



## **INTEGRATING SUSTAINABILITY AND LIFE CYCLE ASSESSMENT INTO CAD-DRIVEN PRODUCT DESIGN: A SYSTEMATIC REVIEW OF FRAMEWORKS, ADDITIVE MANUFACTURING TRADE-OFFS AND INDUSTRY 4.0 ENABLERS**

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Open Access Research Journal of Science and Technology, 2026, 18(01), 126–141

Publication history: Received on 26 August 2026; revised on 02 October 2026; accepted on 05 October 2026

Article DOI: <https://doi.org/10.53022/oarjst.2026.18.1.0092>

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### **ABSTRACT**

With decarbonisation goals and new ecodesign regulations, life cycle assessment (LCA) is increasingly becoming a function of computer-aided design (CAD). This paper undertakes a systematic review following PRISMA 2020 statement of research related to integrating sustainability and LCA into CAD driven product design. Peer-reviewed journal articles and conference papers published from 2016 to 2026 were retrieved from the databases Scopus, Web of Science, IEEE Xplore and ScienceDirect (Google Scholar was used as a supporting database) and synthesized in a thematic synthesis. The evidence is presented in six streams: CAD–LCA integration frameworks; sustainable and generative optimisation; design for additive manufacturing (DfAM) and topology optimisation; process-parameter optimisation as a source for life cycle inventory (LCI) data; Industry 4.0 and digital twin (DT) based assessment; and social and organisational enablers of adoption. The review concludes that most of the life cycle impact occurs at the conceptual stage, and that tools for environmental assessment at the conceptual level are not sufficiently mature at the detailed design stage, when geometry and material are fixed. There is a constant dilemma between the material savings possible with topology optimisation and AM, and the extra energy needed to produce structures using these routes does not necessarily mean they have a smaller footprint. Experimental process-optimisation studies demonstrate that the choice of process parameters has a significant effect on the energy used, scrap produced and the consumption of tools, in the cases of machining, moulding, finishing and material-extrusion printing, but the results from these studies are generally not transferred to inventories to use in design tools. The social aspect and the conditions of organisation and skills for adoption, especially in developing economies are under-represented. There are six research priorities identified: uncertainty-aware early-stage LCA, joint material–energy optimisation in DfAM, process-parameter-linked inventory models, interoperability of CAD, LCA, product lifecycle management, and digital twin platforms, AI purpose-built for ecodesign, integration of social and circularity indicators. A closed-loop system which integrates design, assessment, process and operation data is suggested to inform future work, which can be layered.

**Keywords:** Life cycle assessment; Computer-aided design; Ecodesign; Design for additive manufacturing; Topology optimisation; Digital twin; Industry 4.0; Sustainable manufacturing; Systematic review

## 1 INTRODUCTION

Sustainability is now a primary need in product development. In the current context of regulatory measures like the European Union's Ecodesign for Sustainable Products Regulation (European Union, 2024), corporate net zero commitments and customer demand for their products to demonstrate environmental performance, manufacturers are now expected to demonstrate, not claim, that products perform well throughout the entire life cycle. A significant part of the life cycle impact of a product occurs before the first part is manufactured, as the choice of materials, geometry, manufacturing route etc. are determined during the design process, which is why this is the time when a lot of the impact can be committed (Tao et al., 2017; Kong et al., 2022). It has fostered a move from post-calculation to a whole design process approach to LCA, using existing CAD and computer-aided engineering (CAE) designed tools. Not only is the pressure at an industrialised nation.

Manufacturers in Zimbabwe and the Southern African region are encountering unreliable and expensive electricity, outdated plants and digital technology availability. The machined based industries are big consumers of electrical energy and experimental studies on honing; wood machining have demonstrated that simple selection of process parameters at planning stage can achieve measurable energy savings without compromising on the surface quality (Tayisepi et al., 2023; Tayisepi et al., 2024.). Concurrently, the uptake of Industry 4.0 technologies is also low and uneven among Zimbabwean manufacturers, which is limited by limited commitment, infrastructure and skills (Muhla et al., 2025a). Sustainability-oriented design tools also have to be evaluated in terms of both their technical level and their ability to be applied in environments with limited data, connectivity and expertise.

