows involved in the AM-based approach are concerned, the amount of metal powder, the atomization-related waste, and the mass of the machining allowance to obtain the final part geometry ($k \cdot m_P$) are listed in Table 3. The k factor, being defined as the ratio of the mass of the re-designed part and the one of the original component, accounts for the weight reduction potential of AM [6].

Table 2. Main material flows for conventional manufacturing (Scenarios #1, #2 and #3, with reference to Table 1).

Component	A		B		C
Scenario	#1	#2	#1	#2	#3
m_{feed} (g)	69	1104	83	370	1202
$m_{w,\,pre\text{-}mfg}$ (g)	14	55	17	19	72
m_{chips} (g)	11	1046	1	288	52
m_{part} (g)	58	58	82	82	1150

Table 3. Main material flows for the AM-based manufacturing approach (Scenarios #4 and #5, with reference to Table 1).

Component	D	E	F
Scenario	#4, #5	#4, #5	#5
m_{pwd} (g)	101	39	1410
$m_{w,\,atom}$ (g)	5	2	71
$m_{support}$ (g)	40	9	700
m_{allow} (g)	11	1	20
$k \cdot m_{part}$ (g)	50	29	690
k	0.86	0.35	0.60

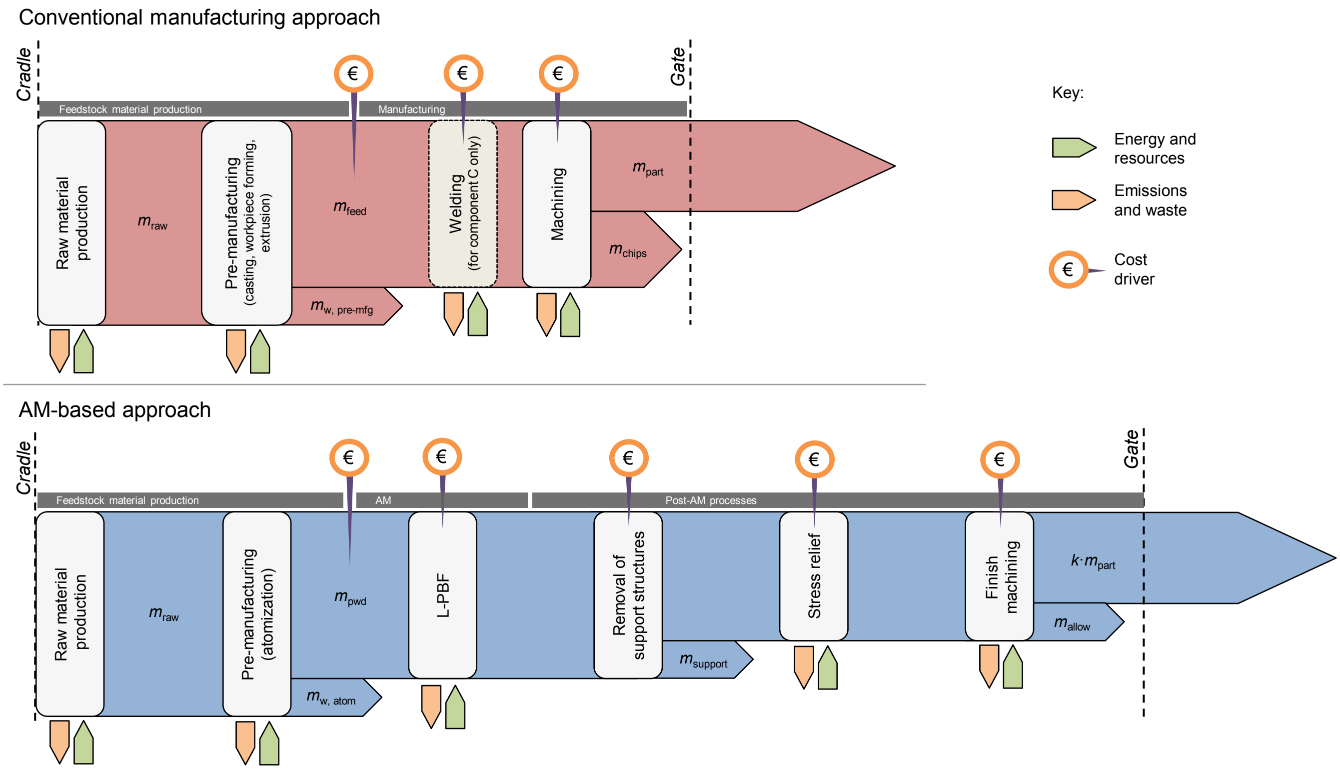

Fig. 2. Qualitative material flowchart and main streams of energy, resources and waste for both CM and AM+FM approaches.

