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ORIGINAL ARTICLE

Definition of a life cycle engineering tool to support the ecodesign in additive manufacturing: application to FDM technology

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Abstract

This study introduces a comprehensive life cycle model and tool to support the ecodesign of 3D printed components. The model, developed for Fused Deposition Modeling (FDM) technology, integrates both product and process-related parameters and encompasses all life cycle stages: (i) raw material production, (ii) part manufacturing, (iii) use, including application context and maintenance, (iv) end-of-life, and (v) transport. The model enables the predictive evaluation of environmental and economic performance through life cycle assessment (LCA) and life cycle costing (LCC), respectively, and using engineering design parameters as input. The FDM life cycle tool aims to guide decision-making during the early design phases by integrating sustainability metrics alongside conventional design requirements. It constitutes the kernel of a broader approach (called eDAM—ecodesign for Additive Manufacturing), which incorporates life cycle models, extensive data inventories, and technology-specific ecodesign guidelines. However, the development and implementation of the framework fall beyond the scope of the present study. The FDM model's applicability is demonstrated through a case study involving the production of a lightweight aerospace component (aircraft interior panel). The bio-inspired optimized 3D printed part exhibits notable reductions in greenhouse gas emissions and life cycle costs, confirming AM's potential for sustainability improvements in dynamic applications, including aeronautical systems. This tool outperforms other commercial tools used for environmental and cost assessment in additive manufacturing, in terms of built-in functionalities, product life cycle phases, and database breadth. The research highlights the scalability of the eDAM approach and its capacity to support engineers in achieving a balance between technical, economic, and environmental performance. Future work will extend the model to additional AM and conventional manufacturing technologies, refine specific life cycle phases (e.g., use-phase and end-of-life scenarios), and evaluate the usability and implementation efficiency of the model within the broader ecodesign framework.

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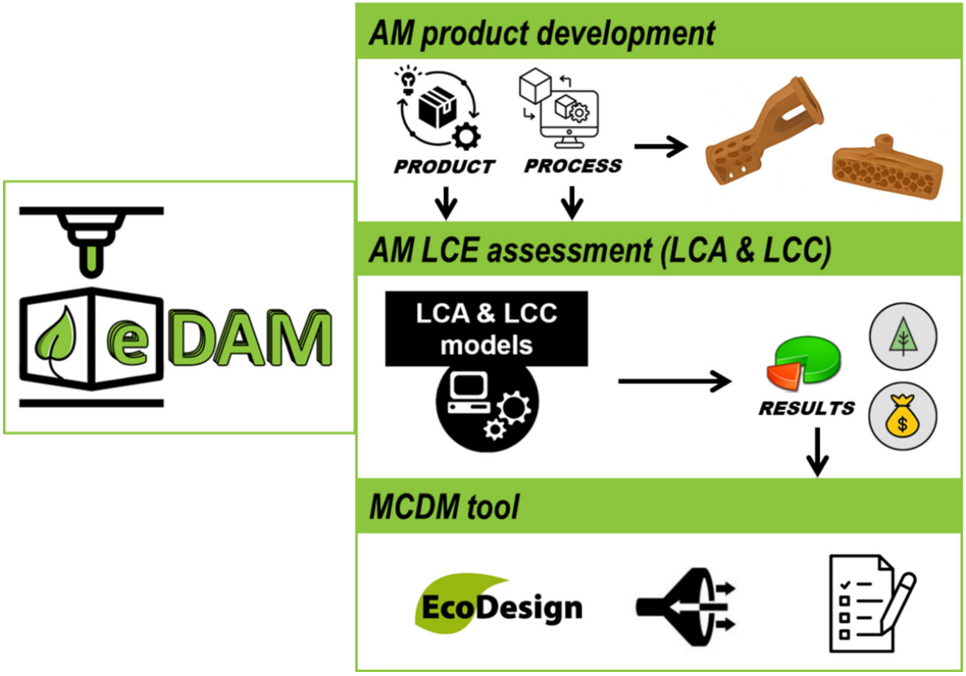
Graphical abstract

eDAM methodological framework



Keywords Ecodesign · Life cycle engineering · LCE · Life cycle assessment · LCA · Life cycle cost · LCC · FDM · Additive manufacturing · Design for sustainability

Abbreviations

ABS	Acrylonitrile butadiene styrene
AHP	Analytical hierarchy process
AM	Additive manufacturing
ASA	Acrylonitrile styrene acrylate
CAD	Computer-aided design
CM	Conventional machining
DED	Direct energy deposition
EI	Environmental impact
EoL	End-of-life
FDM	Fusion deposition modelling
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle cost
LCE	Life cycle engineering
LCIA	Life cycle impact assessment
MCDM	Multi-criteria decision-making
PA	Polyamide
PETG	Polyethylene terephthalate glycol
PLA	Polylactic acid
SLS	Selective laser sintering
SLM	Selective laser melting
TOPSIS	Technique for order of preference by similarity to ideal solution
TPU	Thermoplastic polyurethane
UN	United Nations
WAAM	Wired arc additive manufacturing

Parameters

C_{Active}	Cost of the active printing sub-phase
C_{RM}	Cost of the raw material phase
C_{Man}	Cost of the manufacturing phase
C_{Maint}	Cost of the maintenance
C_{Use}	Cost of the use phase
C_{Tran}	Cost of the transport phase
C_{EoL}	Cost of the EoL phase
C_{Print}	Cost of the printing stage
C_{Post}	Cost of the post-processing stage
C_{Set-up}	Cost of the set-up sub-phase
$C_{A.Use}$	Cost for the active use sub-phase
d	Discount rate
D	Average distance travelled by the vehicle in one year
I_{Active}	Environmental impact of the active printing sub-phase
I_{RM}	Environmental impact of the raw material phase

I_{Man}	Environmental impact of the manufacturing phase
I_{Maint}	Environmental impact of the maintenance
I_{Use}	Environmental impact of the use phase
I_{EoL}	Environmental Impact of the EoL phase
I_{Print}	Environmental impact of the printing stage
I_{Post}	Environmental impact of the post-processing stage
I_{Set-up}	Environmental impact of the set-up sub-phase
I_{Tran}	Environmental impact of the transport phase
I_{RMS}	Environmental Impact of the raw material sub-phase
I_{PPs}	EI for the generic printing process sub-phase
$I_{A.Use}$	EI for the active use sub-phase
m_{Part}	Mass of the part
m_{RM}	Mass of the raw material
$m_{Vehicle}$	Mass of the vehicle
m_{EoL}	Mass that undergoes EoL
n	N-th year
N	Total life of the product in years
P_{PPs}	Rated power required during the specific sub-phase
r	Recyclability rate
$SFC_{Vehicle}$	Specific fuel consumption of the vehicle
t_{PPs}	Time elapsed during the specific sub-phase
β_{FM}	Unitary EI for the filament manufacturing (polymer extrusion)
β_{RM}	Unitary EI for the Raw Material sub-phase
$\beta_{elec.energy}$	Unitary EI for the electric energy production
β_{fuel}	Unitary EI of the fuel
$\beta_{extract}$	Unitary EI for the extraction of raw material
$\beta_{landfill}$	Unitary EI of landfilling as municipal waste
$\gamma_{elec.energy}$	Unitary cost for the electric energy
γ_{fuel}	Unitary cost of the fuel
$\gamma_{landfill}$	Unitary cost of landfilling as municipal waste
γ_{RM}	Unitary cost for the Raw Material phase
ρ_{fuel}	Fuel density

1 Introduction

The industrial sector currently accounts for approximately 54% of total global energy consumption, significantly contributing to greenhouse gas emissions and global warming [1]. Manufacturing activities are responsible for 19% of global greenhouse gas emissions [2]. To address the urgent need for environmentally sustainable methods in mass production, Additive Manufacturing (AM) is emerging as a promising alternative to drive innovation in the industrial sector [3, 4]. AM encompasses a group of processes that fabricate three-dimensional objects by successively adding layers of material based on a digital design [5]. This innovative approach offers numerous advantages over traditional manufacturing methods, including design flexibility, rapid prototyping, reduced material usage and waste, and the ability to produce complex geometries [6, 7]. AM empowers designers to create intricate designs, lightweight structures, and customized parts, resulting in enhanced functionality and improved resource efficiency. The layer-wise nature of AM allows the production of parts with complex internal features, including lattice structures that can improve strength while minimizing weight. Moreover, AM enables part consolidation, where multiple components are combined into a single, more efficient design, reducing assembly complexity and material consumption [8, 9].

As sustainability becomes increasingly paramount, researchers are exploring also the environmental implications of AM processes, focusing on energy consumption, material usage, and emissions. However, assessing the sustainability performance of components manufactured with AM technologies requires a thorough analysis that considers the entire product life cycle, rather than focusing solely on the production phase [10]. AM is often associated with "green" and waste-free production, but the literature debates these statements, as AM processes require high energy consumption, the use of materials with high embodied energy, and present challenges in recycling waste materials [11, 12]. The growing awareness of global environmental challenges and the sustainability goals set by the United Nations (UN) has led to increased attention to the environmental and economic performance of products throughout their entire life cycle [13]. In this context, the traditional approach to design, which primarily focuses on the production phase, proves insufficient to fully assess a product's impact on the environment and the economy [14]. Adopting a Life Cycle Engineering (LCE) approach is essential, encompassing all stages of a product's life cycle, from raw material extraction to end-of-life (EoL), including transportation, use, and disposal. LCE is defined as "*engineering activities which include the application of technological and scientific principles to manufacturing products to protect the environment, conserve resources, encourage economic progress, keeping in mind social concerns, and the need for sustainability, while optimizing the product life cycle and minimizing pollution and waste*" [15]. LCE provides a comprehensive framework for analyzing and improving a product's performance in terms of sustainability, integrating environmental, economic, and social aspects. Two fundamental tools of LCE are Life Cycle Assessment (LCA) and Life Cycle Cost (LCC). LCA, standardized by ISO 14040/14044:2020, focuses on quantifying the environmental impacts of a product throughout its life cycle, considering aspects such as greenhouse gas emissions, resource consumption, and pollution. LCC, standardized by ISO 15686-5:2008 and IEC 60300-3-3:2017, evaluates the costs incurred over a product's entire life cycle—including production, operation, maintenance, and disposal—by incorporating cost actualization to express all expenditures in present value terms.

In the context of AM, ensuring the completeness of life cycle analyses is a fundamental pillar, as assessments limited to a single stage of a product's life cycle can risk generating misleading results, depriving the necessary overall perspective [16, 17]. This is the case of transport vehicles (e.g., automotive, aerospace) where the weight reduction of components achieved through AM leads to lower fuel consumption during the use phase, offsetting the environmental impacts generated in the production phase [18, 19]. Additionally, the ability to repair and reuse 3D-printed components helps extend the product's lifespan, generating significant long-term economic and environmental benefits. Thus, when evaluated from a life cycle perspective, AM offers both advantages and disadvantages. On the positive side, weight reduction is a key topic. AM demonstrates significant material efficiency by utilizing only the necessary material for object construction, substantially reducing waste compared to subtractive manufacturing methods. This efficiency translates into improved resource utilization and reduced environmental/cost impact associated with raw material extraction, transportation, and processing [7, 18]. AM enables the creation of complex lattice structures and topology-optimized designs, resulting in reduced component weight. AM facilitates part consolidation, allowing multiple components to be integrated into a single piece, which simplifies assembly processes, reduces part count, and potentially increases product reliability while further decreasing weight [8, 9, 20]. Product circularity is another positive aspect, since AM potentially offers the possibility of regenerating and repairing obsolete or damaged parts, extending their useful life [21, 22]. On the negative side, energy demand for material production and part manufacturing is a significant challenge. For example, some technologies require high energy consumption (e.g., laser and electron beam melting), due to the heat needed for material melting and the generally long time necessary to complete the job with AM machines [23]. Many authors like Kokare et al. [24] used LCA and LCC methodologies to compare Wire-Arc AM (WAAM), Selective Laser Melting (SLM), and Conventional Machining (CM) technologies, concluding that, considering the manufacturing phase, the SLM technology, one of the most prominent in the industry, is less sustainable, both economically and environmentally, than CM. Ingarao et al. [25] performed a similar study, comparing only SLM and CM in a cradle-to-grave LCA, reaching a similar conclusion. These research works also claimed that AM could become competitive with CM only if the use phase is included in the analysis, especially for applications in the aviation sector. A primary source of uncertainty concerning the sustainability of AM lies in the high energy demand associated with raw material extraction and processing, particularly for metal powders, which is generally greater than that required for bulk materials [26]. Process waste management and recycling difficulties present another challenge, as unused powders and support structures can be complicated to recycle, potentially leading to additional negative environmental impacts [27]. The high costs associated with AM equipment, materials, and skilled labor limit its widespread adoption, particularly for high-volume production [28]. Finally, the need for post-processing operations, such as surface finishing or heat treatment, which can incur other costs and environmental impacts [29], further hinders its adoption.