CAD driven design and sustainability are a combination of several research areas that have evolved in isolation so far: LCA methodology, design for additive manufacturing (DfAM) and topology optimisation, CAD/CAE, digital twin and Industry 4.0 infrastructure and artificial intelligence (AI) driven generative design. Each strand provides a different pathway toward the same goal: to provide environmental feedback to designers timely and actionable with a minimum disruption to existing workflows. Current reviews tend to focus on a single strand, such as LCA of additive manufacturing processes (Saade, Yahia and Amor, 2020; Kokare, Oliveira and Godina, 2023), life cycle engineering in DfAM (Favi et al., 2025) or digitally integrated sustainability assessment (Tschilttschke, Riedelsheimer and Lindow, 2024). There has been less focus on the intersections of the strands, how shop-floor process data can be utilized for assessment during the design process, and conditions for adoption in resource limited environments.

This paper addresses that gap through a systematic review of the literature at the intersection of these strands. It is guided by four research questions (RQs):

- RQ1: How is LCA methodologically and technically integrated with CAD-based product design workflows?
- RQ2: What role do DfAM, topology optimisation and process-parameter optimisation play in reconciling structural, functional and environmental performance?
- RQ3: How are Industry 4.0 technologies, particularly digital twins and AI, being applied to extend sustainability assessment beyond the design phase and beyond single-objective optimisation?
- RQ4: What gaps remain regarding the practical, validated deployment of sustainability-aware CAD tools across the full product life cycle, including in developing economies?

The contribution of the review is threefold. First, it provides a structured taxonomy of CAD-driven sustainability research across six streams. Second, it brings experimental process-optimisation evidence into the discussion as a largely untapped source of life cycle inventory (LCI) data. Third, it proposes a layered closed-loop framework and a research agenda that explicitly accounts for skills, organisational readiness and social sustainability.

## 2 BACKGROUND AND THEORETICAL FOUNDATIONS

### 2.1 Sustainability and life cycle assessment in product design

The choices made in the design process impact the use of materials, the energy used to manufacture the product, waste generated during use, and the product's end-of-life. Accordingly, sustainability is now a central component of the product development strategy. Research on LCSA indicates a growing interest in integrated environmental, economic and social assessment in the life cycle of the product, and analysis of 105 LCSA publications reveals that most publications focus on environmental indicators (for example, acidification, eutrophication), most papers on economic indicators (for example, costs, employment) and most papers on how the results are combined (multi-criteria decision analysis) (Visentin et al., 2020).

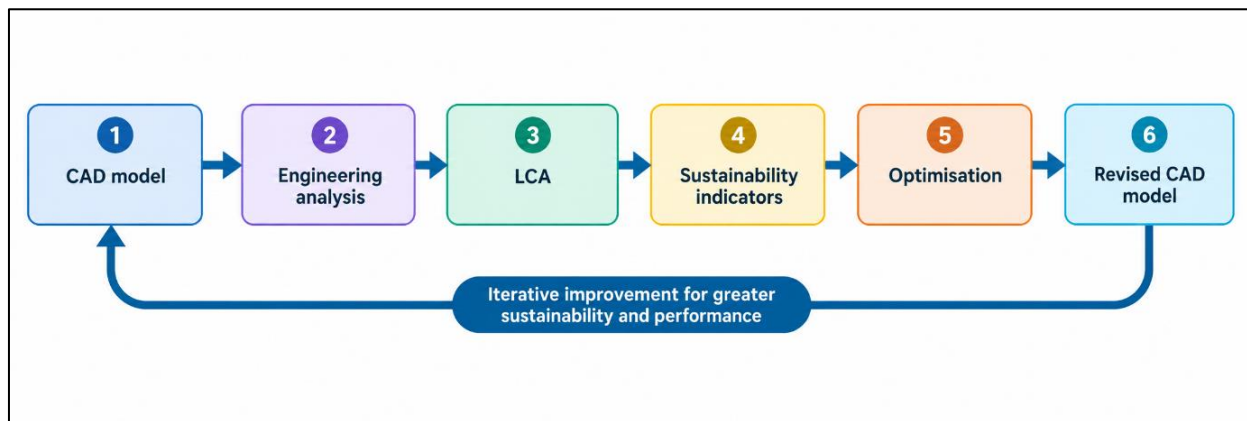
In some cases, however, within LCSA, the economic dimension is evaluated only from the producer's point of view, and end-of-life costs are only accounted for in a very small number of research studies (Padilla-Rivera et al., 2023). LCA is

