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ORIGINAL ARTICLE

Eco-design for metal additive manufacturing (EcoDAM): an integrated framework linking material, process, and lightweight design

Francesca Campana[1] · **Paolo Cicconi**[2] · **Daniele Landi**[3] · **Christian Spreafico**[3]

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Abstract

Metal powder-based Additive Manufacturing (AM) presents significant sustainability potential, but its environmental performance is highly sensitive to the interactions between material quality, process conditions, and lightweight design. This study addresses this challenge by developing EcoDAM, an integrated eco-design framework specifically tailored to metal AM, aimed at overcoming the limitations of isolated design or process optimizations. The methodology combines a parametric Life Cycle Assessment (LCA) model, an AI-supported FMEA-TRIZ failure investigation method, and advanced lattice-based structural optimization to evaluate sustainability as a coupled material-process-design problem. Results from the parametric LCA show that powder atomization and refining remain dominant environmental hotspots, but that controlled powder quality relaxation can reduce Global Warming Potential by 15–30% depending on regional energy mixes. The failure analysis identifies the admissible boundaries of powder degradation, ensuring that environmentally favorable configurations remain compatible with LPBF stability and mechanical reliability. The lightweight redesign of a diesel engine connecting rod demonstrates the operational power of the framework: a Gyroid-based solution achieved a 52.1% mass reduction while remaining structurally robust under conservative degradation scenarios. Overall, the study shows that sustainable AM outcomes emerge only within a constrained, co-optimized design region. EcoDAM provides a systematic basis for navigating this region and supports more informed, sustainability-oriented decisions in metal AM.

✉ Christian Spreafico
christian.spreafico@unibg.it

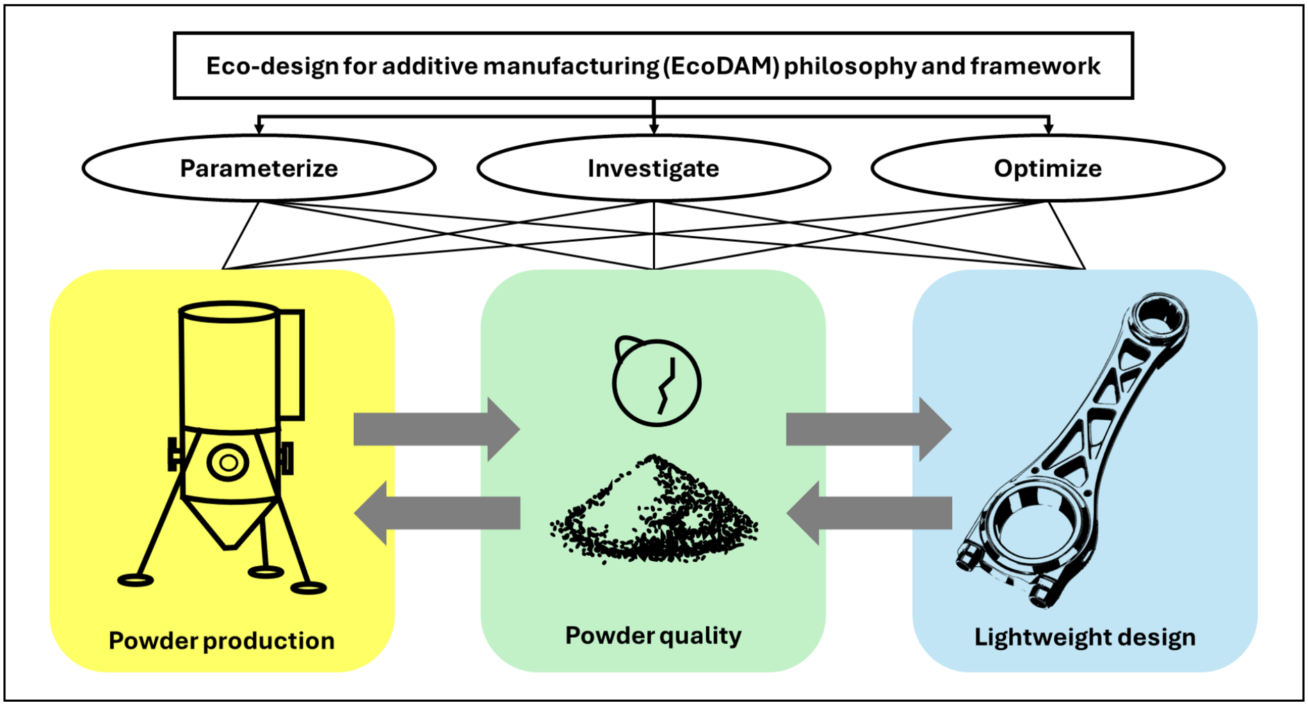
[1] Sapienza University Rome, Rome, Italy

[2] Roma Tre University, Rome, Italy

[3] University of Bergamo, Viale Marconi 5, 24044 Dalmine, BG, Italy

Graphical abstract

EcoDAM: an integrated eco-design framework for metal additive manufacturing linking powder production, powder quality, and lightweight design through environmental assessment, failure analysis, and design optimization.



Keywords Eco-design · Additive manufacturing · Parametric LCA · FMEA · Lightweight design

1 Introduction

Eco-design in metal powder-based Additive Manufacturing (AM) can be framed as an inherently contradictory, multi-level problem, structured around three tightly coupled dimensions: (i) the sustainability of the AM technology, (ii) the sustainability of the material, namely metal powders, and (iii) the lightweight design strategies enabled by AM. The tight interdependence between material selection, process parameters, and design solutions is a well-established characteristic of metal AM systems, where stable and economically viable production relies on highly optimized and mutually dependent material-process-design configurations [6].

Within this tightly coupled system, sustainability-oriented interventions targeting one dimension frequently induce trade-offs that shift environmental or performance burdens to the others. Life cycle assessment (LCA) studies on metal additive manufacturing consistently show that environmental outcomes are highly sensitive to the specific combination of process parameters, material characteristics, and design choices, making isolated improvements at the process level prone to burden-shifting effects. In particular, attempts to improve process efficiency through increased productivity or reduced build time are constrained by the process window and may indirectly increase defect formation, scrap rates, or post-processing requirements, thereby offsetting potential energy savings at the machine level [13],[14].

From a material perspective, the sustainability of metal powders is a critical element of this triad. In powder bed fusion, powder characteristics, particularly particle size distribution and particle morphology, strongly affect spreadability and powder-bed uniformity, with direct implications for process stability and part quality [12]. As AM increasingly exploits advanced lightweight and topology-optimized geometries, sensitivity to feedstock variability and powder handling tends to increase, reinforcing the need for tighter powder specifications and robust powder management practices [7]. These requirements are often linked to upstream burdens because industrial gas atomization and inert gas use can contribute substantially to the environmental footprint of metal powder supply [5]. While powder reuse and recycling strategies are frequently proposed as effective eco-design levers, their environmental benefits are highly sensitive to reuse limits, inspection protocols, and material-specific degradation mechanisms. Recent experimental evidence shows that repeated reuse of Ti-6Al-4 V powder in laser powder bed fusion leads to oxidation, changes in particle morphology, and deterioration of mechanical properties, directly affecting process robustness and component performance [20].

From a design perspective, lightweight design remains one of the most promising contributors to sustainability in metal additive manufacturing, particularly when assessed from a life cycle perspective that explicitly includes the use phase of the product. However, life cycle-based studies emphasize that lightweighting alone does not guarantee environmental benefits, as potential gains during the use phase may be offset by increased energy demand, material intensity, or post-processing requirements during manufacturing. Consequently, the environmental performance of lightweight AM designs strongly depends on their coherent alignment with material properties, process efficiency, and downstream processing. This highlights the need for co-optimization approaches that simultaneously address geometry, material behavior, and process constraints, rather than treating design, material, and technology as independent eco-design levers [14].