Despite the well-known importance and the growing interest in applying the LCE approach to products manufactured with AM technologies, significant research gaps remain underexplored. The first one is the lack of comprehensive and reliable life cycle models capable of predicting the environmental and economic impacts of different AM technologies. Existing studies address only selected life cycle stages, such as manufacturing or EoL, without assessing the overall performance across the entire product life cycle. Moreover, available models are often tailored to the specific characteristics of a single AM technology, which hinders the comparison of alternative technologies [30]. This research gap challenges engineers' ability to compare AM and CM technologies and to identify the most suitable solution for a given application. The second limitation identified in the body of knowledge concerns the generation of Life Cycle Inventory (LCI) and the retrieval of relevant data from the digital thread available at the design stage. A key challenge lies in predicting life cycle impacts based solely on information available before manufacturing and product integration, rather than relying on data collected after production. Automating LCI generation through engineering design tools (e.g., Computer-Aided Design – CAD and AM process simulation environments) would enable the extraction of accurate, consistent, and timely data. This approach would strongly reduce the dependence on manual data entry, which is both time-consuming and prone to errors.

Within this complex context, the objective of this work is to propose and test an LCA/LCC-based tool dedicated to supporting the life cycle design of parts realized with AM technologies, explicitly targeting the Fused Deposition Modeling (FDM) technology. It has been designed to encompass all relevant aspects necessary for a comprehensive evaluation of environmental and economic sustainability, addressing all life cycle phases from raw material extraction to EoL, including the use phase. Such a tool is based on a detailed and flexible life cycle model, specifically targeted to the FDM technology, but potentially customizable for all the different AM technologies, representing the main contribution of the present paper. The preliminary testing of the tool in the context of an industrial case study related to the aviation sector proved its usefulness and applicability. The proposed tool is part of a broader structured approach, called eDAM (ecoDesign for AM), which aims to integrate LCE considerations and various design aspects, including technical, environmental, and economic performance metrics, within a unified framework to guide the decision-making process in engineering design for AM. However, the description and the development of the overall ecodesign framework is out of the scope of the present research work.

After this introduction, the paper is structured as follows. Section 2 provides an overview of the eDAM approach with a specific focus on its kernel (life cycle models). Section 3 describes how the LCA/LCC modeling and assessment tool has been developed considering the FDM technology. Section 4 reports the application of the proposed tool to analyze a component in the aviation sector (interior panel) from a life cycle perspective. Section 5 presents the overall results and the robustness of the tool, including a benchmark analysis with other available LCA/LCC tools. Finally, Sect. 6 draws relevant conclusions and outlines future directions for further expanding the research results.

2 The eDAM approach

The eDAM approach aims to integrate LCE principles for emerging technologies, such as AM. Addressing both environmental and economic dimensions, the eDAM goal is to redefine the perception and application of AM technologies across the entire product life cycle. Traditional ecodesign approaches often fail to adopt a holistic view of the potential impacts of AM across the life cycle, leaving designers unaware of the opportunities and challenges that arise when considering sustainability from a comprehensive perspective. Figure 1 illustrates an overview of the eDAM approach, where the LCA and LCC models play a central role (kernel).

The proposed approach consists of several interconnected blocks, each with a specific role in capturing inputs, processing data, and producing outputs that provide actionable ecodesign insights. The first block of the eDAM approach, referred to as the *eDAM product development process*, begins with the designer or user, who provides manual parameters and design intent (i.e., technical specifications). These inputs typically include a set of requirements that the product must satisfy. The CAD tool then supports engineers in translating the design intents into geometrical data, which serves as a key input for both the eDAM kernel and the job/machine simulation module. In particular, the 3D printing job simulation generates a process plan that defines how the part will be manufactured. At the core of the framework lies the *eDAM LCE assessment tool*, which represents both the kernel of the system and the primary focus of this research. This block relies on life cycle models—specifically LCA and LCC—designed to incorporate primary data originating from the product development process of AM parts (e.g., CAD files and manufacturing simulation data). The kernel processes primary data (e.g., geometry, process parameters, and production data) through life cycle models that are linked to dedicated repositories of secondary data. This integration of primary and secondary datasets enables the calculation of both LCA and LCC indicators. The results from the kernel are expressed as quantitative indicators, covering environmental impacts and economic performance. These outputs feed into the *eDAM multi-criteria decision-making (MCDM) tool*. This block supports scenario analyses by establishing a feedback loop with the LCE assessment tool, enabling comparative evaluations and helping users make evidence-based design decisions. The iterative connection with the kernel allows for continuous product re-evaluation as new data or revised process plans become available. Furthermore, the MCDM tool incorporates an ecodesign rules repository, which systematically stores and reuses guidelines tailored explicitly to AM technologies, consolidating and valorizing domain knowledge in ecodesign for AM.

2.1 Implementation of the eDAM life cycle design tool

The *eDAM approach* has been implemented in a comprehensive Excel-based application, called *eDAM life cycle design tool*, which includes:

- Input interfaces to specify input data deriving from the *eDAM product development process,*
- The databases of the secondary data needed,
- The LCA/LCC calculation models able to perform environmental and economic assessment of AM parts, which constitute the *LCE assessment tool*.

In addition, the developed application also integrates the *eDAM multi-criteria decision-making (MCDM) tool* to conduct comparative analyses among scenarios and to collect and store ecodesign guidelines, which are briefly introduced but not tested in the context of the present study. The overall architecture and the working principle of the developed application are depicted in Fig. 2.

The eDAM application consists of two main interconnected and interoperable (in terms of automatic and user-transparent data exchange) Excel-based files: the *LCA/LCC tool* and the *Master tool*.

The *LCA/LCC tool* represents the implementation of the foundational LCA/LCC model (briefly described in

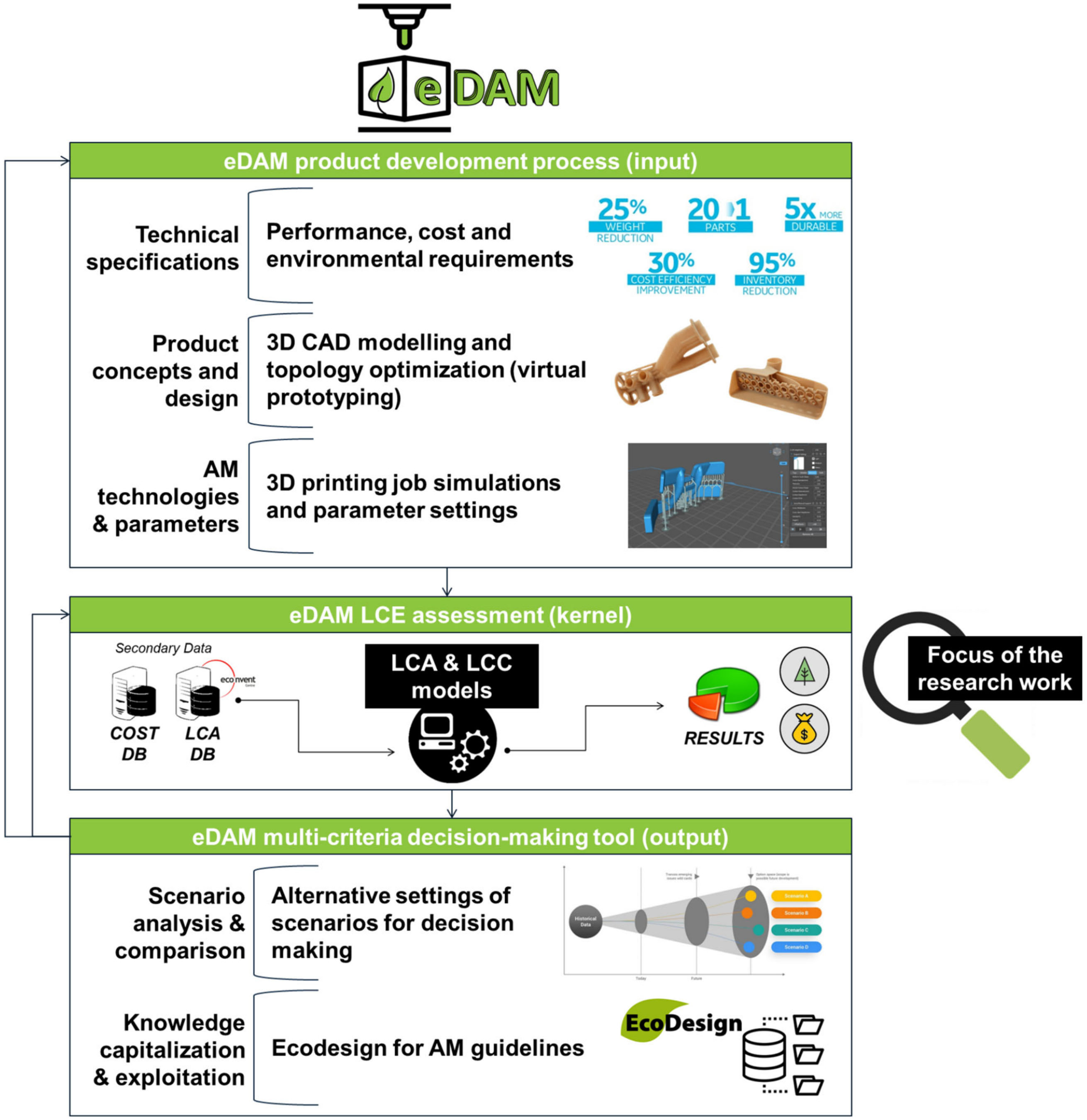


Fig. 1 Overview of the eDAM approach and its core LCA/LCC models

Sect. 2.2), which can be customized for each specific technology, as illustrated in Sect. 3 for the polymeric FDM. Such a tool accepts as input data derived from the *Master tool* (e.g., data related to the part, such as mass, volume, and material), and provides the user with the possibility to input specific additional information (e.g., technological parameters of the AM process) needed to make the LCA/LCC assessments, quantified by using the secondary data (e.g., unitary impacts of electric energy, unitary costs of raw materials) stored in the internal database (*LCA_DB* and *COST_DB*). The Ecoinvent database was employed to build the *LCA_DB*, which contains secondary data on unitary environmental impacts. In parallel, the company's expertise in AM processes and services, together with economic data collected from various suppliers and other online sources, was used to develop the *COST_DB*, which provides unitary material and energy costs. For instance, unitary costs related to materials and fuels,

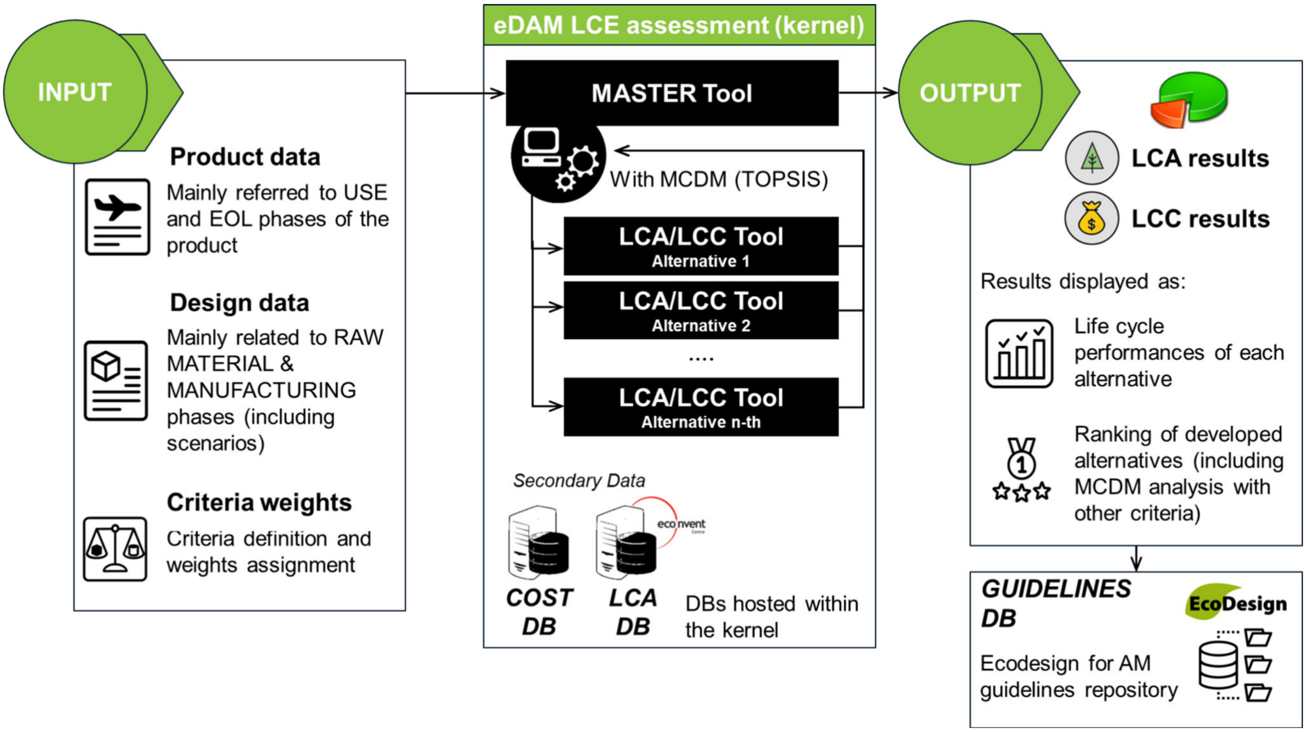


Fig. 2 eDAM Life Cycle design tool working principle

as well as labor and machine hourly costs, have been estimated or derived from online databases, such as Global Petrol Prices [31] or Eurostat [32]. It is worth highlighting that the *LCA/LCC tool* can be used in combination with the *Master tool* in case of comparative analyses, but also includes some specific output interfaces that allow practitioners to deeply evaluate all available environmental and economic results of a single design solution, considering the individual AM part with or without its context of application (e.g. an AM part mounted on a car considering the use phase and the needed maintenance), the whole part lifecycle or specific phases as the manufacturing, the details of particular sub-phases (e.g. post-processing) or even a single item (e.g. energy consumption contribution for the raw material feedstock production).