the main tool to quantify the potential environmental impact of a product or a process. It consists of four phases are defined in ISO 14040 and ISO 14044: Goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006a; ISO, 2006b). The significance of LCA in design is to reveal the trade-offs between life cycle stages. Minimizing part weight, for instance, decreases material use, use-phase energy consumption when moving products, and can increase the energy use or less mature manufacturing process. The literature in recent years emphasizes the evaluation of the whole life cycle, not just the manufacturing stage (Visentin et al., 2020; Kokare, Oliveira and Godina, 2023).

## 2.2 CAD-LCA integration

CAD is no longer just a drawing tool. It can be combined with CAE techniques, like the finite element analysis (FEA) or computational fluid dynamics (CFD), to allow designers to consider other options without constructing a prototype; it contains much of the data required by LCA, including geometry, mass, material and, more and more, manufacturing characteristics. Tao et al. (2017) suggested a feature-based approach which maps the features of the product and the process defined in CAD to life cycle inventory data, enabling the retrieval of environmental information from existing CAD tools and the linkage of design decisions with the sustainability outcomes.

Tao, Li and Yu (2018) built upon this and combined LCA with CAD/CAE and optimisation tools, enabling environmental and functional performances to be evaluated simultaneously, which made environmental assessment a true part of the engineering optimisation process. CAD-integrated LCA tools for cradle-to-grave evaluation had been demonstrated to exist earlier (Morbidoni et al., 2012) and commercial CAD packages are now available with built-in screening tools, such as the sustainability module of SolidWorks (Popa and Popa, 2017); service CAD tools coupled with a life cycle simulator for product-service systems had been developed earlier (Komoto and Tomiyama, 2008). The resulting integrated design process may be symbolized as a loop of operations in which the CAD model is analysed for engineering performance, assessed with LCA, and represented as sustainability indicators and optimised before revision of the model (Figure 1). In this loop the environment becomes a design element, rather than a factor at the end of the design process.



**Figure 1: Iterative CAD-LCA integrated ecodesign loop. Adapted from the integrated LCA-CAD/CAE-optimisation approach of Tao, Li and Yu (2018) and the feature-based CAD-LCA linkage of Tao et al. (2017).**

## 2.3 Topology optimisation and design for additive manufacturing

Topology optimisation is a computational technique, which can be used to find the optimal distribution of material within a design domain that satisfies stiffness or strength criteria while using the minimum amount of material. There are three primary families, density-based, evolutionary and level-set formulations, all of which are necessary when accompanied by manufacturing constraints like minimum length scale, enclosed-void restrictions and overhang limits if the result is to be producible (El Khadiri et al., 2023). Topology optimisation can minimise material usage and the mass of a product and can incorporate environmental goals directly into the sustainable product design process. For example, Lu et al. (2019) optimized the structure of abrasive particles in oilstone components based on structural compliance and carbon emissions, which reduced the carbon emission by approximately 29% and structural compliance by approximately 39% from the traditional structure.

The fact that additive manufacturing (AM) can be used to fabricate the complex, organic geometries which are generated by topology optimisation makes the whole concept of DfAM very natural. DfAM covers the areas of part consolidation, material selection, build orientation, support structure and cellular or lattice structures (Alfaify et al., 2020). Laverne et al. (2019) demonstrated that resource usage during the early stages of AM-based design can be impacted by choices made and they applied topology optimisation to reduce resource use. Similarly Junk, Fleig and Fink (2017) used topology optimisation of an additively manufactured brake mount to enhance the brake's sustainability performance. The same design freedom is used at the university level: Tandi et al. (2025) designed a passive upper-limb exoskeleton

using SolidWorks, simulated it in ANSYS and optimized it for minimum mass, resulting in a total mass of 2.6 kg with a bill of materials cost of approximately US\$387, well below similar commercial devices. The lower the mass, however, the less it means the lower the impact. The sustainability value of AM-based part consolidation is complex and, as shown by Yang et al. (2019), is a function of both weight reduction and product life and functionality. Therefore, LCA would be required to assess this balance between weight reduction and the effect of the manufacturing route.