Overall, the literature indicates that eco-design for metal powder-based AM must be addressed through an integrated perspective capable of capturing the interactions between technology, material, and design. However, existing approaches remain only partially integrated and often emphasize one dimension over the others, such as structural optimization, environmental assessment, or material/process characterization. As a result, current methods still provide limited support for consistently guiding eco-design decisions across tightly coupled AM systems. In response, this manuscript proposes the Eco-Design for Additive Manufacturing (EcoDAM) framework, specifically tailored to metal powder-based processes, to support the coherent evaluation of sustainability trade-offs across product, process, and material dimensions.

The novelty of this work lies in its explicit conceptualization and operationalization of eco-design for metal additive manufacturing as a tightly coupled triadic system encompassing technology, material, and design. Unlike existing approaches that primarily focus on numerical optimization, isolated environmental indicators, or task-specific guidelines, the proposed framework provides a unified structure capable of capturing the non-linear interactions and trade-offs that characterize metal powder-based additive manufacturing.

Unlike existing approaches that primarily focus on numerical optimization, isolated environmental indicators, or task-specific guidelines, the proposed framework provides a unified structure to capture the main interactions and trade-offs that characterize metal powder-based AM.

By systematically integrating lightweight design strategies with material sustainability considerations and process-specific constraints within a life cycle perspective, the framework advances beyond state-of-the-art methods that remain fragmented or context-dependent. This contribution therefore offers a more comprehensive and transferable basis for eco-design decision-making in additive manufacturing, addressing a critical gap between methodological developments and practical sustainability challenges. While the framework adopts a life cycle perspective, the present implementation primarily focuses on upstream material production and manufacturing stages, where the most significant environmental impacts are concentrated.

This contribution therefore offers a more structured and transferable basis for eco-design decision-making in additive manufacturing, addressing a critical gap between methodological developments and practical sustainability challenges.

To facilitate the understanding of the proposed approach, the operational logic of the EcoDAM framework can be summarized as follows. First, the eco-design problem is structured through the definition of an Eco-Design Decision Context, which formalizes product requirements, manufacturing configurations, powder specifications, and environmental evaluation dimensions. Second, a parametric LCA model is used to explore the environmental implications of alternative powder and process configurations. Third, a failure investigation method based on FMEA-TRIZ principles is employed to identify admissible technical boundaries associated with powder quality variations. Finally, lightweight design optimization is used to evaluate and validate product-level feasibility under the identified environmental and technical constraints.

These elements are integrated to enable the exploration of a feasible eco-design region, where environmental performance, process stability, and structural requirements are simultaneously satisfied.

This work builds upon research activities carried out within the Italian PRIN project “Eco-Design for Additive Manufacturing—EcoDAM”, funded under the EU Next Generation framework.

2 Literature background

To improve the clarity of the discussion, the reviewed contributions can be interpreted according to their primary integration perspective. In particular, existing approaches can be broadly grouped into: (i) design-driven approaches, mainly centered on topology optimization; (ii) process- and data-driven approaches, focusing on process-structure–property relationships; and (iii) environmentally driven approaches, integrating life cycle assessment into design workflows. The following discussion adopts this perspective to highlight similarities, differences, and remaining gaps.

Recent research on eco-design for additive manufacturing has increasingly recognized that environmental performance cannot be addressed through isolated design interventions, but rather emerges from the tight coupling between design choices, process conditions, and material characteristics. Within this context, several methodological contributions have attempted to operationalize this coupling by integrating topology optimization, process modeling, material selection, and life cycle assessment into unified or partially unified design frameworks.

Duriez et al. [4] propose one of the most explicit attempts to simultaneously address material, process, and design selection from a life cycle perspective. Their method formulates eco-design as a simultaneous optimization problem in which topology optimization is combined with a database of additively manufactured materials and processes, explicitly aiming to minimize greenhouse gas emissions over the entire life cycle. To manage the strong interdependence between material properties and manufacturing processes, the authors adopt a pairing strategy inspired by generalized Ashby indices, allowing material–process combinations to be screened and ranked in a computationally efficient manner. The use of surrogate models further reduces computational cost, enabling rapid exploration of alternative design configurations. Validation through aeronautical and civil engineering case studies demonstrates that material and process choices cannot be evaluated independently of the mass reductions achieved through design optimization, as environmentally intensive material-process pairs may still become preferable when significant lightweighting benefits are realized during the use phase. This work clearly illustrates the necessity of treating material, process, and geometry as a coupled system when assessing environmental performance.

A complementary line of research focuses on integrating process-induced material behavior directly into the design optimization stage. Li et al. [10] introduce a multidisciplinary topology optimization framework that explicitly incorporates process-structure–property-performance relationships into the optimization loop. Using data-driven models, the authors map laser and process parameters to resulting material properties and structural performance, allowing both topology and process parameters to be optimized concurrently. This approach establishes a quantitative linkage between process settings, in-situ material behavior, and structural performance, thereby enabling the exploration of trade-offs between lightweight design, manufacturability, and mechanical performance. Rather than treating material properties as fixed inputs, the method recognizes them as outcomes of process decisions, reinforcing the need for integrated design and manufacturing optimization in additive manufacturing.

Related efforts further emphasize the importance of accounting for process-induced material heterogeneity and anisotropy during design optimization. Xian et al. propose a topology optimization formulation that explicitly integrates anisotropic and heterogeneous material properties arising from additive manufacturing processes. Their approach distinguishes between bulk and near-surface regions, reflecting differences in microstructure and mechanical behavior induced by scan strategies and local thermal histories. By embedding these effects directly into the topology optimization framework, the method reduces the mismatch between numerically optimized designs and the actual performance of additively manufactured parts. This contribution highlights how process-dependent material characteristics fundamentally shape feasible and efficient lightweight designs, reinforcing the inseparability of process and material considerations from design optimization.

Other works extend this integration by explicitly incorporating environmental assessment into the topology optimization process. Hoschke et al. [8] present a sustainability-oriented topology optimization framework embedded within a generative design workflow. Their method evaluates intermediate topology optimization results using predictive life cycle assessment models, while simultaneously considering mechanical performance, build orientation, support structures, and process-related quality indicators. Environmental impacts are assessed across multiple categories, including climate change and resource depletion, and are balanced against structural and manufacturability objectives. This approach enables designers to explore trade-offs between lightweight design, process feasibility, and environmental performance within a single optimization problem, moving beyond sequential design–assessment workflows.

Earlier foundational work by Tang et al. [18] laid important groundwork for integrating design optimization and environmental assessment in additive manufacturing. Their framework formulates eco-design as a design optimization problem guided by life cycle indicators, explicitly recognizing that the design freedom offered by additive manufacturing can substantially influence environmental outcomes. By embedding life cycle assessment within the design stage, the authors demonstrate that topology-optimized geometries can significantly reduce energy consumption and emissions compared to conventionally manufactured counterparts. Although originally developed for binder jetting processes, this work remains a key reference for subsequent studies seeking to link design optimization and environmental performance in additive manufacturing.

More recent contributions have expanded the scope of eco-design by explicitly addressing material sustainability, particularly in relation to powder reuse and recycling strategies. Amicarelli et al. [1] propose an eco-design approach for laser powder bed fusion in which the material input is modeled as a mix of virgin, reused, and recycled powders. This material strategy is integrated into a design optimization and life cycle assessment workflow, allowing designers to evaluate the combined effects of geometry optimization, process feasibility, and powder management strategies on environmental performance. The work highlights how feedstock quality and reuse strategies directly influence both process robustness and life cycle impacts, further reinforcing the need for integrated decision-making across material, process, and design dimensions.

Finally, Wang et al. [19] address eco-design from a knowledge-based perspective by formalizing eco-design rules for additive manufacturing within a design advisor system. Rather than focusing on numerical optimization, their approach codifies sustainability-related design knowledge, linking material selection, lightweight design strategies, and process considerations across different stages of the design process. By structuring eco-design guidelines into a machine-readable and reusable rule-based system, the authors provide a complementary pathway for supporting sustainability-oriented decision-making in additive manufacturing, particularly in early design stages where quantitative data may be limited.