The *Master tool*, on the other hand, is positioned at a higher hierarchical level than the *LCA/LCC tool* and represents a tool capable of managing comparisons among different design alternatives (e.g., the same part realized with different technologies, different geometries realized with the same technology, or different technologies and geometries). When comparing multiple design alternatives, some data concerning the application typically remains constant, while others, such as geometrical parameters or technological parameters, may change. For this reason, input data are separated in two different categories within the *Master tool*: (i) *Product Data*, which remain constant and are mainly related to the End of Life and Use phases (e.g. vehicle type, vehicle fuel, vehicle mass, etc.) and (ii) *Design Data*, which could vary among the different scenarios and are mainly related to the Raw Material and Manufacturing phases (e.g. overall dimensions, volume, support volume, AM technology, printing machine, etc.). With its output interfaces, the *Master tool* allows to comparatively evaluate the environmental and economic results of all the analyzed alternatives, in both tabular and graphical format, considering a reduced set of indicators (e.g., GWP, Ozone Formation, Terrestrial Acidification indicators for the LCA) for a rapid and concise overview, while specific details can be extrapolated from the *LCA/LCC tools* dedicated to each design scenario. In addition, the *Master tool* integrates a multi-criteria decision-making (MCDM) module, based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) algorithm, to jointly consider environmental and economic indicators, as well as additional design/technical criteria (e.g., productivity, time, quality). This enables the possibility of ranking the design alternatives and guiding the decision-making process toward selecting the most suitable solution from different, and sometimes conflicting, perspectives. Finally, within the *Master tool*, the recurring insights derived from the LCA and LCC results can be captured and codified into ecodesign rules, stored in a specific repository (*GUIDELINES_DB*). These actionable rules provide design guidance that can be reused in future design contexts, thus supporting the embedding of ecodesign for AM considerations into the design process.

Table 1 Life cycle phases description with input/output parameters

Life cycle phase	Description	Input parameter	Output parameter
Raw Material	Extraction, production, and procurement of materials needed for AM manufacturing	Amount of material used for a job (including material for part supports and machining allowances) Feedstock raw material manufacturing process (including consumables) Energy consumption of the raw material manufacturing process	Raw Material cost Raw material environmental impacts (impact categories)
Manufacturing	Printing and post-printing processes, including machines, equipment, and ancillaries	Printing parameters (e.g., print orientation, support volume, component volume, infill, process efficiency, percentages of material reused/discarded, etc.) Post-processing technologies (e.g., sandblasting, support removal, coating, thermal treatments, etc.) Printer type or model	Manufacturing costs Manufacturing environmental impacts (impact categories) together with material loss and recyclability rate* *Recyclability rate (amount of material used for the part, material not used for the part but recyclable or reusable, and material loss and not recyclable or reusable)
Transport	Logistics for delivering materials to the production site (upstream) and the component to the assembly site or maintenance location (downstream)	Transport vehicle type (e.g., airplane, freight, lorry, etc.) Distance traveled (including fuel consumption per volume of material transported)	Transport costs Transport environmental impacts (impact categories)
Use phase	Use of a product where the AM component is assembled, defined as a reduction of energy/fuel consumption of the whole assembly (e.g., a vehicle) due to the replacement of the component manufactured with AM technology	Total number of AM components replaced in the product Product type (e.g., type of vehicle in which the AM component is assembled) Fuel type (e.g., type of fuel/energy used by the product in the life cycle) Weight reduction (e.g., the difference between the original weight of the product and the weight after the replacement of a part manufactured with AM technologies) Expected lifetime (of AM components and product)	Use costs Use environmental impacts (impact categories)
EoL	EoL scenario definition for product and AM components, such as recycling or landfill disposal	EoL scenario (e.g., recycling or disposal) Recyclability rates of the materials (percentage of recyclability)	EoL costs EoL environmental impacts (impact categories)

2.2 The LCA and LCC models

The eDAM approach is grounded by life cycle models tailored to specific AM processes (e.g., SLM, FDM), which are used to generate both LCA and LCC results. These results, combined with additional parameters such as productivity, manufacturing time, and quality, provide the basis for comparing alternative process scenarios. Each life cycle model is developed in a generalizable and reproducible manner for its respective AM technology, with formulas and supplementary parameters adapted as needed to reflect the characteristics of each process. Although the model is not intended to replace conventional LCA and LCC tools, it is structured in accordance with standardized methodologies (ISO standards). The first step involves defining the system boundaries. In this framework, all life cycle phases are included in the calculations, establishing a cradle-to-grave boundary that accounts for both energy and material flows. The description of each life cycle phase, together with the input and output parameters, is summarized in Table 1.

Always in accordance with ISO standards, the functional unit is defined as "*a single AM part, mounted on a hosting product (assembly)*", which provides the flexibility required to model different components. To formally express the relationships between the phases considered in the boundaries of the model, the environmental evaluation (LCA) can be performed by using Eq. 1, as the sum of the Environmental Impacts (EI) obtained for each phase of the life cycle:

$$LCA = I_{RM} + I_{Man} + I_{Use} + I_{EoL} + I_{Tran} \tag{1}$$

With I_{RM}. as the EI of the Raw Material phase, I_{Man} as the EI of the Manufacturing phase, I_{Use} as the EI of the Use phase, I_{EoL} as the EI of the End of Life phase and I_{Tran} as the EI of the Transport phase. For the LCA evaluation, the ReCiPe Midpoint (H) life cycle impact assessment method (LCIA) is employed, resulting in the calculation of midpoint indicators used in the tool (Table 2).

A similar formulation can be also adopted for the economic evaluation (LCC) by using Eq. 2, which sums the costs obtained r each life cycle phase. According to the discount cash flow method, each future cost is discounted back with a chosen discount rate to calculate the net present value:

$$LCC = \sum_{n=1}^{N} \frac{C_{RM,n} + C_{Man,n} + C_{Use,n} + C_{Tran,n}}{(1+d)^n} + \frac{C_{EoL,N}}{(1+d)^N} \tag{2}$$

With C_{RM} as the Cost of the Raw Material phase, C_{Man} as the Cost of the Manufacturing phase, C_{Use} as the Cost of the Use phase, C_{EoL} as the Cost of the EoL phase and C_{Tran} as the Cost of the Transport phase. Additionally, the subscript n indicates that the cost is evaluated at the n-th year, N represents the total life of the product, expressed in years, and d is the discount rate. In this case, the LCC indicator is the sole metric considered as an economic indicator and can be expressed in monetary units (e.g., euros or US dollars).

3 LCA and LCC models for FDM technology

The eDAM LCE assessment block was customized for the FDM technology, with a dedicated LCA/LCC model. The following sections provide a detailed description of this calculation model across the various life cycle phases, including the details of the key terms and parameters used in each equation.

3.1 Raw material

The Raw Material phase comprises two sub-phases: the extraction of the raw material (e.g., PLA, PA) and its processing into feedstock material (i.e., extrusion of a filament in the case of FDM), which is then ready for use in the Manufacturing phase. Both impacts can be evaluated separately as the product of the mass needed and the unitary impact of each contribution (i.e., extraction and extrusion) and then summed according to Eq. 3.

$$I_{RM} = m_{RM} * \beta_{extract} + m_{RM} * \beta_{FM} \tag{3}$$

where I_{RM} is the EI of the entire Raw Material phase, m_{RM} is the mass of the Raw Material, comprehensive of all the eventual losses, $\beta_{extract}$ is the unitary impact for the extraction of raw material, β_{FM} is the unitary impact for the production of the filament (polymer extrusion). Regarding the costs related to this phase, the formulation can be assumed similarly to the formulation of the feedstock production impact, as the price of feedstock material typically includes both material extraction and filament production. In Eq. 4, a simplified formulation of the Raw Material costs is proposed:

$$C_{RM} = m_{RM} * \gamma_{RM} \tag{4}$$

where C_{RM} is the Cost of the entire Raw Material phase, m_{RM} is the mass of the Raw Material, including all the eventual losses, γ_{RM} is the unitary cost of the raw material (filament).

In addition to the unitary impacts and costs (stored in the eDAM tool database), to perform such evaluations, the only input data required is the amount of mass needed. This value can be obtained from the nominal volume of the analyzed

Table 2 Impact categories description

Impact category	Acronym	Detailed category	Unit
Climate change (Global Warming Potential)	GWP	Climate Change—Human Health	kg CO2 eq
		Climate Change—Ecosystems	
Ozone depletion	ODP	–	kg CFC-11 eq
Terrestrial Acidification	TAP	–	kg SO_2 eq
Freshwater Eutrophication	FEP	–	kg P eq
Marine Eutrophication	MEP	–	kg N eq
Photochemical Ozone Formation	POCP	–	kg NO_x eq
Particulate Matter Formation	PMF	–	kg $PM_{2.5}$ eq
Ionising radiation	IRP	–	kBq Co-60 eq
Human toxicity	HTP	Human toxicity, non-cancer	kg 1,4-DCB eq
		Human toxicity, non-cancer	kg 1,4-DCB eq
Terrestrial Ecotoxicity	TETP	–	kg 1,4-DCB eq
Freshwater Ecotoxicity	FETP	–	kg 1,4-DCB eq
Marine Ecotoxicity	METP	–	kg 1,4-DCB eq
Agricultural Land Occupation	ALOP	–	m^2a
Urban Land Occupation	ULOP	–	m^2a
Natural Land Transformation	NLTP	–	m^2
Water Depletion	WDP	–	m^3
Mineral Resource Scarcity	MRS	–	kg Cu eq
Fossil Resource Scarcity	FRS	–	kg oil eq

part, its support volume, and the material chosen for the analysis, data that can be easily derived from commonly available design documents (e.g., CAD models, slicer tools files).

3.2 Manufacturing

The Manufacturing phase can generally be divided into two stages: the printing process, during which the AM part is produced, and the post-processing stage, where the part is finalized through operations such as support removal, surface finishing, and thermal treatments. The printing process can be further divided into three typical sub-phases: the set-up phase, during which the machine carries out initial preparation tasks (e.g., extrusion chamber and build plate heating); the active printing phase, in which the filament is deposited to form the part; and the cooldown phase, where the part and printing environment are cooled to complete the cycle. However, focusing on the polymeric FDM technologies, some relevant considerations could be made:

- The cooldown phase is absent since the majority of materials used do not require temperature-controlled environments; therefore, the costs and impacts of this sub-phase can be neglected in the model.
- Since the FDM process does not require the usage of specific assist gas during printing, no contributions from consumables are considered in the calculation model.
- During the printing process, no relevant quantities of scrap materials are generated; therefore, it is possible to set to zero their environmental impacts and costs. Scraps are only generated during the post-processing stage when support removal occurs. This contribution is considered in the EoL.
- The support removal during the post-processing stage is generally carried out manually, with no impact on LCA.