2.4.1. Energy requirements and carbon footprint

The embodied energy of the raw material was computed considering both primary and secondary material resources, according to [8], by using average values extracted from the CES Selector database [9]. When specific material data were absent, the search of the eco-properties was made on the basis of the chemical composition of the material. The recycle fraction in the current supply for all the employed materials was set to 0.43. The resultant embodied energies were 129 MJ/kg for Al 6061, and 125 MJ/kg for the other alloys. Also, the carbon footprint was 8.2 kgCO_2/kg for Al 356.0 and AlSi10Mg, and 8.7 kgCO_2/kg for Al 7075 and Al 6061. A best estimate concerning the impacts of the pre-manufacturing phases is given in Table 4. Unless otherwise specified, values were obtained from [9].

Table 4. Specific energy demand and carbon footprint of the pre-manufacturing phases.

Process	Energy demand (MJ/kg)	CO_2 footprint (kgCO_2/kg)
Casting	11.4	0.7
Workpiece forming	11.2	0.8
Beam extrusion	12.4	0.9
Atomization [10]	8.1	0.5

The Specific Energy Consumption (SEC) of additive manufacturing was here computed for the different scenarios, by considering the process parameters and the components' height in the build chamber. Melting power values of 3 and 16 kW were assumed for EOS M290 and M400-4, respectively [11]. The melting rates, as given by the machine datasheets, were equal to 26.7 cm^3/h for M290, and 106.8 cm^3/h for M400-4 [11]. These values are strictly related to the material being deposited and the layer thickness. In the present case study, a layer thickness of 30 μm was chosen to obtain the best surface condition. The powder spreading time was assumed on the basis of data available in [12]. The Specific (electric) Energy Consumption values for the EOS M290 machine during the production of the components 'D' and 'E' were assumed to be 243 MJ/kg and 215 MJ/kg, respectively. For the M400-4 machine, the computed SEC values were 283 MJ/kg, 261 MJ/kg and 383 MJ/kg for the components 'D', 'E' and 'F'. These values are comparable with the available literature data concerning the AlSi10Mg deposition by means of L-PBF (e.g., 364 MJ/kg in a full-capacity configuration [13]). In addition, the setup time of the machine was fixed to 2 h, on the basis of practical experience. The conversion from electric energy to primary energy was done by considering a conversion efficiency of 0.38 [10], and the carbon emission signature of the electric grid was 0.447 kgCO_2/kWh [7]. The creation of the gas atmosphere needed to perform the L-PBF process required a consumption of Argon of 3 m^3 for EOS M290 and 4.8 m^3 for M400-4, while the consumption rate during the process was 0.6 m^3/h for EOS M290 and 1.2 m^3/h for EOS M400-4 [11]. The embodied energy of the gas was 0.69 MJ/kg [14]. The post-AM stress relief was included assuming a specific energy consumption of 1.53 MJ/kg [14]. For the joining of the footboard tubulars, the TIG welding operations were characterized by a 4-kW constant power demand and an assumed process time of 20 min.

Table 5. Main parameters of the machining unit process.

Parameter	Rough machining	Finish machining
Energy demand (MJ/kg) [9]	0.9 - 2.1	4.6 - 16.8
CO_2 footprint (kgCO_2/kg) [9]	0.1 - 0.2	0.3 - 1.3
Material Removal Rate (kg/h) [15]	18.7 - 26.3	0.9 - 1.3

As for the burden of the CM approach, the main data are listed in Table 5. The here-estimated ranges were assumed as representative of an industrial production, taking into account the environmental and technological performance of different equipment architectures. Overall, the excess material in the form of chips was removed 80% when roughing and 20% under finishing process conditions. In addition, aiming to a system-level analysis of the machining unit process, the impacts of tools and cutting fluids, as well as the contributions of the non-cutting phases, were all included in the assessment. The embodied energy of the tungsten carbide tools was 400 MJ/kg [16, and references therein], whereas the tool change time and the tool life were 2 and 30 min, respectively [7]. The embodied energy of the lubricant was set to 1.4 MJ/kg, while its consumption rate was estimated to be 0.48 kg/h [17].