3 Proposal

As a prerequisite of the reasoning process and system boundary definition, the framework explicitly focuses on metal powder- based additive manufacturing, as this class of technologies represents the dominant industrial route for high-performance metal AM and concentrates the largest share of environmental impacts along the lifecycle.

Within this boundary, eco-design decisions are formulated through the definition of an Eco-Design Decision Context, which represents the complete set of system definition entities, configuration entities, contextual boundary conditions, and evaluation dimensions that jointly define the decision space, constraints, and evaluation criteria of an eco-design problem. The Eco-Design Decision Context consists of:

- *Product design specification* The formal specification of a product instance, defined by a set of functional, mechanical, geometrical, and performance requirements, together with the constraints that govern its feasible realization across manufacturing technologies and material systems.
- *Manufacturing technology configuration* An abstract representation of a selected manufacturing technology and its associated lifecycle stages, including material and powder production routes, defined through admissible ranges of operational parameters rather than fixed settings, and intended to be refined through parametric models, simulations, and experimental validation.
- *Powder specification configuration* An abstract representation of a powder defined by admissible ranges of physical, chemical, and morphological properties, including allowable defect types and levels, intended to be compatible with a given manufacturing technology configuration and to be refined through parametric life cycle assessment, risk-based quality models, simulations, and experimental testing.
- *Application context* Is an abstract representation of the external conditions under which a product is manufactured and assessed, primarily defined by geographical and infrastructural factors, such as energy supply mixes, that influence environmental performance without being decision variables of the design or manufacturing configurations.
- *Environmental impact dimension* Is an abstract sustainability perspective representing a specific environmental concern, such as an environmental impact category used in LCA (e.g., global warming, water acidification), through which the performance of a product and its manufacturing system is evaluated and compared.

The relationships between the Eco-Design Decision Context, the eco-design for AM philosophy, and the operational components of the EcoDAM framework are schematically illustrated in Fig. 1.

To clarify the operational logic of the EcoDAM framework, the overall workflow can be summarized as follows:

1. The eco-design problem is defined through the Eco-Design Decision Context, specifying product requirements, manufacturing configurations, powder specifications, and environmental objectives (input: design requirements, process configurations; output: structured decision context).
2. A parametric LCA model is used to explore the environmental implications of alternative powder and process configurations (input: process parameters and powder specifications; output: environmental impact indicators).
3. A failure investigation based on FMEA-TRIZ principles is performed to identify the technical admissibility boundaries associated with variations in powder quality and process conditions (input: powder/process variations; output: admissible constraints and failure relationships).
4. These admissibility constraints are translated into design and process limitations (output: constrained design space).

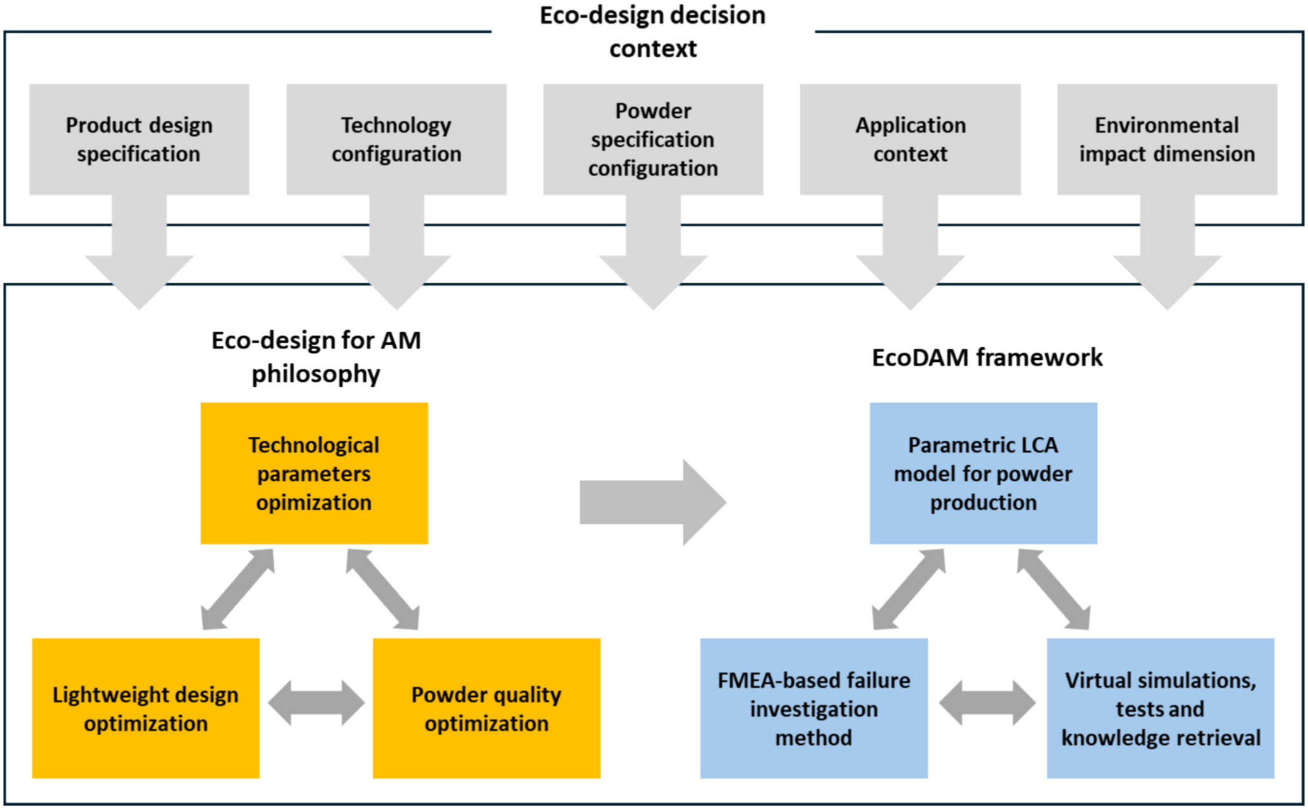


Fig. 1 Conceptual overview of the EcoDAM framework, showing the Eco-Design Decision Context, the eco-design philosophy based on the co-optimization of technological parameters, powder quality, and lightweight design, and the integrated operational components used to support eco-design decisions in metal additive manufacturing

5. Lightweight design optimization is then carried out under both environmental and technical constraints (corresponding to the redesign and structural optimization stage presented in Sect. 4.3)
6. The results are iteratively evaluated and integrated to identify a feasible eco-design region (corresponding to the integrated trade-off analysis presented in Sect. 4.4).

Building on this decision context, the proposed approach is articulated into two complementary components. Section 3.1 formalizes the considered eco-design for AM philosophy, framing sustainability as a co-optimization problem across technological parameters, powder quality, and lightweight design. Section 3.2 then presents the EcoDAM framework itself, detailing how parametric environmental modelling, failure-based knowledge, and product-specific validation are integrated to operationalize this philosophy.

To better clarify the operational logic of the proposed framework, Fig. 2 illustrates the staged workflow of the methodology, highlighting the input–output relationships among the design generation, co-optimization, trade-off evaluation, and final decision-making phases.

3.1 Eco-design for AM philosophy

Eco-design for AM is addressed in this work as a multi-dimensional optimization problem in which environmental sustainability emerges from the coordinated interaction between technological parameters, material quality, and product design. Rather than treating these aspects independently, the proposed philosophy explicitly recognizes their strong interdependence and frames eco-design as a problem of balancing competing objectives across multiple levels of the additive manufacturing system.

From a formal perspective, this problem can be interpreted as a constrained multi-objective optimization problem, where environmental impact (e.g., GWP), structural performance, and manufacturability are simultaneously optimized under process and material constraints.