Considering the aforementioned peculiarities of the FDM, the life cycle model can be slightly simplified by eliminating certain contributions. The final formulations for the environmental and economic evaluations are reported in the following Eq. 5 and Eq. 6, respectively:

$$I_{Man} = I_{Print} + I_{Post} = \left(I_{Set-up} + I_{Active}\right) + I_{Post} \quad (5)$$

$$C_{Man} = C_{Print} + C_{Post} = \left(C_{Set-up} + C_{Active}\right) + C_{Post} \quad (6)$$

where considering the environmental assessment I_{Man} is the EI of the entire Manufacturing phase, I_{Print} is the EI of the printing stage, I_{Post} is the EI of the post-processing stage (without considering the support removal, which is generally performed manually), I_{Set-up} is the EI of the set-up sub-phase within the printing, I_{Active} is the EI of the active printing sub-phase within the printing. Considering, instead, the cost assessment C_{Man} is the cost of the entire Manufacturing phase, C_{Print} is the cost of the printing stage, C_{Post} is the cost of the post-processing stage (including also the contribution of support removal, if any), C_{Set-up} is the cost of the set-up sub-phase within the printing, C_{Active} is the cost of the active printing sub-phase within the printing.

To evaluate the contribution of each printing sub-phase, the proposed general formulation is expressed in Eq. 7 for the environmental impacts and in Eq. 8 for the costs:

$$I_{PPs} = P_{PPs} * t_{PPs} * \beta_{elec.energy} \quad (7)$$

$$C_{PPs} = P_{PPs} * t_{PPs} * \gamma_{elec.energy} \quad (8)$$

where I_{PPs} is the EI for the generic printing process sub-phase, C_{PPs} is the Cost for the generic printing process sub-phase, P_{PPs} is the rated power required during the specific sub-phase, t_{PPs} is the time elapsed during the specific sub-phase, $\beta_{elec.energy}$ is the unitary impact of the electric energy production and $\gamma_{elec.energy}$ is the unitary cost of electric energy. Such calculation models are derived from well-known literature studies, for instance [33, 34]. It is worth highlighting that if the AM production cycle includes more than one post-processing steps, the I_{Post} and C_{Post} can be obtained by summing different I_{PPs} and C_{PPs}, contributions, respectively.

To conduct such evaluations, the required input data can be categorized as geometry-related (e.g., print orientation), which may be manually defined or extracted from design documents such as CAD models; process-related (e.g., layer thickness, raster width, print speed), which can be estimated or obtained through dedicated software tools (e.g., slicers); and printer-related, which are typically available from machine datasheets.

3.3 Use

The Use phase EI I_{Use} and cost C_{Use} include the contributions of two sub-phases: the active use of the part ($I_{A.Use}$ and $C_{A.Use}$) in the host product where it is mounted and its maintenance (I_{Maint} and C_{Maint}). When the host product can be considered stationary in operation (e.g., equipment that does not consume fuels or energy during use), then the active use sub-phase can be neglected, considering only its maintenance. Additionally, if the analyzed part does not require maintenance, then the whole Use phase can be neglected from the analysis. On the other hand, if the application of the host product can be considered as active (e.g., automotive or aviation vehicles), related to fuel or electric energy consumptions, then the environmental impacts and cost of the active use sub-phase are evaluated according to the following equations (Eq. 9 – 11):

$$I_{A.Use} = SFC_{Vehicle} * D * \rho_{fuel} * CV * \beta_{fuel} * N \quad (9)$$

$$C_{A.Use} = SFC_{Vehicle} * D * \rho_{fuel} * CV * \gamma_{fuel} * N \quad (10)$$

$$CV = \frac{m_{part}}{m_{Vehicle}} \quad (11)$$

where $I_{A.Use}$ is the EI of the active use sub-phase, $C_{A.Use}$ is the cost of the active use-phase, ρ_{fuel} is the density of the fuel, β_{fuel} is the unitary impact of the production of fuel, γ_{fuel} is the unitary cost of the fuel, D is the average distance travelled by the vehicle in one representative year, N is the duration of the total life of the product in years, and $SFC_{Vehicle}$ is the specific fuel consumption of the vehicle extracted from Greene et al. [35] for the aviation sector and estimated for the automotive industry. CV is the component to vehicle ratio with m_{part} as the mass of the part and $m_{Vehicle}$ as the mass of the host vehicle. This parameter allows for determining the percentage of fuel theoretically consumed by the component compared to the consumption of the entire application during the Use phase. Although this approach is simplified, it enables a comparative analysis among different scenarios, allowing for consideration of benefits during the use phase due to mass optimization strategies, which are frequently adopted in the context of AM.

Regarding the maintenance sub-phase, a substitution scenario is employed in the model. This foresees the replacement of the obsolete/damaged part with a new equivalent part that needs to be manufactured with the same AM technology in the same production conditions, with related generation of new environmental impacts and costs related to Raw Material and Manufacturing phases. In addition, the replaced part reaches the EoL when it is substituted, and it generates a contribution in terms of waste to be managed, according to the EoL modeling, described in Sect. 3.4. Therefore, the maintenance impacts and costs can be calculated according to the following Eqs. 12 and 13:

$$I_{Maint} = I_{RM,new} + I_{Man,new} + I_{EoL,old} \quad (12)$$

$$C_{Maint} = C_{RM,new} + C_{Man,new} + C_{EoL,old} \tag{13}$$

where I_{Maint} and C_{Maint} are the EI and cost of the maintenance, $I_{RM,new}$ and $C_{RM,new}$ are the EI and cost of the Raw Material of the new part (calculated according to the formulas explained in Sect. 3.1), $I_{Man,new}$ and $C_{Man,new}$ are the EI and cost of the Manufacturing of the new part, $I_{EoL,old}$ and $C_{EoL,old}$ are the EI and cost of the EoL of the old substituted part. It is worth noting that during the product's useful life, a single part can be replaced multiple times. In such cases, numerous maintenance contributions must be accounted for to assess the overall EI and costs.

To perform this evaluation, the required input parameters are the mass of the component, which is evaluated using the volume inserted in the manufacturing phase, the mass and the years of life of the host product and its average travelled distance, which can be manually inserted, the life (in years) of the component mounted on the host product and the unitary impacts and unitary costs that can be extracted from the databases included in the eDAM tool.

3.4 EoL

The EoL phase allows the modeling and quantification of the EI and costs related to the disposal/recovery of scrap materials generated in earlier stages (e.g., Manufacturing, Use), which are directly accounted in the specific phases, as specified in the previous sections, or at the end of the product's useful life. The proposed model includes two scenarios: (i) landfill disposal and (ii) recycling. The landfill scenario can be evaluated considering only the mass sent to the landfill and its associated unitary impact or unitary cost. For the recycling scenario, the model adopts an avoided impact approach, considering that the availability of recycled materials contributes to reducing the need for producing virgin material feedstocks. Thus, such contributions (i.e., negative values) represent benefits for the LCA and LCC evaluations. However, given that in a realistic scenario the recyclability rate is always less than 100% due to unavoidable losses in the recycling chain, a portion of the material is always assumed to be landfilled. The proposed formulation for the EoL phase, jointly considering the landfill and recycling scenarios, is reported in Eq. 14 for the environmental evaluation and in Eq. 15 for the cost assessment:

$$I_{EoL} = -m_{EoL} * r * \beta_{extract} + m_{EoL} * (1 - r) * \beta_{landfill} \tag{14}$$

$$C_{EoL} = -m_{EoL} * r * \gamma_{RM} + m_{EoL} * (1 - r) * \gamma_{landfill} \tag{15}$$

where I_{EoL} and C_{EoL} are the EI and cost of the EoL phase, m_{EoL} is the mass that undergoes EoL, $\beta_{extract}$ is the unitary impact for the extraction of raw material, $\gamma_{landfill}$ is the unitary cost of landfilling as municipal waste, $\beta_{landfill}$ is the unitary impact of landfilling as municipal waste, and r is the recyclability rate specific for each material considered in the application. For instance, regarding polymeric materials, the recyclability rates can be extracted from the Sustainable Development Summit report [36].

All the parameters needed to carry out the assessments can be automatically derived from the computations performed in the previous phases. No additional input is required from the user, while the unitary impacts and costs are available within the tool databases.

3.5 Transport

The Transport phase spans the entire life cycle. It generates EI (I_{Tran}) and cost EI (C_{Tran}) due to the sum of three main contributions: (i) transport of the feedstock material to the production site (Raw Material phase), (ii) transport of the part to the assembly site (Manufacturing phase), and (iii) transport of the part to the maintenance site (Use phase). Each contribution can be calculated by multiplying the transported mass (e.g., mass of the raw material, mass of the part, etc.), the traveled distance to cover the transport route (e.g., distance between the raw material supplier and the AM manufacturing site, distance between the AM manufacturing site and the maintenance site, etc.), and the impact/cost of the specific transport vehicle used for the route (e.g., lorries, ships, aircrafts, trains, etc.).

The required information to perform the assessments refers to the traveled distance, which needs to be inserted as input data, and the type of transport vehicle adopted, which are directly correlated to the unitary impacts and costs stored in the available databases.

4 Case study

The case study aims to test the eDAM tool during the redesign process of a real component from the aeronautical sector, evaluating LCA and LCC indicators for a baseline scenario (S1) and four alternative design and manufacturing scenarios (S2–S5).

4.1 Cabin bionic spacer panel

The eDAM tool is applied to a spacer panel used at the end of cabin overhead compartments of an aircraft. Such components occasionally need to be modified or altered when newly planned cabin features (such as aircraft retrofitting) are integrated with pre-existing components. AM may help aircraft

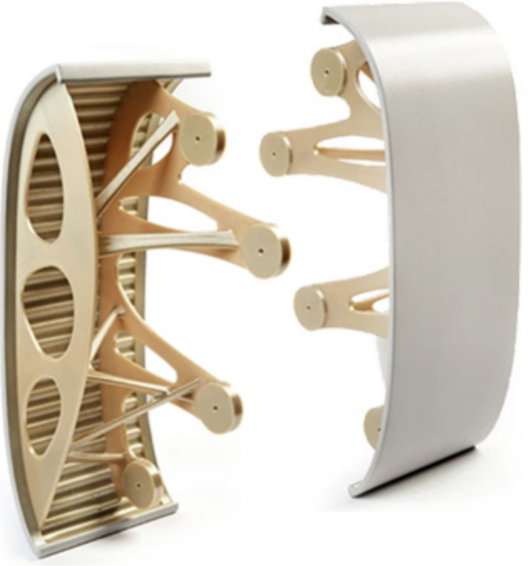


Fig. 3 AM panels for aircraft cabins (developed by Materialise [37])

Table 3 Product Data for the spacer panel

Parameter	Value	References
Application field	Aviation	–
Vehicle type	A-300-B4	[35]
Vehicle weight [kg]	70,000	[40]
Vehicle useful life [Years]	30	[39]
Fuel type	Kerosene	–
Distance per year [km/Year]	31,750,000	[39]
Number of equal components in the vehicle	30	[40]
Component useful life	20	[38]
Recycling of components from the useful life phase	Yes	[41]
Filament recycling	Yes	[41]
Recycling of scrap materials from post-processing	Yes	[41]
Recycling of components at the EoL of the vehicle	Yes	[41]

manufacturers quickly realizing small batches of such parts. The complexity-free opportunity provided by AM allows engineers to redesign lightweight components, as seen in the case of the spacer, which Airbus optimized using a bio-inspired lattice support. This solution enabled a 15% weight reduction against the original solution manufactured with CM technologies, while maintaining compliance with the civil aviation authority (Fig. 3).

For this test, a short-range Airbus A-300-B4 (with a range of 3.175.000 km/year [38, 39] and a maximum take-off weight of 70.000 kg [40]) equipped with 30 spacers (one panel per seating row), and a lifespan of 30 years was considered. During the airplane use phase, it was considered a retrofit after 20 years. At this stage, new spacers must be manufactured. Concerning the EoL phase, the recycling of components in the aerospace sector is challenging but of increasing interest, as demonstrated by a recent literature study focused on the closed-loop recycling of polymeric aircraft parts [41]. For this reason, recycling was assumed as a scenario that can be realistically implemented. Additional data about the case study is available in Table 3.

4.2 Baseline scenario

All scenarios consider the same topology-optimized geometry, realized in ULTEM 9085, a high-performance thermoplastic filament widely used in the aerospace and automotive industries due to its heat and flame resistance. ULTEM 9085 is compliant with UL 94 V-0, 5VA regulation, and FAR 25.853 aerospace standards. Regarding the design data, the optimized CAD file of the spacer was used to derive the dimensional and geometric input parameters, as well as the support volume and print orientation (Table 4). The transport data were estimated based on a three-stage route for transportation from the feedstock manufacturer to the production company, and a two-stage route for transportation from the production company to both the assembly site and the maintenance site (Table 5).