2.4.2. Main cost drivers

The cost assessment was made by accounting for the purchasing costs of materials and consumables, the production costs (including machine setup and preparation), the labour costs, the administrative and production overheads. To quantify the cost of each feedstock material, the cost of pre-manufacturing phases was included (as computed by means of [9]). It resulted to be 26.6 €/part for casting ('A' and 'B'), 4.4 €/part and 1.5 €/part respectively for the workpiece of the components 'A' and 'B', and 2.8 €/part for the tubulars to be welded. For these CM scenarios, the considered specific cost for the raw aluminium purchase ranged from 1.78 to 3.51 €/kg. As for the AlSi10Mg powder, the cost was 92 €/kg, on the basis of a market quotation. For the computation of the indirect costs in the manufacturing steps, the approach proposed by Baumers [18] was followed. A depreciation period of 8 years, 5000 working hours per year, a maintenance cost equal to the 6% of the machine purchase cost and 5.46 €/h for production and administration overheads were assumed. The indirect cost rate was 23.2 €/h and 58.0 €/h for the EOS M290 and the M400-4 systems (taking the machine purchase costs from [19]), 12.5 €/h for the milling machine [7], and 6.1 €/h for the TIG welding equipment (adapted from [9]). An average cost rate for the operator of 21.7 €/h was assumed [7], with a rate of employment of 5% for AM, 10% for machining and 100% for TIG welding. The costs of the electric energy and for the purchase of the consumables are listed in Table 6.

3. Results and Discussion

Figure 3 shows the results in terms of Cumulative Energy Demand (CED), carbon dioxide emissions and product costs on a per-part basis and for all the scenarios envisaged in Table 1. The variability in the results that is highlighted by the error bars is due to a ± 10% variability in the input data, which was imposed to all the average input variables collected from literature or database in order to account for data uncertainty. Among the different scenarios, a similar trend can be observed for both the CED and carbon dioxide emissions. As for the N-yoke, Scenario #1 and Scenario #2 allowed the lowest and the highest energy demand to be achieved, respectively, whereas the AM-based approaches (Scenarios #4 and #5) provided intermediate results. The results concerning the conventional manufacturing approaches are heavily affected by the material-usage efficiency [6]. The machining of the N-yoke from a massive workpiece is characterized by a solid-to-cavity ratio (i.e., the ratio of the mass of the final part and the mass of the workpiece) of 0.05, therefore the mass of the needed raw material is more than 10 times higher in comparison to that of all the other scenarios. The finish machining applied to casting or additively manufactured near-to-net shape parts permitted a reduction of the energy embedded in the feedstock materials. However, as far as the AM-based approach is concerned, the highest share in energy demand was due to the L-PBF process. This evidence, which is attributable to the differences in the specific energy consumption of additive and subtractive manufacturing processes [12, 20, 21], is widely confirmed by the available literature [22-24]. The same discussion can be extended to the results concerning the 'Steering' part. In such case, the higher solid-to-cavity ratio of Scenario #2 (i.e., 0.22) reduced the differences among the environmental impacts of the different scenarios. Overall, when moving towards massive components, the contribution due to the pure manufacturing phase increases for the additive-based approach and decreases for the material removal [7]. Moreover, the 'one resource - one impact' assessment here presented was loosely affected by the consumables (such as the cutting tools, the cutting fluids, the shielding gas). For the same re-designed part (i.e., for components 'D' and 'E' in Scenarios #4 and #5), slightly higher energy requirements and carbon emissions were estimated for the EOS M400-4 machine, despite the higher melting rate and the larger build chamber. This is likely due to the different machine architectures, with the smaller machine (M290) requiring lower specific energy demands. Finally, the production with AM of the 'Footboard' (Scenario #5) appears to be unsustainable with respect to the welding of the tubulars, and this result is partly related to the positioning of the single component within the build volume of the machine, which requires a mass of support structures comparable to that of the final part and do not allow the saturation of the build capacity.

On the other hand, the cost assessment provided different trends. The minimum costs for producing the 'N-yoke' and the 'Steering' were achieved by means of Scenario #2, despite the higher (labour, indirect and processing) costs related to machining, since the purchase cost of the workpiece was lower than that of the casting. Under the above-mentioned assumptions, the costs of the parts produced by the additive-based approach are generally higher than those of the other manufacturing routes. The costs of AM are dominated by the indirect cost rate, which in turn mainly depends on the machine depreciation. The analysis highlighted that, even though the purchase cost of the EOS M400-4 system was assumed to be about 2.5 times higher than that of the EOS M290, Scenario #4 would be more expensive than Scenario #5. This was due to the higher productivity rate of the machine, enabling more components to be produced in the same job (please see Section 2.2) and reducing the costs on a per-part basis. In this context, the differences among the indirect costs of the produced parts are directly related to the deposition time, which is affected by the height of the job in the build chamber (thus, by the number of layers). The cost of the 'Footboard' increased by two orders of magnitude when compared to the original component.