Within this perspective, technological parameters optimization, powder quality optimization, and lightweight design optimization are considered three coupled and non-separable eco-design levers. Technological parameters optimization refers to the adjustment of process and production parameters across the additive manufacturing value

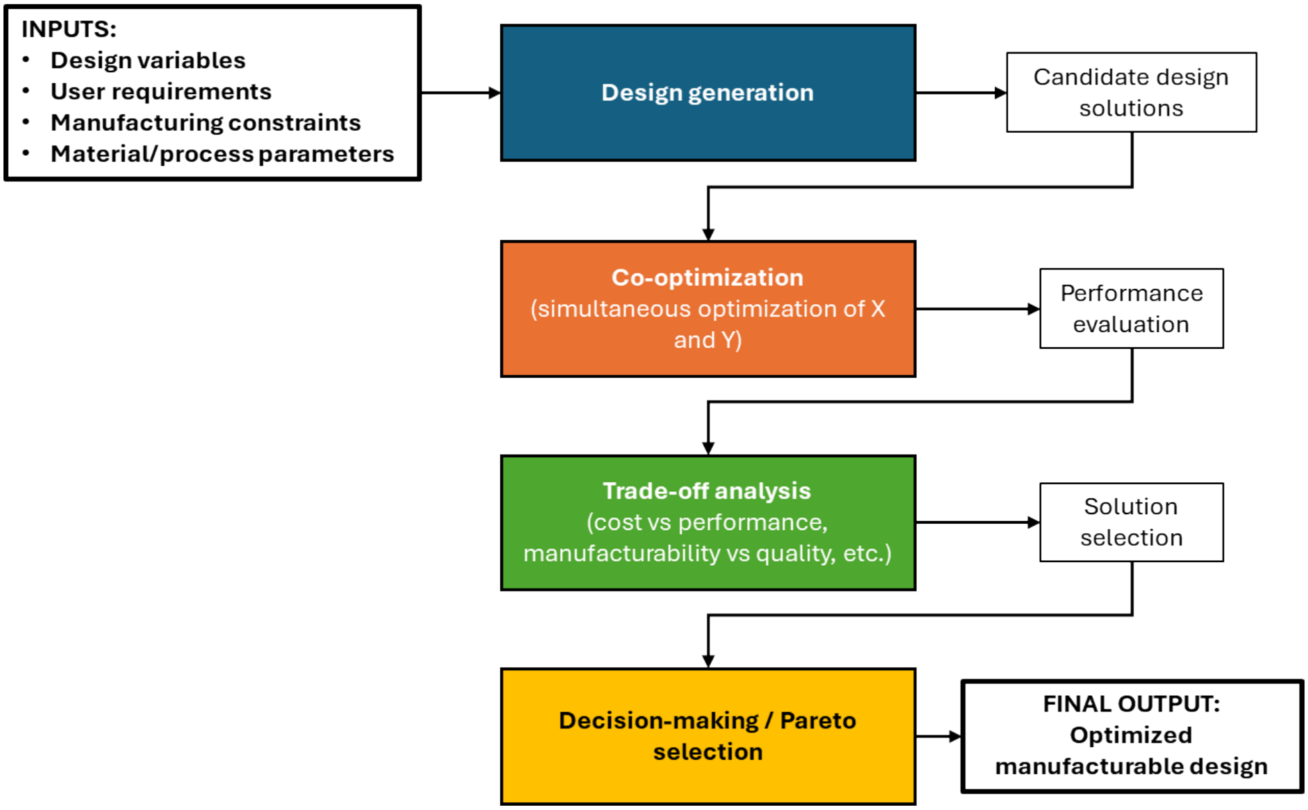


Fig. 2 Operational workflow of the proposed co-optimization framework and corresponding input–output relationships among the main methodological stages

chain, including upstream stages such as powder production and downstream manufacturing operations, with the aim of reducing energy consumption and environmental impacts. Powder quality optimization concerns the deliberate definition of admissible powder quality levels, expressed through bounded ranges of physical, chemical, and morphological properties, acknowledging that higher powder quality typically entails higher environmental burdens during production. Lightweight design optimization focuses on reducing material usage at the product level through geometry and topology optimization, while maintaining functional and mechanical requirements.

From a conceptual perspective, the structured definition of these dimensions and their interactions can also be interpreted as an ontology of eco-design for additive manufacturing, as it formalizes the key entities, relationships, and constraints that characterize the decision space.

Crucially, improvements along one of these dimensions inevitably affect the others. For instance, aggressive lightweight design strategies often increase sensitivity to defects and variability, thereby imposing stricter requirements on powder quality and process stability. Conversely, relaxing powder quality requirements may significantly reduce upstream environmental impacts, but can increase the likelihood of process instabilities or performance degradation, which may only be acceptable for specific product designs or technological configurations. Similarly, the optimization of technological parameters can compensate for reduced powder quality or enable more aggressive lightweighting, albeit often at the cost of increased process energy or complexity.

The eco-design philosophy adopted in this framework therefore rejects single-objective or sequential optimization approaches. Instead, it treats additive manufacturing eco-design as a co-optimization problem, in which technological parameters, powder quality, and lightweight design are explored simultaneously within a unified decision context. Sustainability is not defined as a fixed target, but as a trade-off space that must be explicitly navigated based on environmental priorities, product requirements, and technological feasibility.

By formalizing these three optimization dimensions and their interactions, the proposed approach provides the conceptual foundation for the integrated framework presented in the following sections. This foundation enables the systematic evaluation of environmentally beneficial design alternatives that would remain invisible when technological parameters, material quality, or product design are optimized in isolation.

3.2 EcoDAM framework

The EcoDAM framework is conceived as a decision-support framework for eco-design in metal additive manufacturing, and represents the implementation stage of the proposed eco-design approach, aimed at managing the trade-off between environmental impact reduction and technical feasibility when powder quality is intentionally relaxed.

The framework is based on the observation that reducing the environmental impact of metal powder production, through modifications in production yield, classification strategy, recycling rate, or purity requirements, inevitably alters powder characteristics. These alterations propagate through the additive manufacturing process and influence defect formation, process stability, and final part performance, particularly in lightweight-optimized designs. Consequently, environmentally driven decisions cannot be evaluated solely through environmental modelling, but require a structured assessment of their technological and product-level implications.

To address this challenge, EcoDAM integrates three complementary elements, each with a distinct and well-defined role:

- A parametric LCA model [15],
- A failure investigation method specific for exploring powder-technology-product features relations based on FMEA-TRIZ principles (Ördek et al. 2026; Spreafico et al. [16]).
- A structured literature analysis, targeted experiments and simulations, explicitly intended as knowledge extraction to support the failure investigation method and to define and constrain the parametric environmental model.

These elements are described in detail in the following subsections, where their individual roles and interactions within the overall workflow are formalized.

From an implementation perspective, these components operate within a structured workflow in which each element provides specific inputs to the others, contributing to the definition of a constrained eco-design solution space.

The interaction between the different components of the framework is not purely sequential. The parametric LCA model provides environmental performance indicators associated with alternative powder configurations, while the FMEA-TRIZ analysis translates powder-related variations into admissible technical constraints. These constraints are then incorporated into the design optimization stage, where they limit the feasible design space. Conversely, design requirements and performance targets feed back into the definition of admissible powder and process configurations.

Although the framework is operationalized through a staged workflow, it conceptually represents a co-optimization problem. The sequential structure is adopted for practical implementation purposes, while the interdependencies between environmental, technical, and design variables are preserved through iterative feedback between the different components.

3.2.1 Parametric LCA model

The parametric LCA model represents the quantitative component of the EcoDAM framework. Its purpose is to explore how variations in powder production and handling parameters affect environmental impact indicators, explicitly treating powder quality as an eco-design lever.