Table 4 Design data (Baseline scenario S1)

Parameter	S1	References
Size X [mm]	94	[42]
Size Y [mm]	260	[42]
Size Z [mm]	200	[42]
Area [mm2]	192,400	[42]
Material	ULTEM 9085	[37]
Technology	FDM	–
Volume [mm3]	723,200	[42]
Production Country	Global	Estimated
Support Volume [%]	30	[42]
Relative density of supports [%]	20	[42]

Modeling the AM part with the eDAM tool involves an initial mandatory step of entering a series of general inputs for all life cycle phases. Table 4 (Design Data) and Table 5 (Transport Data) show the general inputs and their values for the Baseline Scenario (S1) across the various life cycle phases of the component. To obtain the geometric parameters and the percentage of support volume, the CAD model of the component was analyzed using Autodesk Netfabb slicer [42].

Table 5 Transport data (Baseline scenario S1)

Transport phase	First stage		Second stage		Third stage	
	Vehicle	Distance [km]	Vehicle	Distance [km]	Vehicle	Distance [km]
From feedstock production to component production	Lorry medium payload	950	Aircraft medium haul	4500	Lorry medium payload	30
From component production to product assembly	Freight train	300	Lorry medium payload	800	/	/
From component production to product maintenance	Lorry medium payload	50	Aircraft medium haul	1500	/	/

Scenario S1 was modelled in the eDAM tool as shown in Fig. 4, which presents the graphical interface of the tool during the input of these parameter values. The color scheme that guides the user through the modeling process is also shown.

After entering the general inputs, it is possible to modify specific parameters within the individual spreadsheets related to each phase. These parameters are provided with default values derived from the tool databases, but can be customized by the user (grey cells in Fig. 5—editable according to the color guide scheme previously reported).

Finally, Fig. 6 displays a screenshot of intermediate calculations performed by the tool during the manufacturing phase, as outlined in Sect. 3. The calculation model then utilizes these values to determine the environmental and economic impacts of the manufacturing phase. Similar calculations are performed to account for the other life cycle phases.

4.3 Scenarios comparison

To demonstrate the tool's versatility and functionality, five life cycle scenarios—based on the same spacer panel described above but differentiated by selected life cycle parameters—have been defined and analyzed, including four alternatives in addition to S1. This approach was adopted both to quantitatively compare the environmental and economic performance of the five alternatives and to evaluate the tool's capability to support practitioners in efficiently comparing different scenarios through adjustments of life cycle parameters.

The five scenarios (Table 6) share the same data as the Baseline, except for one specific parameter, which was modified to reflect the variation under investigation. More specifically:

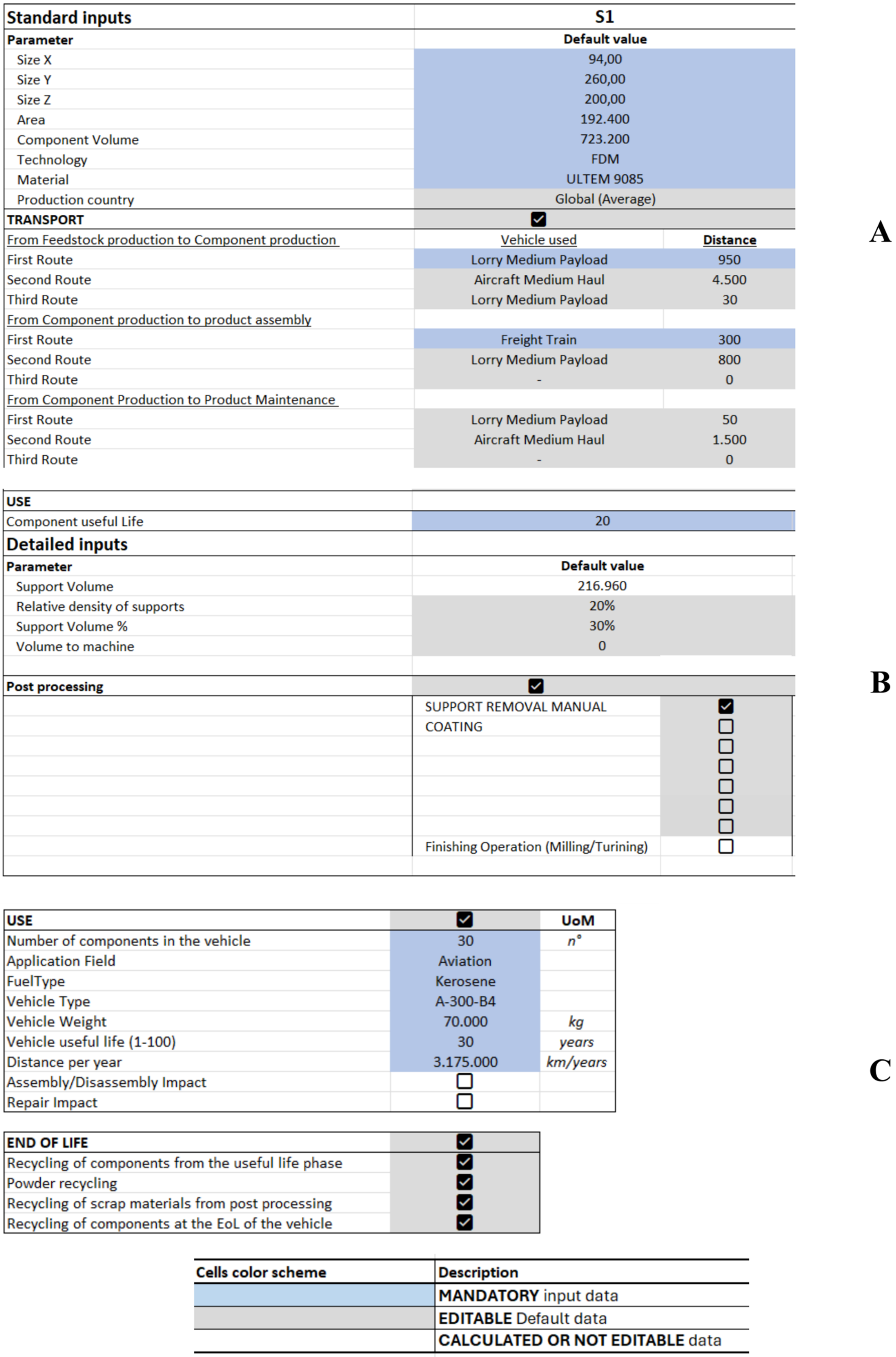
- Scenario 2 (S2) considers a 15% increase in volume, simulating a comparison between an optimized component (S1) and a non-optimized one (S2);
- Scenario 3 (S3) involves the use of a different 3D printer: Stratasys F900 vs Stratasys Fortus 370;
- Scenario 4 (S4) intends to simulate production in a different location, assuming a change in production place, and, consequently, logistics. This means to pass from a "Global", thus generic production place with generic energy mix and energy and labor costs (set in S1), to a production based in the United States;
- Scenario 5 (S5) assumes more intensive use of the host product compared to the other scenarios, simulating the switch from a short-range aircraft (3.175.000 km/year) to a long-range one (5.000.000) [39].

Table 6 summarizes the main characteristics of each considered scenario, with changed values highlighted in bold.

Through the *Master tool* interfaces, the eDAM tool enabled the easy modification of parameters and creation of scenarios, as well as their concurrent simulation. As shown in Fig. 7, the alternatives are arranged in five different columns within the main tool interface. The modeling of the Use phase and End of Life phase is not displayed for all scenarios, only for S1, due to graphical limitations.

5 Results and discussion

This section presents and discusses the results achieved using the eDAM tool on the spacer panel, considering the five scenarios described in Sect. 4. Moreover, the tool's functionalities and capabilities are compared to those of other commercially available software solutions.



Standard inputs	S1	
Parameter	**Default value**	
Size X	94,00	
Size Y	260,00	
Size Z	200,00	
Area	192.400	
Component Volume	723.200	
Technology	FDM	
Material	ULTEM 9085	
Production country	Global (Average)	
TRANSPORT	☑	
From Feedstock production to Component production	Vehicle used	**Distance**
First Route	Lorry Medium Payload	950
Second Route	Aircraft Medium Haul	4.500
Third Route	Lorry Medium Payload	30
From Component production to product assembly		
First Route	Freight Train	300
Second Route	Lorry Medium Payload	800
Third Route	-	0
From Component Production to Product Maintenance		
First Route	Lorry Medium Payload	50
Second Route	Aircraft Medium Haul	1.500
Third Route	-	0

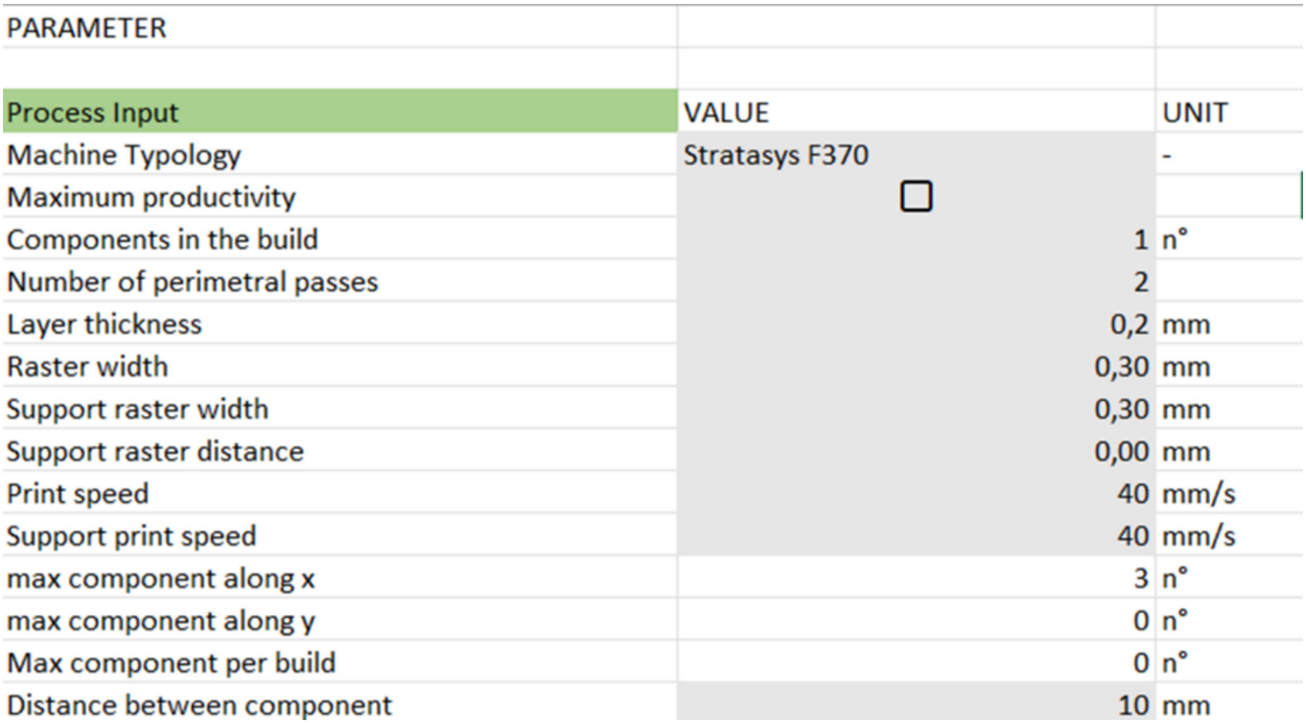
USE		
Component useful Life	20	
Detailed inputs		
Parameter	**Default value**	
Support Volume	216.960	
Relative density of supports	20%	
Support Volume %	30%	
Volume to machine	0	
Post processing	☑	
	SUPPORT REMOVAL MANUAL	☑
	COATING	☐
		☐
		☐
		☐
		☐
		☐
	Finishing Operation (Milling/Turining)	☐

USE	☑	**UoM**
Number of components in the vehicle	30	*n°*
Application Field	Aviation	
FuelType	Kerosene	
Vehicle Type	A-300-B4	
Vehicle Weight	70.000	*kg*
Vehicle useful life (1-100)	30	*years*
Distance per year	3.175.000	*km/years*
Assembly/Disassembly Impact	☐	
Repair Impact	☐	

END OF LIFE	☑
Recycling of components from the useful life phase	☑
Powder recycling	☑
Recycling of scrap materials from post processing	☑
Recycling of components at the EoL of the vehicle	☑