## 2.4 Industry 4.0 and digital sustainability

The Industrial Internet of Things (IIoT), simulation, data analytics and interconnected manufacturing systems offer product and process data that can be used to support sustainability assessment during production and use, which, in turn, can be leveraged for Industry 4.0 technologies. Product and process data generated by Industry 4.0 technologies such as the Industrial Internet of Things (IIoT), simulation, data analytics and interconnected manufacturing systems can support sustainability assessment during production and use. Ching et al. (2022) conducted a systematic review, identifying 15 sustainability functions of Industry 4.0 that beneficially impact sustainable manufacturing, covering resource efficiency, environmental performance and improved decision-making.

A fundamental part of this vision is digital twins; virtual copies of a real product or process that are linked to operational data (Huang et al., 2021; Soori, Arezoo and Dastres, 2023). Even if they are in the midst of being used for sustainable applications, their use is still largely tied to energy and resource efficiency, and not to the full life cycle impact (Ball and Badakhshan, 2022). The theoretical background for this review is thus based on sustainability science and LCA and on CAD/CAE, topology optimisation, DfAM, and Industry 4.0. These technologies enable the design process in which products are evaluated, modified, and updated prior to manufacture, and in more recent times, as evidence of manufacture and use. Further recent reviews have suggested improved integration, standardisation and automation of LCA in digital product-development environments (Kokare, Oliveira and Godina, 2023; Favi et al., 2025).

## 3 REVIEW METHODOLOGY

### 3.1 Research design

Designing the study was done in the form of a systematic literature review according to the PRISMA 2020 statement (Page et al., 2021). The review process took place in five stages: identification, screening, eligibility assessment, quality appraisal and data extraction and synthesis. Search strings, databases, and eligibility criteria were a priori formulated and the items and fields to be evaluated for the appraisals and extraction were defined to minimize selective reporting.

### 3.2 Search strategy

The main multidisciplinary databases used were Scopus and Web of Science. The IEEE Xplore was selected for its coverage of digital manufacturing and Industry 4.0, ScienceDirect for its focus on cleaner production and manufacturing systems and Grey literature and Google Scholar for regional and grey literature. The time frame of the search window was from January 2016 to September 2026, coinciding with the advent of the Industry 4.0, and the current sustainable manufacturing practice; earlier works were included only as a reference to seminal ones. Four sets of keywords (Table 1) were joined together using the boolean operators. All syntax was tailored for each database, and search dates, strings, filters and retrieved-record counts were recorded. Backward and forward citation tracking of included studies was used to identify additional records.

**Table 1: Keyword groups and representative search string.**

| Group               | Terms (combined with OR within groups)                                                                                                              |
|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| G1 Design           | "computer-aided design" OR CAD OR CAE OR "product development" OR "product design" OR ecodesign OR "eco-design"                                     |
| G2 Sustainability   | "life cycle assessment" OR LCA OR "life cycle sustainability" OR "carbon footprint" OR sustainab* OR "environmental impact"                         |
| G3 Design methods   | "topology optimi*" OR "generative design" OR "design for additive manufacturing" OR DfAM OR "additive manufacturing" OR "process parameter optimi*" |
| G4 Digital enablers | "Industry 4.0" OR "digital twin" OR IoT OR "smart manufacturing" OR "machine learning"                                                              |
| Core string         | (G1) AND (G2) AND ((G3) OR (G4)); targeted variants substituted G3 or G4 individually to test sensitivity                                           |