At its core, the model represents the entire powder manufacturing route, from raw material processing to final powder sieving, through a set of interdependent process models whose mass and energy flows are expressed as functions of controllable operational parameters. Typical parameters include energy demand, material yield, recycling rate, classification efficiency, purity requirements, slag composition, atomization conditions, and powder size targets. Unlike conventional static LCAs, the model does not assume fixed production conditions, but explicitly links key process parameters governing powder characteristics to environmental impacts, enabling numerical scenario analysis and optimization.

This formulation allows the systematic exploration of alternative powder specification configurations and their associated upstream environmental burdens. In particular, relaxed powder quality requirements, such as broader particle size distributions or higher fractions of off-spec or reused material, can lead to substantial reductions in energy consumption and emissions during powder production. This phase is widely recognized as the most environmentally impactful stage of the metal additive manufacturing lifecycle [3, 9, 11].

However, the parametric LCA model is inherently limited to environmental aspects and remains agnostic with respect to downstream manufacturing performance and product-specific requirements. While it quantifies how changes in powder-related process parameters affect environmental impacts, it does not account for additive manufacturing process stability, defect formation, or the functional performance of the final part. For this reason, the parametric LCA model alone cannot define admissible ranges for powder quality parameters. Without additional technical constraints, environmental optimization would systematically favor lower-quality powders, regardless of their manufacturability or suitability for lightweight applications.

In Spreafico and Ördek [15], the parametric LCA model is explored through a numerical investigation aimed at demonstrating the internal consistency of the modelling approach and its suitability for integration within the EcoDAM framework. The analysis is intentionally theoretical and illustrative, as the focus of that work is on methodological development rather than on the experimental validation of specific powder–process–part scenarios.

The modelling approach adopted in this work builds on recent methodological advances in prospective LCA applied to titanium powder atomization [17]. In particular, the EcoDAM parametric LCA model inherits the forward-looking logic of prospective assessment by embedding technological evolution, process parameter variability, and upstream material transformations into a unified analytical structure. This allows the model to move beyond static representations of powder production and to represent future or hypothetical operating conditions through parameterized relationships instead of fixed inventories. Moreover, the emphasis on linking powder production parameters (e.g., argon pressure, induction power, classification yield) to environmental outcomes is consistent with the prospective LCA evidence showing that atomization impacts are highly sensitive to technology configurations and performance improvements over time. By grounding the model in this methodological lineage, EcoDAM positions its environmental analysis within an explicitly dynamic and scenario-dependent framework, enabling systematic exploration of sustainable powder specification configurations that would remain invisible under traditional static LCA modelling.

The parametric LCA model is implemented based on literature-derived process data, engineering assumptions, and prospective modelling approaches described in previous works [15, 17]. The model structure, parameters, and assumptions are explicitly defined to enable reproducibility of the analysis, and can be adapted to different material systems and process configurations by modifying the corresponding input parameters.

It should be noted that the environmental analysis presented in this work is based on modelling and simulation, and does not include direct experimental validation. The focus of the study is on methodological development and scenario exploration rather than on the empirical validation of specific industrial configurations.

3.2.2 FMEA-based failure investigation method

To complement the parametric LCA model, EcoDAM adopts a failure investigation method based on FMEA-TRIZ principles. The role of this method is to structure the technical problem arising from environmentally motivated powder quality reduction, rather than to provide predefined correlations or a ready-made knowledge base.

Within EcoDAM, powder quality degradation is treated as a controlled perturbation of the additive manufacturing system. The failure investigation method is used to systematically identify and organize the relationships between powder, process, and part levels.

From an operational perspective, the method follows a structured procedure consisting of: (i) identification of relevant powder, process, and part-level variables; (ii) mapping of failure modes, causes, and effects based on literature and domain knowledge; (iii) qualitative assessment of the relationships between variables; and (iv) definition of admissible constraints and operating conditions.

While the FMEA-TRIZ method is supported by AI-based knowledge extraction, its structure remains fully transparent and reproducible, as it relies on explicitly defined failure modes, causes, and effects. The AI component is used to support knowledge retrieval rather than to replace expert-driven analysis, facilitating the identification of relevant failure relationships while maintaining full traceability and interpretability of the results.

The methodology relies on explicitly defined relationships between failure modes, causes, and effects, which can be systematically constructed using publicly available literature, experimental evidence, and expert knowledge, ensuring that the analysis can be reproduced independently of the specific software tools used.

In particular, the relationships are structured as follows:

- Failure modes, corresponding to deviations in powder characteristics (e.g., particle size distribution, oxygen content, morphology);
- Failure causes, associated with powder production parameters or additive manufacturing process settings;
- Failure effects, expressed in terms of part-level physical, mechanical, and functional properties, including those critical for lightweight design.

By enforcing a structured decomposition of the system, the method ensures that interactions between powder, process, and part are explicitly considered, rather than selected opportunistically. In addition, the method supports a qualitative assessment of the relevance and criticality of identified failure modes and effects, providing a rational basis for defining technical constraints and admissible operating regions.

3.2.3 Literature analysis, experiments and simulations as knowledge extraction

Within EcoDAM, knowledge extraction is structured as a systematic process guided by the failure investigation method. Rather than performing a broad or exploratory review, the analysis is organized into the following steps: (i) identification of critical failure mode-cause-effect relationships; (ii) targeted literature review focused on these relationships; (iii) evaluation of the consistency and validity of available evidence; and (iv) identification of knowledge gaps requiring further investigation.

In this process, the literature analysis is used to extract and contextualize existing knowledge…

The role of the literature analysis is to extract and contextualize existing knowledge on powder-process-part interactions, identifying the direction of effects, conditions of validity, and relevance for lightweight design. This process allows distinguishing between well-established relationships, partially supported hypotheses, and areas where evidence is lacking.

When the literature does not provide sufficient or consistent information, targeted experiments and simulations are introduced to address specific knowledge gaps identified by the failure investigation method. These activities are explicitly designed to reduce uncertainty in the most critical interactions, rather than to perform broad exploratory testing.

The outcomes of literature analysis, experiments, and simulations are used to define constraints, admissible parameter ranges, or conditional scenarios within the parametric LCA model, ensuring that environmental optimization remains grounded in technically feasible and physically meaningful solutions.

This structured approach ensures that knowledge extraction is not exploratory but directly aligned with the requirements of the eco-design decision context and the definition of admissible solution spaces.

4 Case study

In order to operationalize the EcoDAM framework and demonstrate its capability to manage the coupled optimization of technological parameters, powder quality, and lightweight design, a case study was developed focusing on the redesign of a diesel engine connecting rod for production via Laser Powder Bed Fusion (LPBF). The purpose of this case study is not only to demonstrate a specific design solution, but to illustrate the applicability of the EcoDAM framework to real-world eco-design problems, highlighting how the different components interact within a structured decision-making process. In this case study, the Eco-Design Decision Context defined in Sect. 3 is explicitly instantiated through the specification of the product (the connecting rod), the LPBF technology configuration, the powder specification configuration, the application context, and the selected environmental impact dimension. In doing so, the conceptual triadic eco-design philosophy of EcoDAM is translated into a fully structured decision-making scenario.

The selected component is a 2.8 L diesel engine connecting rod originally manufactured in chrome-molybdenum steel. The reference geometry has a center-to-center distance of 157 mm, a big-end diameter of 60.5 mm, and a small-end diameter of 32 mm, with an initial mass of 1277.6 g. During operation, the connecting rod is subjected to cyclic roto-translational motion, with peak compressive loads occurring immediately after combustion. For the purposes of this study, the governing load case was defined as the maximum compressive load corresponding to a peak cylinder pressure of approximately 50 bar, leading to a compressive force of approximately 35 kN, consistent with the mechanical modelling and experimental characterizations reported within the EcoDAM project.