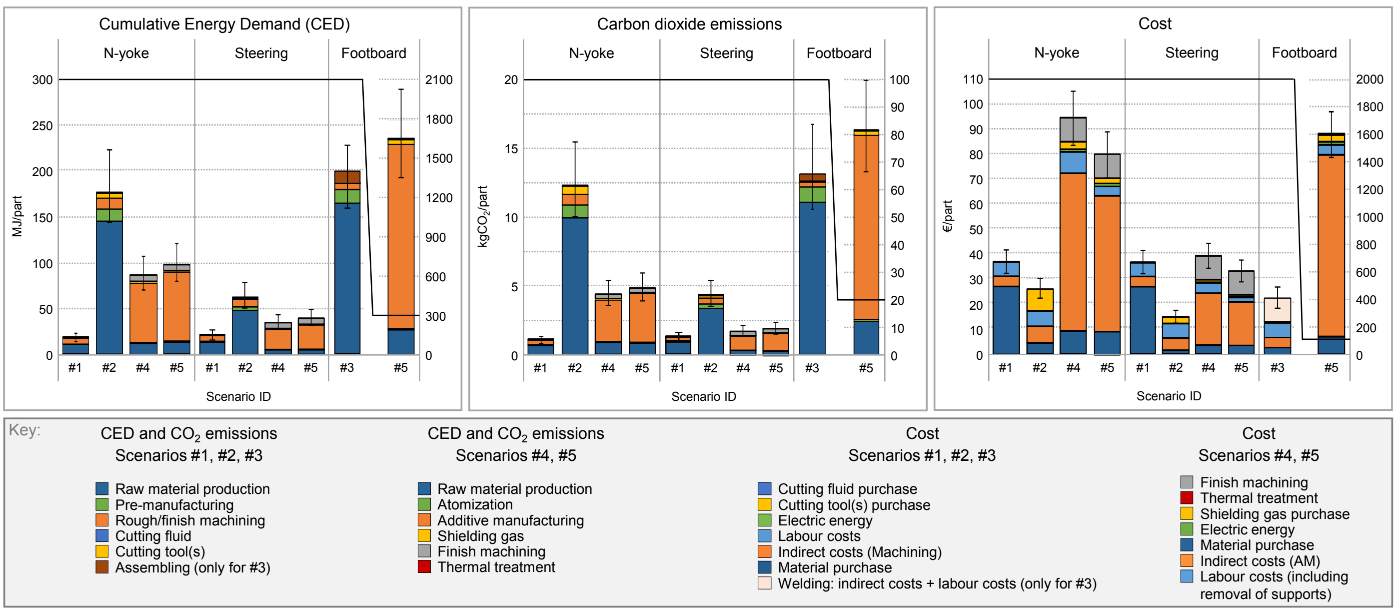

Fig. 3. CED, carbon dioxide emissions and cost results under cradle-to-gate system boundaries.

Table 6. Purchase costs of the consumables.

Cost driver	Value
Electric energy	0.15 €/kWh [7]
Cutting tool	20 €/tool [7]
Cutting fluid	0.93 €/kg [17]
Argon	1.63 €/m^3 [Quotation]

4. Conclusions and outlooks

The design choices do not influence only the added value that can be given to a product, since they often impose a manufacturing approach to be chosen. Moreover, both design and manufacturing (or, better, their correlation) are expected to cause a non-negligible economic and environmental impact. In this paper, a new Portable Assisted Mobile Device (PAMD) prototype was presented. Some of its components were re-designed for additive manufacturing, and the research has been focused on the environmental and economic impact assessment of alternative manufacturing approaches to realize both the original and the AM-ed parts. The results show that, a significant light-weighting (while guaranteeing the same in-use performance) can be achieved by adopting AM, even if the product costs appear to be higher than those of more traditional design and processes. From the environmental sustainability viewpoint, AM proved to be advantageous when exploiting its higher material-usage efficiency, particularly in comparison to the material removal processes from massive workpieces. However, AM might not be always the optimum choice due to the high specific electric energy consumption of the currently available systems. Overall, the results are case-specific, and this kind of analysis (further extended to the evaluation of the benefits deriving from the lower consumption of lightened vehicles) are necessary to properly position AM within the sustainable manufacturing context.

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