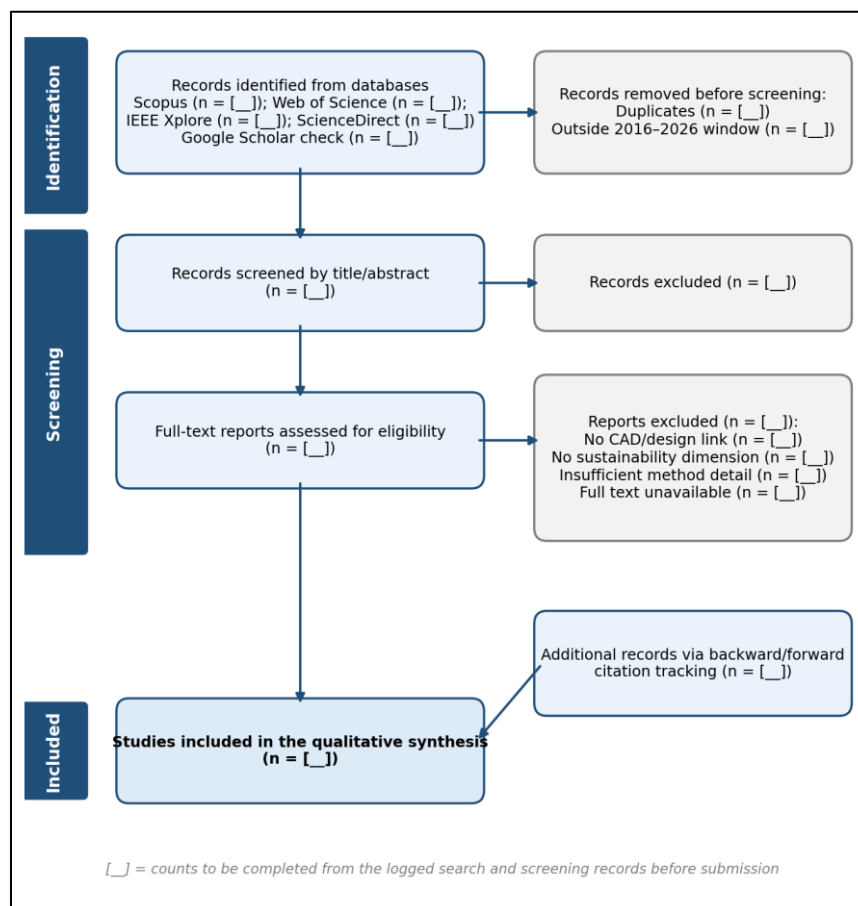
### 3.3 Eligibility criteria

Eligibility criteria are summarised in Table 2. Conference papers were considered where they added substantive value, for example where they reported an implemented framework or tool not yet published in a journal.

**Table 2: Inclusion and exclusion criteria.**

| Inclusion criteria                                                                                                                                                                                       | Exclusion criteria                                                                                                                                                            |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Peer-reviewed journal article or full conference paper in English, published 2016–2026 (seminal earlier works retained)                                                                                  | Editorials, opinion pieces, news items and other non-scholarly sources; duplicate records                                                                                     |
| Engages meaningfully with CAD-driven design, LCA or environmental performance, DfAM, additive manufacturing, topology or process optimisation, or Industry 4.0 applied to product or process development | No substantive connection to design or manufacturing; environmental studies with no link to products or processes; CAD-functionality studies with no sustainability dimension |
| Contributes to answering at least one research question                                                                                                                                                  | Insufficient methodological detail for quality appraisal, or full text unavailable                                                                                            |

### 3.4 Screening, quality appraisal and data extraction



**Figure 2: PRISMA 2020 flow diagram of the study selection process (template after Page et al., 2021). Record counts are to be completed from the logged search and screening records.**

All records from all sources were combined, deduplicated and screened on title and abstract using the criteria and then evaluated in full text. The results of the review are assigned to the flow in Figure 2. All studies that met the selection criteria were appraised in terms of objectives, method appropriateness, transparency, limitations and suitability of the LCA or sustainability method. Special focus was given to the variations in functional units, system boundaries and impact categories, and whether a DfAM and optimisation study quantified the environmental performance or considered it only conceptually.

The data that were extracted for each study were author and year, geographical context, CAD approach, methodology used for LCA, sustainability indicators, manufacturing process, optimisation technique, Industry 4.0 technology, key findings, limitations and identified gaps. The same was done for extraction and the results were used to identify whether the assessment took place at the conceptual or detailed design stage, and whether energy, waste and emissions data were measured, modelled or assumed.