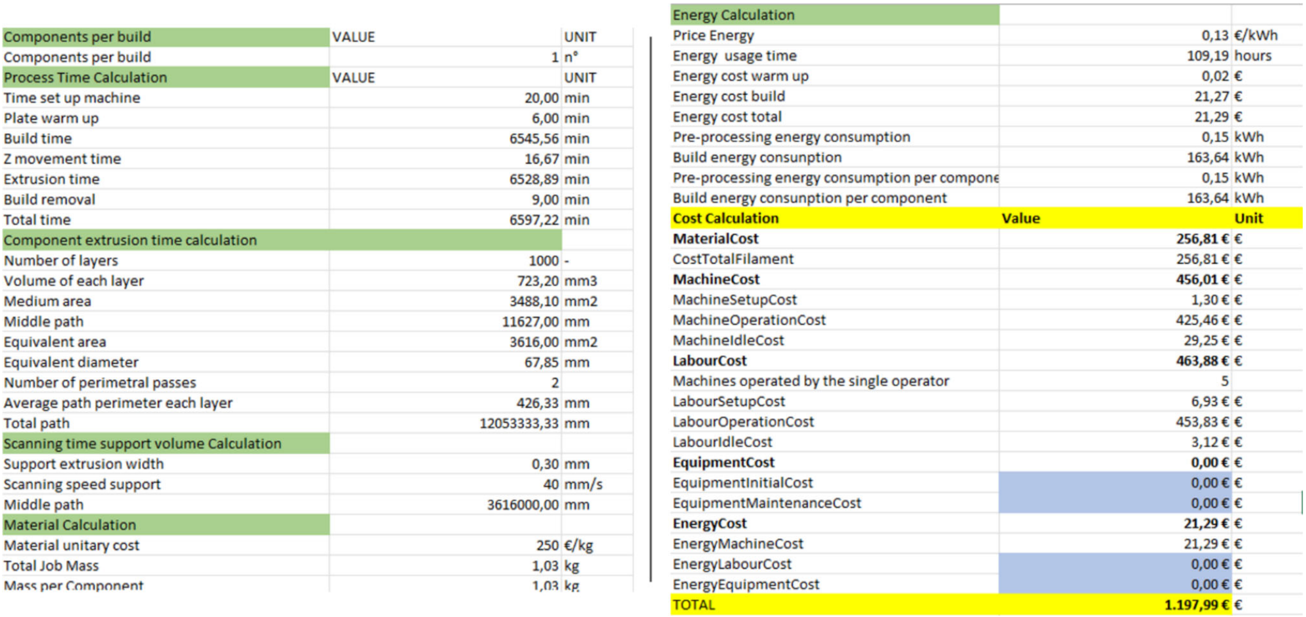
Cells color scheme	Description
🟦	**MANDATORY** input data
▨	**EDITABLE** Default data
	CALCULATED OR NOT EDITABLE data

Fig. 4 eDAM tool User Interface with color guide scheme for the end user: **A** Standard inputs interface. **B** Component useful life, detailed inputs and post processing section. **C** Use phase and End of life interface



PARAMETER		
Process Input	VALUE	UNIT
Machine Typology	Stratasys F370	-
Maximum productivity	☐	
Components in the build	1	n°
Number of perimetral passes	2	
Layer thickness	0,2	mm
Raster width	0,30	mm
Support raster width	0,30	mm
Support raster distance	0,00	mm
Print speed	40	mm/s
Support print speed	40	mm/s
max component along x	3	n°
max component along y	0	n°
Max component per build	0	n°
Distance between component	10	mm

Fig. 5 Process parameters within the eDAM tool interface



Components per build	VALUE	UNIT
Components per build	1	n°
Process Time Calculation	VALUE	UNIT
Time set up machine	20,00	min
Plate warm up	6,00	min
Build time	6545,56	min
Z movement time	16,67	min
Extrusion time	6528,89	min
Build removal	9,00	min
Total time	6597,22	min
Component extrusion time calculation		
Number of layers	1000	-
Volume of each layer	723,20	mm3
Medium area	3488,10	mm2
Middle path	11627,00	mm
Equivalent area	3616,00	mm2
Equivalent diameter	67,85	mm
Number of perimetral passes	2	
Average path perimeter each layer	426,33	mm
Total path	12053333,33	mm
Scanning time support volume Calculation		
Support extrusion width	0,30	mm
Scanning speed support	40	mm/s
Middle path	3616000,00	mm
Material Calculation		
Material unitary cost	250	€/kg
Total Job Mass	1,03	kg
Mass per Component	1,03	kg

Energy Calculation		
Price Energy	0,13	€/kWh
Energy usage time	109,19	hours
Energy cost warm up	0,02	€
Energy cost build	21,27	€
Energy cost total	21,29	€
Pre-processing energy consumption	0,15	kWh
Build energy consunption	163,64	kWh
Pre-processing energy consumption per compone	0,15	kWh
Build energy consunption per component	163,64	kWh
Cost Calculation	**Value**	**Unit**
MaterialCost	**256,81 €**	€
CostTotalFilament	256,81 €	€
MachineCost	**456,01 €**	€
MachineSetupCost	1,30 €	€
MachineOperationCost	425,46 €	€
MachineIdleCost	29,25 €	€
LabourCost	**463,88 €**	€
Machines operated by the single operator	5	
LabourSetupCost	6,93 €	€
LabourOperationCost	453,83 €	€
LabourIdleCost	3,12 €	€
EquipmentCost	**0,00 €**	€
EquipmentInitialCost	0,00 €	€
EquipmentMaintenanceCost	0,00 €	€
EnergyCost	**21,29 €**	€
EnergyMachineCost	21,29 €	€
EnergyLabourCost	0,00 €	€
EnergyEquipmentCost	0,00 €	€
TOTAL	**1.197,99 €**	€

Fig. 6 Process Calculations within the eDAM tool interface

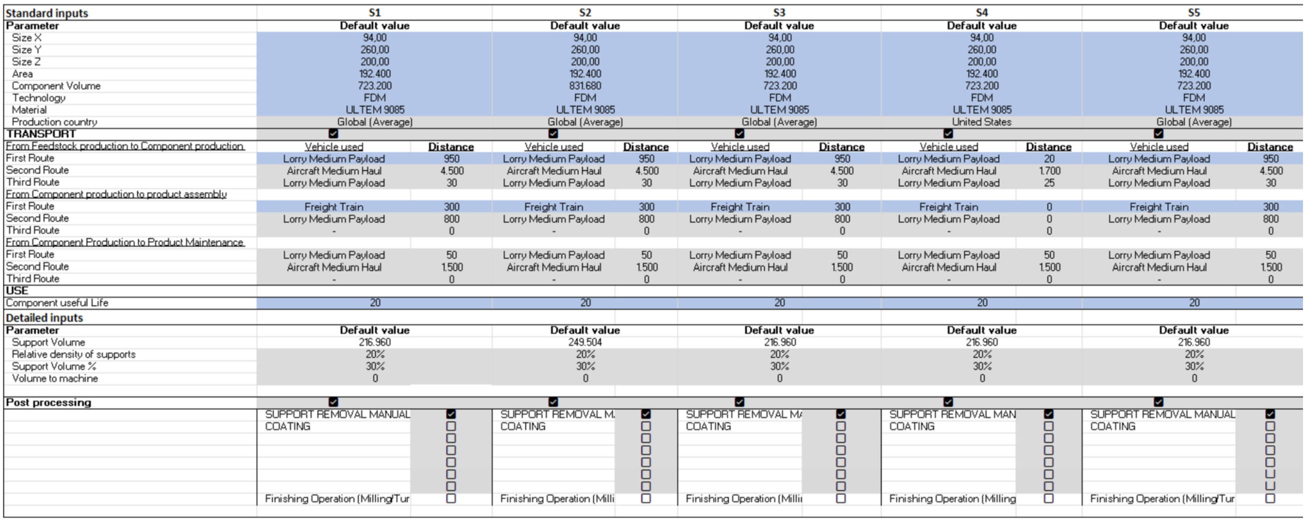
5.1 Case study results

The eDAM tool allowed the assessment of the spacer panels throughout the aircraft's lifespan, calculating the EI in terms of the eighteen ReCiPe midpoint impact categories, as well as the life cycle cost. Regarding this latter point, it is worth noting that the discount rate used for the LCC calculations has been set to 5% (an editable parameter). For example, Fig. 8 presents the life cycle results for scenario S1 in tabular format, detailing the total impacts and the breakdown of contributions for each indicator and main life cycle phase.

For an easy comparative analysis among the five considered alternatives, the output interfaces of the *Master tool* present both graphical results, facilitating rapid visual

Table 6 Changed parameters for the different scenarios

Scenario	Part Volume [mm^3]	3D Printer	Production Country	Use [km/year]
Baseline Scenario (S1)	723.200	Fortus 370	Global	3.175.000
Part Volume Variation (S2)	**831.680**	Fortus 370	Global	3.175.000
3D Printer Variation (S3)	723.200	**F900**	Global	3.175.000
Product Country Variation (S4)	723.200	Fortus 370	**USA**	3.175.000
Product Lifetime Variation (S5)	723.200	Fortus 370	Global	**5.000.000**