The eco-design objective was defined as achieving a mass reduction of at least 50% while maintaining structural integrity under the prescribed loading condition and ensuring compatibility with LPBF manufacturing constraints. The redesigned component was intended to be manufactured in Ti-6Al-4V alloy, selected for its high specific strength and established suitability for LPBF processing. Within the EcoDAM logic, this component constitutes the Product Design Specification, while LPBF processing of Ti-6Al-4V powder defines the Manufacturing Technology Configuration. Unlike conventional design studies, the Powder Specification Configuration is not treated as a fixed material input but as an explicit eco-design lever: powder quality (including virgin, reused, and recycled powder states) is intentionally formulated as a variable dimension of the decision space, enabling systematic exploration of environmentally motivated powder quality relaxation and its downstream effects on process and part performance.

4.1 Environmental assessment of powder production via parametric LCA

Given that powder production is widely recognized as the dominant environmental hotspot in metal additive manufacturing life cycles, the first stage of the analysis focused on quantifying the environmental implications of alternative powder specification configurations. This was achieved through a constrained nonlinear programming framework implemented in MATLAB, utilizing the *fmincon* function from the Optimization Toolbox to iteratively solve the parametric LCA model.

The LCA is performed using a parametric modelling approach based on literature-derived inventory data and prospective modelling assumptions. The system boundary focuses on powder production and upstream material processing stages, together with the manufacturing stage relevant to LPBF-based component production, as these are consistently identified as the dominant contributors to environmental impacts in metal additive manufacturing. The inventory is constructed from process-level data reported in the literature, including energy consumption, material yields, gas usage, and process-related operational parameters, and is parameterized to enable scenario-based analysis. In the present implementation, downstream phases such as use and end-of-life are considered only at a conceptual level and are not explicitly modelled.

Unlike conventional static LCA models, the EcoDAM parametric formulation expresses mass and energy flows as explicit functions of controllable operational parameters. The optimization vector included the electrode diameter ($\Phi_{ATelectrode}$) in remelting operations, the argon pressure ($p_{ATargon}$) during atomization, and the TiO_2 content in slag (β_{TiO2}) during mineral processing. To enhance the robustness of the assessment, a patent-based prospective LCA methodology was integrated, allowing for the comparison of mature technologies against future technological evolutions, such as Electrode Induction Gas Atomization (EIGA) and Plasma Rotating Electrode Process (PREP), using data extracted from recent patent documents.

Optimization results show that the atomization and chlorination/refining phases consistently dominate the environmental profile, jointly contributing approximately 65–85% of the minimized total impact across midpoint categories. Global Warming Potential (GWP) proved to be particularly sensitive to argon use; the model consistently optimized $p_{ATargon}$ to its lower bound (5.5 MPa), highlighting the significant environmental burden of gas compression energy. Furthermore, the acceptance of broader particle size distributions-reflecting relaxed powder specifications-led to measurable decreases in electricity consumption. Depending on the regional context (e.g., EU vs. CN) and the associated electricity mix, minimized impact values varied by 15–30%. These findings confirm that powder quality relaxation, when driven by the simultaneous optimization of key process variables, constitutes a highly effective eco-design lever.

However, as this purely environmental optimization remains agnostic to downstream manufacturing feasibility, it does not account for how changes in powder characteristics (such as morphology or oxygen uptake) propagate through the LPBF process. Therefore, these LCA-optimal configurations must be constrained by the failure-oriented analysis presented in Sect. 4.2, ensuring that environmental gains do not compromise the structural performance and manufacturability of the component.

4.2 Failure-oriented analysis of powder-process-part interactions

To evaluate the technical admissibility of powder quality relaxation, a multi-step AI-supported FMEA-TRIZ methodology was applied. This approach moved beyond traditional risk assessment by structuring the LPBF system into interconnected domains of powder characteristics, process parameters, and part-level performance, preventing environmentally driven decisions from being assessed in isolation.

The literature analysis and knowledge extraction step described in Sect. 3.2.3 is embedded within the failure investigation process, supporting the identification and validation of relevant powder–process–part relationships.

The analysis was supported by Omnia, a proprietary platform utilizing a Retrieval-Augmented Generation (RAG) architecture to systematically extract and synthesize failure modes from extensive patent and scientific databases. This AI-driven knowledge retrieval enabled the construction of a hierarchical failure map, which was further refined through a TRIZ functional analysis of the main Selective Laser Melting (SLM) assemblies (e.g., Laser, Powder Handling, and Gas Flow systems). Interactions were classified into Correct (C), Insufficient (I), and Harmful (H) categories. For instance, the analysis identified that reused powders exhibit a high frequency of satellite particles-typically characterized by a 20–50 µm globe diameter with 5–10 µm satellites, which directly correlate with a harmful (H) function in the powder dispensing system, leading to uneven layer thickness.

A subverted risk analysis was then performed to calculate the Risk Priority Number (RPN), accounting for noise factors such as machinery aging and sensor drift. Key degradation mechanisms identified include oxidation, oxygen uptake, and the balling effect, an intricate metallurgical behavior occurring when low energy input leads to poor wettability and droplet splashing (as detailed in Fig. 3 of the project report). These powder-level deviations propagate through the LPBF process, potentially compromising melt-pool stability and layer homogeneity. At the part level, these phenomena translate into process-induced material defects, such as internal porosity and microstructural irregularities, leading to a slight decrease in yield strength, which are particularly critical for the thin-walled lattice structures (e.g., 0.5 mm wall thickness) used in the connecting rod's lightweight design.

Ultimately, this failure investigation served to define admissible bounds for powder quality relaxation by mapping specific powder deviations to their mechanical consequences. These technical constraints provided the necessary "safety envelope" to interpret the environmental optimization results, ensuring that the selected sustainable powder configurations remain compatible with the structural reliability and manufacturability requirements of high-performance automotive components.

The final optimized connecting rod and the corresponding Gyroid lattice configuration are shown in Fig. 3.