### 3.5 Classification and synthesis

A thematic synthesis was used, not a summative synthesis, which involved summarising each study separately. Findings that differed were explained by differences in material, manufacturing technology, system boundary, energy mix, and product-lifetime assumptions, so as to differentiate true lack of consensus from lack of consensus that is merely a function of how it was captured. The literature was considered as falling into six streams (Table 3), that is the structure of Section 4.

**Table 3: Taxonomy of the reviewed literature.**

| Stream                                     | Representative methods                                                   | Main contribution                                                 | Main limitation                                             |
|--------------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------|
| S1 CAD–LCA integration                     | Feature-based LCA, parametric LCA, voxel mapping, CAD-embedded screening | Early environmental feedback and traceability to geometry         | Data mapping and interoperability; weak at conceptual stage |
| S2 Sustainable and generative optimisation | Topology and multi-objective optimisation, generative ecodesign          | Simultaneous performance, material and environmental optimisation | Objective weighting; computational cost                     |
| S3 DfAM and AM sustainability              | Lightweighting, lattices, part consolidation, build orientation          | Uses AM design freedom to reduce material and add function        | Energy, support and post-processing impacts                 |
| S4 Process-parameter optimisation          | Taguchi DOE, ANOVA, grey relational analysis                             | Quantifies how settings change energy, scrap and tool use         | Rarely converted into LCI data or linked to CAD             |
| S5 Industry 4.0 and digital twins          | IoT, PLC/OPC, multi-agent systems, ML, dynamic LCA                       | Automated data acquisition and in-use assessment                  | Data governance, interoperability, maturity                 |
| S6 Social and organisational enablers      | Human factors, circular design, agility, learning factories              | Addresses social pillar and adoption capacity                     | Fragmented and weakly quantified                            |

## 4 CLASSIFICATION AND SYNTHESIS OF THE EVIDENCE

### 4.1 Overview of the evidence base

In terms of literature included, the majority of the papers are reviews and methodological proposals published since 2019, and the number of papers related to digital twin and AI has significantly risen since 2023. Representative studies have been summarised in each stream, their approach and their main findings in Table 4. There are three highlights. First, most CAD–LCA frameworks have been shown in the case of individual components or assemblies of components, not in the case of a product. Second, AM sustainability studies differ primarily due to the differences in system boundary, utilisation of machines, and part geometry and not due to the technology itself. Third, responses related to energy, scrap and tool-wear from experimental process-optimisation studies, many of which have been drawn from developing-economy settings, are given that relate directly to the responses of interest to LCI and are not generally referenced in LCA literature.

**Table 4: Representative studies by stream.**

| Study                   | Stream | Approach                                             | Principal finding                                                              |
|-------------------------|--------|------------------------------------------------------|--------------------------------------------------------------------------------|
| Tao et al. (2017)       | S1     | Feature-based life cycle modelling linked to CAD     | LCI data can be retrieved from CAD features, linking design choices to impacts |
| Tao, Li and Yu (2018)   | S1     | LCA integrated with CAD/CAE and optimisation         | Environmental and functional performance evaluated simultaneously              |
| Bernstein et al. (2020) | S1     | Automated workflow via standard reference models     | Impact indicators respond to parametric design changes                         |
| Vernica et al. (2023)   | S1     | Voxel-based mapping of LCI onto CAD models           | Environmental hotspots visualised within product geometry                      |
| Kong et al. (2022)      | S2     | Life cycle-integrated conceptual design model        | Function–structure–material–process relations enable early optimisation        |
| Lee et al. (2025)       | S2     | Generative design with ecodesign workflow            | 153 solutions from 50 materials screened on carbon emissions                   |
| Lu et al. (2019)        | S2     | Bi-level topology optimisation with carbon objective | Compliance and carbon reduced by about 39% and 29%                             |
| Favi et al. (2025)      | S3     | Review of 87 LCE–DfAM studies                        | Weight reductions of 15.5–80%; LCE and DfAM remain weakly integrated           |
| Faludi et al. (2017)    | S3     | LCA of selective laser melting                       | Electricity use and machine utilisation dominate impacts                       |
| Pusateri et al. (2024)  | S3     | Review of metal AM sustainability                    | Benefits mainly for complex, high-value parts                                  |
| Tayisepi et al. (2024)  | S4     | Taguchi L16 honing experiments                       | Distinct optima for surface finish, power and total energy                     |
| Mapindu et al. (2026c)  | S4     | Taguchi–ANOVA–GRA for FDM                            | Infill density drives strength; layer height drives print time                 |
| Winter et al. (2025)    | S5     | Integral digital twin for product carbon footprint   | 31% electricity saving per component in case study                             |
| Mashava et al. (2026)   | S5     | Multi-agent condition monitoring with PLC/OPC        | Autonomous fault detection in a resource-constrained plant                     |
| Falsafi et al. (2025)   | S6     | Review of LCA in circular design                     | AM appears in only about 2% of circular-design LCA studies                     |