Standard inputs	**S1**		**S2**		**S3**		**S4**		**S5**	
Parameter	**Default value**		**Default value**		**Default value**		**Default value**		**Default value**	
Size X	94,00		94,00		94,00		94,00		94,00	
Size Y	260,00		260,00		260,00		260,00		260,00	
Size Z	200,00		200,00		200,00		200,00		200,00	
Area	192.400		192.400		192.400		192.400		192.400	
Component Volume	723.200		831.680		723.200		723.200		723.200	
Technology	FDM		FDM		FDM		FDM		FDM	
Material	ULTEM 9085		ULTEM 9085		ULTEM 9085		ULTEM 9085		ULTEM 9085	
Production country	Global (Average)		Global (Average)		Global (Average)		United States		Global (Average)	
TRANSPORT	☑		☑		☑		☑		☑	
From Feedstock production to Component production	Vehicle used	**Distance**	Vehicle used	**Distance**	Vehicle used	**Distance**	Vehicle used	**Distance**	Vehicle used	**Distance**
First Route	Lorry Medium Payload	950	Lorry Medium Payload	950	Lorry Medium Payload	950	Lorry Medium Payload	20	Lorry Medium Payload	950
Second Route	Aircraft Medium Haul	4.500	Aircraft Medium Haul	4.500	Aircraft Medium Haul	4.500	Aircraft Medium Haul	1.700	Aircraft Medium Haul	4.500
Third Route	Lorry Medium Payload	30	Lorry Medium Payload	30	Lorry Medium Payload	30	Lorry Medium Payload	25	Lorry Medium Payload	30
From Component production to product assembly										
First Route	Freight Train	300	Freight Train	300	Freight Train	300	Freight Train	0	Freight Train	300
Second Route	Lorry Medium Payload	800	Lorry Medium Payload	800	Lorry Medium Payload	800	Lorry Medium Payload	0	Lorry Medium Payload	800
Third Route	-	0	-	0	-	0	-	0	-	0
From Component Production to Product Maintenance										
First Route	Lorry Medium Payload	50	Lorry Medium Payload	50	Lorry Medium Payload	50	Lorry Medium Payload	50	Lorry Medium Payload	50
Second Route	Aircraft Medium Haul	1.500	Aircraft Medium Haul	1.500	Aircraft Medium Haul	1.500	Aircraft Medium Haul	1.500	Aircraft Medium Haul	1.500
Third Route	-	0	-	0	-	0	-	0	-	0
USE										
Component useful Life	20		20		20		20		20	
Detailed inputs										
Parameter	**Default value**		**Default value**		**Default value**		**Default value**		**Default value**	
Support Volume	216.960		249.504		216.960		216.960		216.960	
Relative density of supports	20%		20%		20%		20%		20%	
Support Volume %	30%		30%		30%		30%		30%	
Volume to machine	0		0		0		0		0	
Post processing	☑		☑		☑		☑		☑	
	SUPPORT REMOVAL MANUAL	☑	SUPPORT REMOVAL M.	☑	SUPPORT REMOVAL M/	☑	SUPPORT REMOVAL MAN	☑	SUPPORT REMOVAL MANUAL	☑
	COATING	☐	COATING	☐	COATING	☐	COATING	☐	COATING	☐
		☐		☐		☐		☐		☐
		☐		☐		☐		☐		☐
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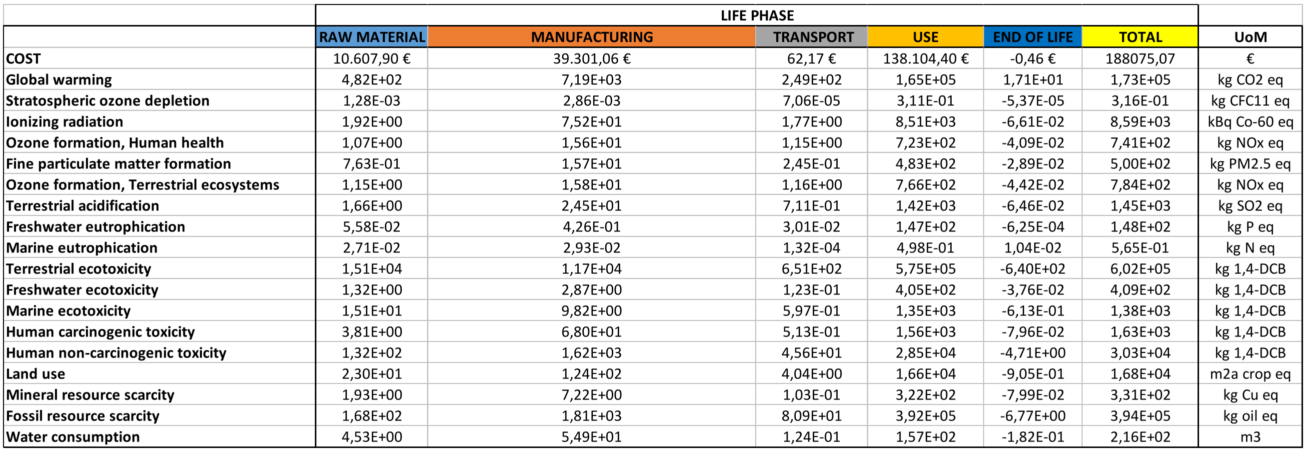
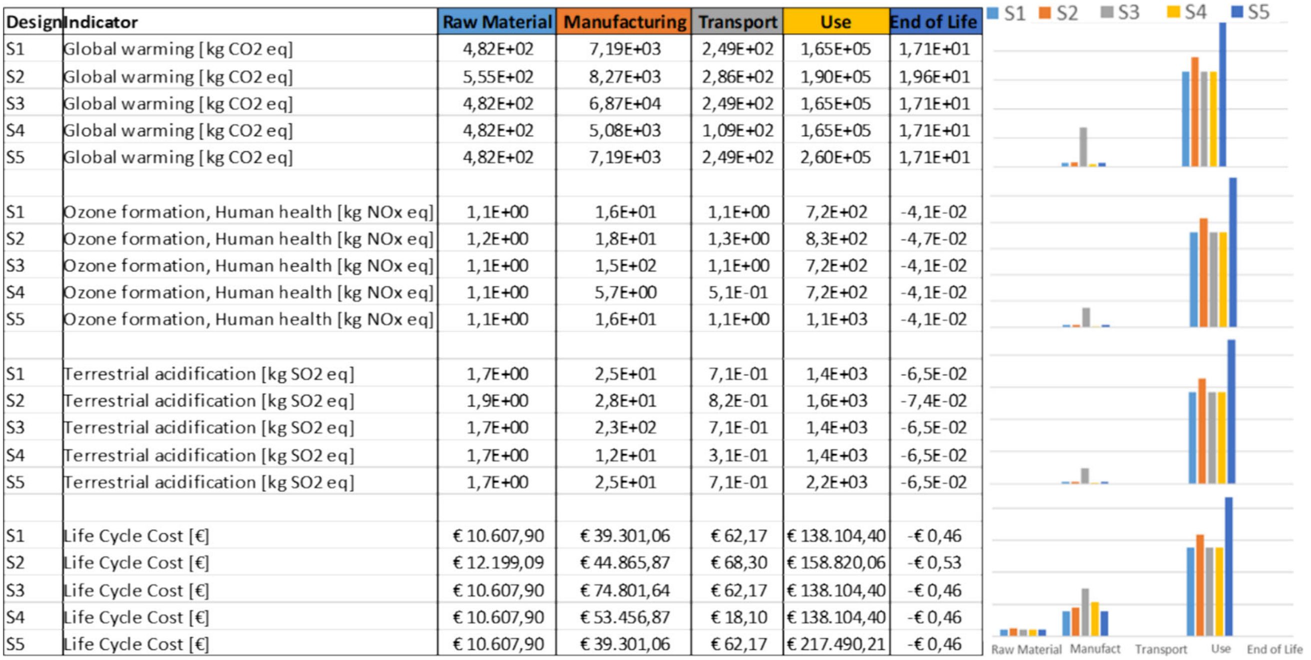
	Finishing Operation (Milling/Tur	☐	Finishing Operation (Milli	☐	Finishing Operation (Millii	☐	Finishing Operation (Milling	☐	Finishing Operation (Milling/Tur	☐

Fig. 7 The five scenarios set within the main interface of the Master tool



	LIFE PHASE						
	RAW MATERIAL	MANUFACTURING	TRANSPORT	USE	END OF LIFE	TOTAL	UoM
COST	10.607,90 €	39.301,06 €	62,17 €	138.104,40 €	-0,46 €	188075,07	€
Global warming	4,82E+02	7,19E+03	2,49E+02	1,65E+05	1,71E+01	1,73E+05	kg CO2 eq
Stratospheric ozone depletion	1,28E-03	2,86E-03	7,06E-05	3,11E-01	-5,37E-05	3,16E-01	kg CFC11 eq
Ionizing radiation	1,92E+00	7,52E+01	1,77E+00	8,51E+03	-6,61E-02	8,59E+03	kBq Co-60 eq
Ozone formation, Human health	1,07E+00	1,56E+01	1,15E+00	7,23E+02	-4,09E-02	7,41E+02	kg NOx eq
Fine particulate matter formation	7,63E-01	1,57E+01	2,45E-01	4,83E+02	-2,89E-02	5,00E+02	kg PM2.5 eq
Ozone formation, Terrestrial ecosystems	1,15E+00	1,58E+01	1,16E+00	7,66E+02	-4,42E-02	7,84E+02	kg NOx eq
Terrestrial acidification	1,66E+00	2,45E+01	7,11E-01	1,42E+03	-6,46E-02	1,45E+03	kg SO2 eq
Freshwater eutrophication	5,58E-02	4,26E-01	3,01E-02	1,47E+02	-6,25E-04	1,48E+02	kg P eq
Marine eutrophication	2,71E-02	2,93E-02	1,32E-04	4,98E-01	1,04E-02	5,65E-01	kg N eq
Terrestrial ecotoxicity	1,51E+04	1,17E+04	6,51E+02	5,75E+05	-6,40E+02	6,02E+05	kg 1,4-DCB
Freshwater ecotoxicity	1,32E+00	2,87E+00	1,23E-01	4,05E+02	-3,76E-02	4,09E+02	kg 1,4-DCB
Marine ecotoxicity	1,51E+01	9,82E+00	5,97E-01	1,35E+03	-6,13E-01	1,38E+03	kg 1,4-DCB
Human carcinogenic toxicity	3,81E+00	6,80E+01	5,13E-01	1,56E+03	-7,96E-02	1,63E+03	kg 1,4-DCB
Human non-carcinogenic toxicity	1,32E+02	1,62E+03	4,56E+01	2,85E+04	-4,71E+00	3,03E+04	kg 1,4-DCB
Land use	2,30E+01	1,24E+02	4,04E+00	1,66E+04	-9,05E-01	1,68E+04	m2a crop eq
Mineral resource scarcity	1,93E+00	7,22E+00	1,03E-01	3,22E+02	-7,99E-02	3,31E+02	kg Cu eq
Fossil resource scarcity	1,68E+02	1,81E+03	8,09E+01	3,92E+05	-6,77E+00	3,94E+05	kg oil eq
Water consumption	4,53E+00	5,49E+01	1,24E-01	1,57E+02	-1,82E-01	2,16E+02	m3

Fig. 8 S1 results within the eDAM tool output interfaces



Design	Indicator	Raw Material	Manufacturing	Transport	Use	End of Life
S1	Global warming [kg CO2 eq]	4,82E+02	7,19E+03	2,49E+02	1,65E+05	1,71E+01
S2	Global warming [kg CO2 eq]	5,55E+02	8,27E+03	2,86E+02	1,90E+05	1,96E+01
S3	Global warming [kg CO2 eq]	4,82E+02	6,87E+04	2,49E+02	1,65E+05	1,71E+01
S4	Global warming [kg CO2 eq]	4,82E+02	5,08E+03	1,09E+02	1,65E+05	1,71E+01
S5	Global warming [kg CO2 eq]	4,82E+02	7,19E+03	2,49E+02	2,60E+05	1,71E+01
S1	Ozone formation, Human health [kg NOx eq]	1,1E+00	1,6E+01	1,1E+00	7,2E+02	-4,1E-02
S2	Ozone formation, Human health [kg NOx eq]	1,2E+00	1,8E+01	1,3E+00	8,3E+02	-4,7E-02
S3	Ozone formation, Human health [kg NOx eq]	1,1E+00	1,5E+02	1,1E+00	7,2E+02	-4,1E-02
S4	Ozone formation, Human health [kg NOx eq]	1,1E+00	5,7E+00	5,1E-01	7,2E+02	-4,1E-02
S5	Ozone formation, Human health [kg NOx eq]	1,1E+00	1,6E+01	1,1E+00	1,1E+03	-4,1E-02
S1	Terrestrial acidification [kg SO2 eq]	1,7E+00	2,5E+01	7,1E-01	1,4E+03	-6,5E-02
S2	Terrestrial acidification [kg SO2 eq]	1,9E+00	2,8E+01	8,2E-01	1,6E+03	-7,4E-02
S3	Terrestrial acidification [kg SO2 eq]	1,7E+00	2,3E+02	7,1E-01	1,4E+03	-6,5E-02
S4	Terrestrial acidification [kg SO2 eq]	1,7E+00	1,2E+01	3,1E-01	1,4E+03	-6,5E-02
S5	Terrestrial acidification [kg SO2 eq]	1,7E+00	2,5E+01	7,1E-01	2,2E+03	-6,5E-02
S1	Life Cycle Cost [€]	€ 10.607,90	€ 39.301,06	€ 62,17	€ 138.104,40	-€ 0,46
S2	Life Cycle Cost [€]	€ 12.199,09	€ 44.865,87	€ 68,30	€ 158.820,06	-€ 0,53
S3	Life Cycle Cost [€]	€ 10.607,90	€ 74.801,64	€ 62,17	€ 138.104,40	-€ 0,46
S4	Life Cycle Cost [€]	€ 10.607,90	€ 53.456,87	€ 18,10	€ 138.104,40	-€ 0,46
S5	Life Cycle Cost [€]	€ 10.607,90	€ 39.301,06	€ 62,17	€ 217.490,21	-€ 0,46

Fig. 9 Tabular and graphical results generated by the eDAM tool (Master tool interfaces)

Table 7 Scenarios results

Scenario	GWP [kg CO_2 eq]	LCC [€]
Baseline Scenario (S1)	172.982	188.075
Part Volume Variation (S2)	198.925	215.953
3D Printer Variation (S3)	234.488	223.576
Product Country Variation (S4)	170.729	202.187
Product Lifetime Variation (S5)	267.836	267.461

comparison, and tabulated results, with details on selected indicators (Fig. 9). More specifically for aviation applications, the GWP (kg CO_2 eq.), POCP (kg NO_x eq.), TAP (kg SO_2 eq.), and Life Cycle Cost (€) have been chosen as the most representative, as demonstrated also by other literature studies [39]. It is worth highlighting that, other than purely comparative results, the eDAM tool (particularly the *LCA/LCC tool*) allows the consultation of the detailed results for each indicator and for each scenario, with total impacts as well as splitting contributions for the different items (e.g., phases, processes, materials, energy).

Figure 10 and Table 7 present the obtained GWP (the most relevant environmental indicator for the aviation industry [43]]) and LCC results for the five scenarios, in graphical and tabular formats, respectively. All the results shown in this section demonstrate the tool's ability to quantify environmental and economic impacts of AM parts, considering the whole life cycle and with the possibility of simulating different design, production, and application scenarios.

5.2 Qualitative benchmark analysis

The same case study related to the bionic spacer panel has also been used to compare the eDAM tool with other similar commercial software solutions used in the context of design for AM, as well as to perform environmental and economic assessments. To find tools comparable to the proposed eDAM tools, three leading solutions were identified and utilized for a simplified qualitative benchmark analysis. The first is SimaPro [44], a professional, globally widespread, and general-purpose software tool for conducting LCA studies in accordance with ISO standards. The second one is a suite offered by AMPOWER [45], a German company that develops three tools for environmental and economic assessment of both polymeric and metal AM technologies (i.e., Sustainability Calculator Metal, Sustainability Calculator Polymer, and Cost Calculator). The third one is 3D Spark [46], an AI-driven manufacturing and procurement tool that compares process costs, lead time, and CO_2 emissions in the context of AM processes.