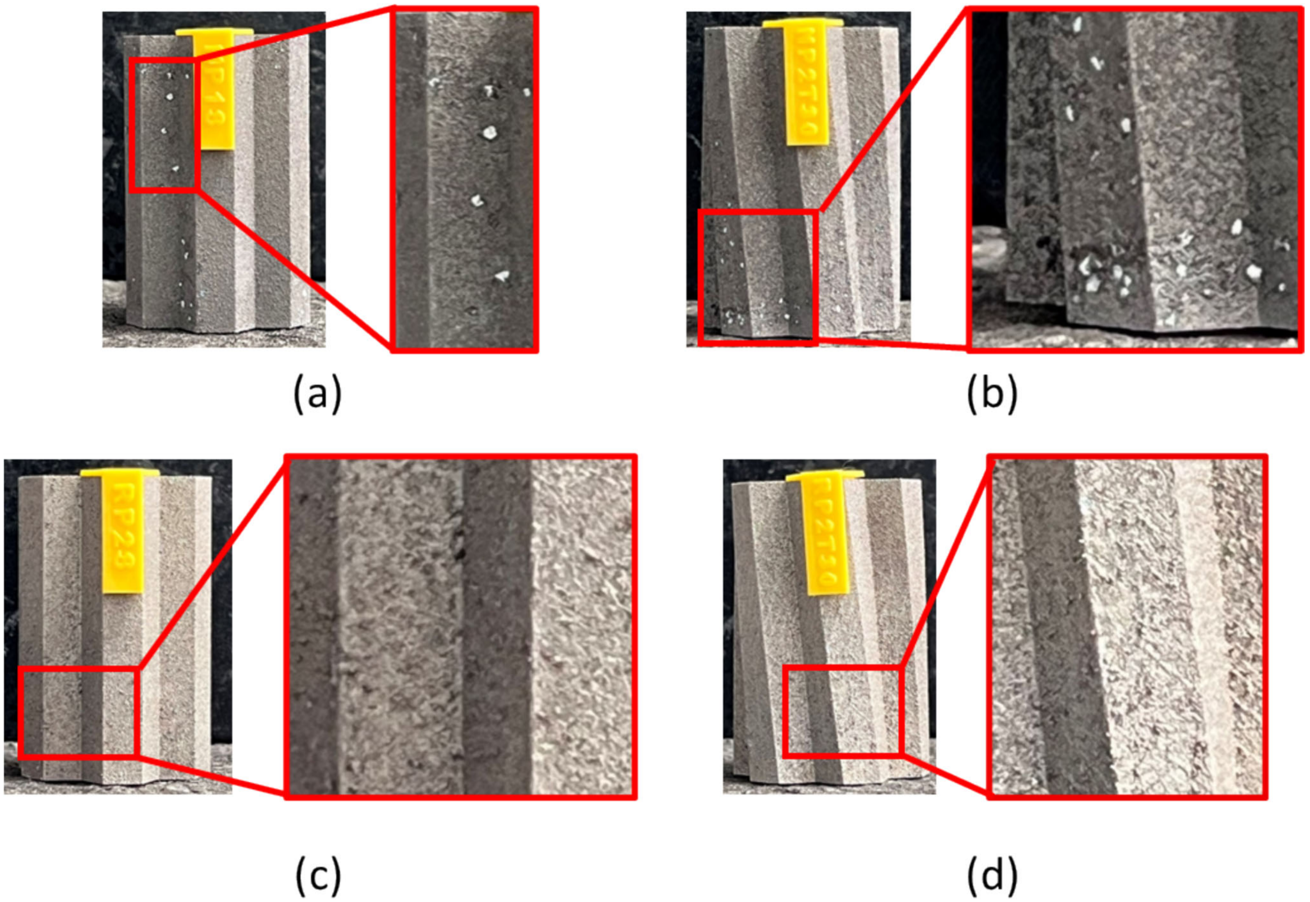


Fig. 3 Experimental characterization of surface defects: **a** unmelted and **b** partially melted powder particles adhered to honeycomb walls; balling effect observed on **c** straight and **d** twisted honeycomb geometries

4.3 Lightweight redesign and structural optimization

From a methodological perspective, this stage takes as input the admissible constraints derived from the LCA and failure analysis stages, including environmental indicators and material-related limitations, and produces as output optimized design configurations evaluated in terms of mass reduction and structural performance.

The connecting rod was redesigned using a lattice-based strategy managed through an integrated digital workflow. A parametric CAD environment was developed in Grasshopper to automate the generation of Triply Periodic Minimal Surface (TPMS) cell types-specifically Gyroid, Diamond, and SplitP. The structural pillar focused on a 2.8 L diesel engine connecting rod, subjected to a peak compressive force of 34,681.3 N (~ 35 kN), calculated from a maximum cylinder pressure (P_{max}) of 50 bar and a 94 mm bore.

To bridge the gap between lattice modeling and structural validation, the nTop (nTopology) platform was utilized to manage the complex geometry and its transition to Altair Optistruct for Finite Element Analysis (FEM). The optimization process was orchestrated via modeFRONTIER, starting with a Design of Experiments (DoE) phase to sample the parameter space (cell size and wall thickness). To minimize computational cost, surrogate models were trained to approximate mass and stress responses. According to the accuracy metrics (Table 1 of the project report), Gaussian Processes were employed for mass prediction ($R^2 = 0.99$), while H2O AutoML and Neural Networks were selected for stress estimation to better capture non-linear concentration phenomena.

The multi-objective Genetic Algorithm (MOGA-II) was executed with 3,000 evaluations to identify the Pareto-optimal configurations. The resulting optimal design was a Gyroid cell with a 4.3 mm dimension and a 0.5 mm wall thickness, the latter being the verified technological lower bound for stable LPBF processing. This configuration yielded a final mass of 614 g, achieving a 52.1% mass reduction compared to the original chrome-molybdenum steel component (1277.6 g).

Table 1 Metrics adopted for the trade-off evaluation and comparative assessment of the alternative configurations

Metric category	Evaluated metric	Description	Role in trade-off analysis
Environmental	Environmental impact	Assessment of material and process-related environmental burden	Sustainability evaluation
	Material utilization	Evaluation of powder/material usage efficiency	Resource optimization
Manufacturing	Process feasibility	Assessment of manufacturability constraints and production compatibility	Feasibility verification
	Process robustness	Evaluation of process reliability and failure susceptibility	Manufacturing reliability
Design	Lightweight performance	Assessment of mass reduction and structural efficiency	Product optimization
	Geometric optimization	Evaluation of design adaptability and configuration efficiency	Design performance
Multi-criteria	Overall trade-off balance	Combined assessment of sustainability, manufacturability, and performance	Final configuration selection

In line with the EcoDAM co-optimization philosophy, the design was not validated under nominal conditions alone. It was re-evaluated by integrating the "safety envelope" derived from the failure analysis in Sect. 4.2. These conditions are modeled by introducing variations in material properties (e.g., reduced yield strength and increased porosity) derived from the failure analysis, and are incorporated into the structural simulations to evaluate their impact on the mechanical response of the optimized design. Specifically, the Von Mises stress maps were scrutinized under conservative assumptions of yield strength reduction and increased effective porosity, typical degradation signatures of reused Ti6Al4V powders. This multi-pillar validation confirmed that while the optimized Gyroid structure remains structurally sound under moderate powder relaxation, more aggressive material degradation would require a compensatory shift in the triadic system, such as increasing the wall thickness to 0.6 mm or local geometric reinforcement.

These findings provide an operational validation of the framework, in which the feasibility of the proposed approach is assessed through the combined evaluation of environmental performance (GWP reduction), structural feasibility (stress distribution and mass reduction), and technical admissibility (failure-derived constraints). In this context, the feasible eco-design region is identified as the intersection of these performance dimensions.

This validation is based on the consistent integration of results obtained from the parametric LCA model, the failure analysis, and the structural optimization, rather than on a single performance indicator.

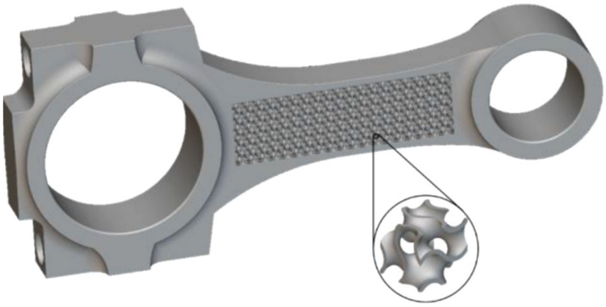
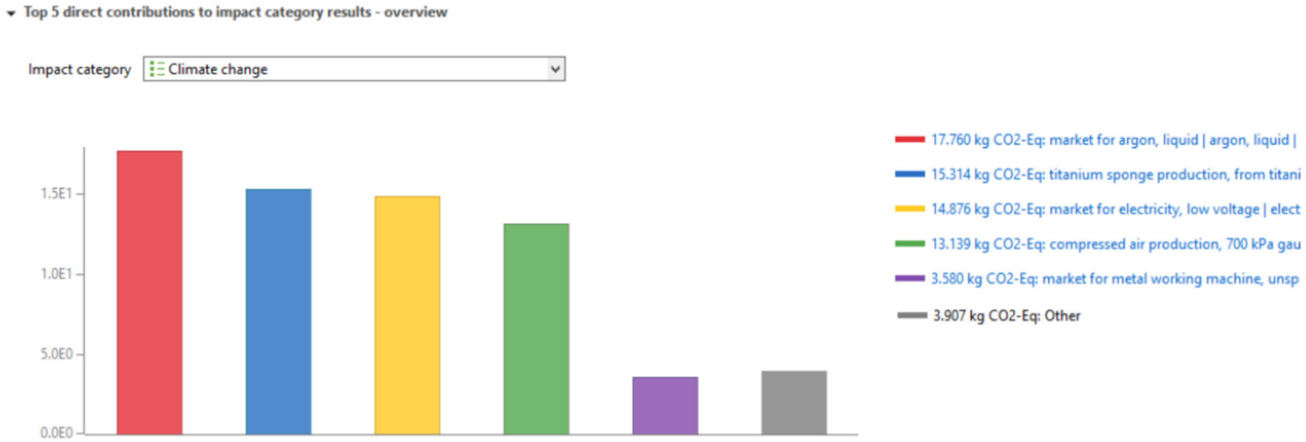


Fig. 4 Final connecting rod with gyroid cell detail [2]

It should be noted that this validation is based on numerical simulations under different material degradation scenarios and does not include direct experimental validation.