The comparison was carried out by using information freely available on the web (e.g., datasheets, tutorials, videos) and evaluating three main categories of criteria:

- Life cycle phases: the list of life cycle phases that the tool can manage;
- Indicators: environmental and economic indicators that the tool can compute;
- Capabilities: actual possibilities provided by the tools to change and manage various input data and to tune single or

	Raw Material	Manufacturing	Transport	Use	End of Life
S1	4,82E+02	7,19E+03	2,49E+02	1,65E+05	1,71E+01
S2	5,55E+02	8,27E+03	2,86E+02	1,90E+05	1,96E+01
S3	4,82E+02	6,87E+04	2,49E+02	1,65E+05	1,71E+01
S4	4,82E+02	5,08E+03	1,09E+02	1,65E+05	1,71E+01
S5	4,82E+02	7,19E+03	2,49E+02	2,60E+05	1,71E+01

	Raw Material	Manufacturing	Transport	Use	End of Life
S1	10.607,90 €	39.301,06 €	62,17 €	138.104,40 €	-0,46 €
S2	12.199,09 €	44.865,87 €	68,30 €	158.820,06 €	-0,53 €
S3	10.607,90 €	74.801,64 €	62,17 €	138.104,40 €	-0,46 €
S4	10.607,90 €	53.456,87 €	18,10 €	138.104,40 €	-0,46 €
S5	10.607,90 €	39.301,06 €	62,17 €	217.490,21 €	-0,46 €

Fig. 10 Comparison among the five scenarios: **a** GWP results, **b** Life Cycle Cost results

multiple analyses, also with comparative purposes among different AM technologies.

Table 8 presents the results of the qualitative benchmark analysis comparing the aforementioned tools with the proposed *eDAM tool*.

The three tools were compared with the *eDAM tool* also considering the effort required to create a scenario and to modify some of the life cycle parameters. To this purpose the previously defined baseline scenario (S1) and the four alternatives (S2 – S5) have been used. The following three-point scale was used to qualitatively judge the tools from the needed effort point of view:

Table 8 eDAM tool benchmark against other commercial software tools

Category	Performance indicator	eDAM	SimaPro	AMPOWER	3DSpark
Life cycle phases	Material & Manufacturing	Yes	Yes	Yes	Yes
	Use	Yes	Yes	No	No
	Transport	Yes	Yes	No	No
	End of Life	Yes	Yes	No	No
Indicators	Indicators—LCC	Yes, all phases	No	Only Material & Manufacturing	Only Material & Manufacturing
	Indicators—LCA	ReCiPe midpoint indicators	Indicators calculated by different LCIA methods (including ReCiPe)	Energy and GWP	GWP
Capabilities	Manage 3D printers	Yes More than one for each AM technology	No It is required to extend the inventory	Yes More than one for each AM technology	Yes At least one for each AM technology
	Manage AM materials	Yes There is a database with 17 metals and 21 polymers specific to AM	No There is no database for AM feedstock	Yes There is a database with 4 metals and 3 polymers specific to AM	Yes There is a database with metals, polymers, and ceramics specific to AM
	Number of AM technologies managed	5	0	10	12
	Manage production volume	Yes	Yes	Yes	Yes
	Manage AM post-processing	Yes	Yes	Yes	Yes
	Manage traditional manufacturing technologies	No	Many others	Milling and sand casting	Injection molding, casting, and other milling
	Manage production parameters	Yes	Yes	Yes	Yes
	Manage the electricity mix	Yes	Yes	Yes	No
	Manage product's EoL scenarios	Landfill and recycling	All	No	No
	Manage different analyses at once	Yes	Yes	Yes	Yes

- Low: the scenario can be easily generated or modified by the tool out of the box. The tool has easy-to-use functions and databases with built-in parameters that can be modified by users in case of special needs. The symbol (*) means that the scenario can be easily generated or modified only if the database contains the related parameters and models;
- Medium: the tool is specific for AM, but some analyses (e.g., use, transport, and EoL lifecycle phases) must be performed outside with other tools (e.g., electronic spreadsheets);
- High: the tool is not specific to AM, and a proper database and functions related to this technology are missing. Some product life cycle models and related parameters must be developed from scratch.
- N/A (Not Applicable): the tool cannot be used to create an AM-based scenario.

Table 9 presents the results of this comparison.

Table 9 Effort needed to generate and modify the different scenarios

	eDAM	SimaPro	AMPOWER	3DSpark
Scenario 1—Baseline development	Low	High	Medium	Medium
Scenario 2—Part volume variation	Low	Low	Low	Low
Scenario 3—3D printer variation	Low*	High	Low*	Low
Scenario 4—Production country variation	Low*	Low*	Low*	N/A
Scenario 5—Product lifetime variation	Low	Low	N/A	N/A

5.3 Discussion

From the analysis of the baseline scenario S1, it is evident that the impacts related to the use phase are the most significant. This conclusion reinforces the importance of considering the product use phase in assessing economic and environmental indicators of 3D printed products, in accordance with the basic principles of the overall *eDAM approach* and life cycle models. Indeed, comparing S1 with S2 (mass variation), the savings obtained during the use phase are significantly higher than the impacts of the material and manufacturing phases. A comparison between S1 and S3 shows that transitioning from a smaller printer to a larger one—without fully exploiting the larger printer's capacity (i.e., keeping the number of parts per build constant)—leads to poorer environmental and economic performance, particularly during the Manufacturing phase. This implies that selecting and adapting the 3D printer to the part's needs can lead to both economic and environmental benefits. Comparing S1 with S4 results, instead, highlights differences in the manufacturing and transport phases. While the differences in logistics can be easily discerned, the change in production countries reveals different trends for the environmental and economic evaluations. Starting from the latter, the switch from global reference values of the unitary costs and impacts, obtained through a mean of all the country-specific values included in the *eDAM tool* databases, to a national-specific one (i.e., the United States) leads to an increase in energy costs and workforce costs, as industrialized countries typically exhibit higher prices compared to non-industrialized ones. Regarding the environmental evaluation, this change resulted in the use of a more environmentally sustainable energy grid mix, leading to a decrease in terms of environmental impacts. Comparing S1 to S5, the only result that changed is related to the Use phase, which provides insight into a possible alternative application of the panel if the product's modularity is feasible.

More generally, it is noteworthy to highlight that all results for each analyzed scenario are evaluable within the same interface of the *eDAM tool* (Fig. 4), allowing the decision-maker to choose the best combination of design, technological, and life cycle parameters to define the most feasible and convenient solution. In particular, the data varied in this analysis showed a direct correlation to the life cycle phases; indeed, changing the printer (S3) or the production country (S4) affected only the manufacturing phase's impacts, while changing the annual traveled distance of the aircraft (S5) affected the Use phase. The part volume variation (S2), on the other hand, affected all life cycle phases, implying that this parameter, among all others, requires specific attention and that it needs to be carefully chosen during the design phase before optimizing the other parameters. A common conclusion across all scenarios is that the impact of the transport phase is always negligible compared to the other life cycle stages, as expected. However, for the purpose of conducting comprehensive analyses and ensuring its applicability in any contest/application, the *eDAM tool* provides results for all phases, leaving it up to the user to decide which phases need to be considered and which can be disregarded.

Evaluating the results obtained in the qualitative comparison of the tools presented in Sect. 5.2, it is possible to highlight the potential benefits and advantages of using the *eDAM tool*. Indeed, starting from the first category "Life cycle phases", the proposed tool aligns with typical LCA tools, providing a more detailed and comprehensive overview than the other AM-dedicated tools available in the market. Assessing the second category (LCA and LCC indicators), all tools (except for SimaPro) provide cost estimations for the life cycle phases they cover. In contrast, from an environmental standpoint, the *eDAM tool* can provide more detailed results for a broader range of impact categories, rather than focusing solely on GWP, allowing engineers to make more refined analyses and thus more aware choices. Regarding the "Capabilities" category, it is evident that SimaPro does not facilitate the assessment of AM technology, as it requires a detailed and novel modeling of both materials and processes, whereas all other tools propose built-in environmental and economic estimators, as well as databases dedicated to specific aspects of AM technologies (e.g., AM feedstocks). What clearly emerges from this category is that the *eDAM tool* aligns with current industrial standards, but it also enables the management of EoL scenarios, which is a feature that the other tools, except for SimaPro, do not offer. A critical limitation of the proposed tool is depicted in the performance indicator "Manage traditional manufacturing technology" (see Table 8). For this category, the *eDAM tool* lacks modeling of CM technologies (e.g., casting, injection molding, material removal processes), restricting its current analysis and comparison capabilities within the AM field.

Lastly, comparing the effort required to model and vary the scenarios, as presented in Table 9, it is possible to extract two distinct results. The first one is related to the initial effort to model the baseline scenario, S1. Indeed, in tools like SimaPro that do not have AM built-in processes or materials, their initial creation may require significant effort and time. Assessing the other tools (AMPOWER and 3DSpark), it is essential to note that modeling the initial life cycle phases may require minimal effort; however, their lack of modeling of subsequent phases (i.e., Use, EoL, and Transport) would represent a significant limitation. This highlights the competitiveness of the proposed tool against the existing ones, specifically in terms of input data variation related to the Raw material and Manufacturing phases, with a notable difference in the case of S4, where 3DSpark does not allow for a change in production country.

Generalizing the outcomes obtained from this preliminary experimentation of the proposed tool for the FDM technology, it is evident that adopting a life cycle perspective enables the comprehension of both the possible benefits and negative impacts of AM applications, as well as the related issues, from the design stage onwards. In addition, the proposed model and tool allow to carry out different simulations regarding the supply/production chain (e.g., various locations of the suppliers or production sites), the energy mixes (e.g., use of different country energy mix or dedicated energy mixes based on renewable sources), the use of different AM machines, the setting of production parameters (e.g., part orientation, support), the design of alternative geometries (e.g., optimized vs non optimized), functional to guide the decision-making process with considerable low efforts. The comprehensive and generalized structure of the proposed life cycle model, which can be adapted for other AM technologies, can be viewed as a key enabler to promote the use of LCE approaches and sustainability metrics during the design for AM stages, in combination with the other classic requirements (e.g., technological requirements, productivity). This is especially essential for enterprises that lack expertise, relevant resources, and time to perform LCA and LCC using specialized tools or by engaging a consultancy service.

6 Conclusions

The paper focuses on the ecodesign for AM by proposing and implementing an LCA/LCC-based model and tool, called eDAM, dedicated to supporting the design of parts realized by using AM technologies, by calculating as output quantitative environmental and economic impacts. The tool requests the user to provide as input the main characteristics of the analyzed part (e.g., dimensions, material, mass) and the product in which it is used (e.g., weight, use scenario). Different design, manufacturing, use, transportation, and EoL scenarios can be simulated and compared. The tool, based on the LCA/LCC model for FDM, was tested on a cabin spacer of an aircraft. The case study highlighted the environmental and economic benefits that AM can provide for the aerospace sector in a life cycle perspective. In particular, results calculated through the eDAM tool suggest that the lightweighting opportunities enabled by the AM could potentially lead to significant benefits during the use phase, compensating for the higher impacts for the manufacturing phase. The eDAM tool was also compared with similar commercial tools for environmental and economic assessment. Among the other identified commercial tools, it was the only one capable of managing the entire product life cycle of 3D printed parts, addressing various AM technologies, machines, and materials through an LCA/LCC-based approach. These characteristics permit engineers to generate LCA and LCC analyses and simulate multiple scenarios quickly. In contrast, it lacks the opportunity to compare AM with CM, which can be considered the main current limitation of the *eDAM tool*.

Looking ahead, it would be possible to adapt the proposed tool towards other AM technologies, such as DED and SLS, and even to CM technologies, broadening the comparison capabilities. Additionally, the adoption of more detailed and reliable modeling for the Use phase, which has demonstrated its key role in overall AM sustainability, should be explored. Future and more updated versions of the tool may include various EoL scenarios, such as reuse or remanufacturing, other than the sole recycling based on the avoided impact approach, to have a more realistic and comprehensive EoL phase modelling. These enhancements will further align the methodology with circular economy principles and increase its relevance across a wider range of industrial applications (e.g., gas turbines, machine tools). To increase the adoption of the eDAM approach, it will be essential to integrate it with CAD design software tools, ultimately enabling engineers and designers to utilize AM technologies as a platform for transformative innovation while addressing sustainability challenges consciously.

When the entire eDAM framework will be developed and exploited in industrial design contexts, the introduction of artificial intelligence algorithms, fed by the results obtained through the proposed LCA/LCC tool, could represent a relevant innovation regarding the guideline-based system to guide the design improvement tasks and thus favor the widespread adoption of AM technologies in several industrial sectors.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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