It is important to note that the parametric nature of the LCA model inherently allows the exploration of variability and sensitivity with respect to key process parameters (e.g., energy demand, argon consumption, yield). While a formal sensitivity analysis is beyond the scope of this study, the presented results already reflect the influence of these parameters across different configurations.

The final geometry of the optimized connecting rod, together with the Gyroid lattice configuration, is illustrated in Fig. 4.



Top 5 direct contributions to impact category results - overview

Impact category: Climate change

Fig. 5 Top 5 direct contributions to Climate Change

4.4 Integrated trade-off and feasible eco-design region

The integrated analysis demonstrates that sustainability in metal powder-based AM does not stem from a single-objective improvement but emerges from a bounded trade-off region defined by the intersection of environmental, technical, and structural performance metrics. The trade-off analysis is based on the combined evaluation of three main performance dimensions: (i) environmental impact, quantified through Global Warming Potential (GWP) derived from the parametric LCA model; (ii) technical feasibility, assessed through the Risk Priority Number (RPN) and admissibility constraints obtained from the FMEA-TRIZ analysis; and (iii) structural performance, evaluated in terms of mass reduction and stress distribution from the design optimization stage.

These metrics are calculated independently within the respective components of the framework and subsequently integrated through a comparative evaluation of alternative configurations, allowing the identification of feasible solutions that simultaneously satisfy environmental, technical, and structural requirements.

A purely environmental optimization, focusing solely on the Manufacturing Technology Configuration, would systematically prioritize the lowest-quality powder states (high recycling/reuse rates). While this approach minimizes the "market for argon" and energy hotspots (representing up to 85% of total GWP in the atomization phase), it simultaneously increases the Risk Priority Number (RPN). As shown in the FMEA-TRIZ analysis, such configurations elevate the likelihood of balling effects and internal porosity, which compromise the structural integrity of the final part.

Conversely, an exclusively structural or process-centric optimization favors conservative Powder Specification Configurations and narrow process windows. While this ensures mechanical reliability, the Contribution Tree for Climate Change (Fig. 5) reveals that such a restrictive approach fails to capitalize on the 15–30% GWP reduction achievable through controlled powder quality relaxation. This highlights the "burden-shifting" risk where isolated improvements in one dimension lead to environmental or technical penalties in the others.

The EcoDAM framework successfully identified a feasible eco-design region, an operational space where the Product Design Specification is satisfied through the coordinated adjustment of all triadic pillars. In this region:

- Powder quality is intentionally relaxed (e.g., using 30–50% recycled Ti6Al4V) only within the technically admissible bounds defined by the AI-supported failure analysis.
- The atomization and LPBF parameters are optimized via *fmincon* to minimize energy and argon intensity while maintaining melt-pool stability.
- The MOGA-II optimized Gyroid lattice compensates for the marginal reductions in yield strength, maintaining a 52.1% mass reduction (614 g) and stable performance under the 35 kN compressive load.

This case study provides an operational validation of the EcoDAM philosophy, proving that eco-design for AM must be addressed as a tightly coupled co-optimization problem. By integrating prospective LCA modelling, structured FMEA-TRIZ investigation, and advanced TPMS-based structural optimization, EcoDAM moves beyond fragmented approaches. It formalizes a new decision-making paradigm: the search for viable, high-performance solutions within an integrated, constraint-informed, and sustainability-oriented design space. While the analysis is based on a specific component and material system, the proposed workflow and decision logic are not case-dependent and can be transferred to other applications, materials, and additive manufacturing processes, provided that the corresponding Eco-Design Decision Context is properly defined.

4.5 Trade-off metrics and evaluation criteria

To support the comparison among the alternative configurations, a set of trade-off evaluation metrics was considered within the proposed framework. The assessment was performed by jointly analysing environmental, manufacturing, and design-related indicators in order to identify balanced solutions rather than optimizing a single objective.

In particular, the evaluation considered: (i) environmental impact indicators associated with the additive manufacturing process and material usage, (ii) manufacturability-related aspects, including process robustness and production feasibility, and (iii) design-oriented indicators related to lightweight performance and geometric optimization.

The alternative configurations were therefore compared through a multi-criteria trade-off analysis, where each solution was evaluated according to its capability to balance sustainability objectives, manufacturing constraints, and product performance requirements. This evaluation approach enabled the identification of configurations characterized by improved overall compromise among the considered objectives.

Table 1 summarizes the main metrics considered for the trade-off evaluation of the alternative configurations analysed within the proposed framework.

5 Conclusions

This work presented EcoDAM, an integrated eco-design framework specifically tailored to metal powder–based AM, and demonstrated its applicability through a full redesign of a Ti-6Al-4 V LPBF connecting rod. By conceptualizing sustainability as a triadic and tightly coupled system, linking technological parameters, powder quality, and lightweight design, the framework contributes to addressing the limitations of fragmented eco-design approaches and supports the systematic exploration of environmental-structural trade-offs. By integrating the parametric LCA model, the FMEA-TRIZ failure analysis, and the lattice-based structural optimization, the study suggests that sustainable and technically feasible solutions emerge when environmental impacts, manufacturability, and structural performance are jointly addressed within a unified design space.

While the present study focuses on a specific component, material, and process, the proposed framework is inherently general and can be extended to different materials, additive manufacturing technologies, and application domains. Its applicability depends primarily on the definition of the Eco-Design Decision Context and the availability of process- and material-specific data, rather than on the particular case considered.

In addition, the current implementation adopts a partial life cycle perspective mainly centered on upstream material production and manufacturing stages, and therefore the conclusions should be interpreted in relation to this modelling boundary and the assumptions underlying the parametric LCA.

The main insights that emerge from this study can be summarized as follows:

- Eco-design in metal AM is fundamentally a co-optimization problem, where material, process, and design decisions must be evaluated simultaneously rather than sequentially or independently.
- Powder quality relaxation is a powerful eco-design lever, but becomes viable only when constrained by failure-informed technical admissibility and balanced by compensatory process or design adjustments.
- Lightweight lattice optimization and environmental modelling must be jointly considered, as structural robustness at reduced mass depends on navigating the trade-offs emerging from both upstream powder production and downstream LPBF process stability.

Despite its comprehensive structure, EcoDAM remains dependent on the quality, completeness, and transferability of available knowledge on powder-process-part interactions. The parametric LCA model, while rigorous, abstracts several stages of powder production and does not yet incorporate machine-specific energy signatures or real-time process deviations. The FMEA-TRIZ analysis, though systematically structured, relies on qualitative judgement and variable availability of literature evidence. The structural validation, although multi-scenario, is based on a single component and a specific LPBF-Ti-6Al-4 V configuration, limiting the immediate generalizability of quantitative thresholds to other alloys, technologies, or geometries.

Future work will extend EcoDAM toward broader applicability and deeper integration of data-driven elements. This includes expanding the parametric LCA to multi-material and multi-technology contexts, strengthening its predictive capability through empirical datasets and machine-specific energy models. The failure investigation pillar will be enhanced through automated knowledge extraction pipelines and real-world process monitoring to reduce uncertainty in powder degradation mechanisms. On the design side, the integration of real-time melt-pool analytics, probabilistic structural methods, and adaptive lattice strategies will enable even more robust co-optimization. Ultimately, EcoDAM will evolve toward a fully digital, continuously learning decision-support environment capable of supporting industrial AM eco-design across diverse sectors and product families. Future work will also include a more systematic uncertainty and sensitivity analysis to further strengthen the robustness of the environmental assessment.

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Data availability The data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly archived datasets were generated or analyzed beyond those included in the article and its supplementary materials.

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