#### 4.2 CAD–LCA integration frameworks (RQ1)

There has been continued interest in the literature of incorporating LCA into CAD, to ensure that environmental considerations are considered at the earliest stage possible. CAD gives much of the information that an LCA needs, such as geometry, mass, material assignment and to some extent manufacturing processes (in feature-based systems). Tao et al. (2017) illustrated that such CAD features can be correlated with LCI data, which can be used to provide environmental information to designers during development and help designers make comparisons for alternatives before adopting the final design. Tao, Li and Yu (2018) adapted the concept to CAD/CAE and optimisation, and suggested that environmental assessment may be a tangible part of engineering optimisation.

Bernstein et al. (2020) presented an automated workflow that connects manufacturing process information with a parametric design software, enabling response to design parameters through impact indicators, via normal reference models. Vernica et al. (2023) have recently been able to map process-based LCI data onto CAD models at a voxel resolution ranging from part level to individual volume elements, enabling designers to visualize environmental hotspots as they were embedded within the CAD model. In spite of all this development CAD and LCA are still perceived as two distinct disciplines. According to a systematic review carried out by Tschiltschke, Riedelsheimer and Lindow (2024), only few approaches connect the design characteristics directly to life cycle impacts over the entire life cycle.

This means that design changes can give rise to other constraints: a lighter product designed with thinner parts and a lower density material can have a shorter useful life elsewhere, and the lower density material can have a higher production cost. What's really important is not whether or not LCA can be integrated into CAD software, but whether or not it can give feedback in the iterative design process in a timely and reliable manner. Automated LCA, in which the design and process parameters create assessments with limited manual activity, is identified by Naser et al. (2023) as an emerging topic and the authors suggest a framework based on machine learning and product–process co-design. This is in support of the shift from post design sustainability assessment to design development sustainability assessment.

The second is stage mismatch. Except for a few CAD–LCA tools, such as those available as commercial screening modules (Popa and Popa, 2017), they need a defined geometry and material; therefore, they are used at the detailed-design stage. Simplified or approximate methods are primarily used in the conceptual stage, which involves making functional architecture and principal material and process decisions. Kong et al. (2022) demonstrated that optimisation opportunities can be identified at the conceptual design stage of a life cycle-integrated model, which takes the interrelationships between function, structure, material and process; in the built environment, LCA is similarly faced with a trade-off between speed and uncertainty (Kumar et al., 2025). Not many product design studies explicitly quantify that uncertainty.

### 4.3 Sustainable optimisation and generative design (RQ2)

Optimisation plays a crucial role in sustainable design, since designers must solve multi-objective trade-offs: weight could be reduced, but at the cost of geometric and/or process complexity. So sustainable design problems must have structural performance and manufacturability limitations as well as environmental goals. Lu et al. (2019) showed that it is possible to directly incorporate carbon emissions as an objective function in topology optimisation by using a game-theoretic bi-level formulation. Parametric LCA has also been proposed as a potential method for product level optimization of discrete products since impact indicators are functions of the same parameters that are used to model the CAD model (Bernstein et al., 2020).

The extension of this is generative design, which generates a number of candidate geometries, instead of improving one. Lee et al. (2025) suggested a seven-step generative ecodesign framework which considers material, manufacturing process and geometry; using this framework, 50 materials were screened, through both additive and subtractive pathways, across formative routes and 153 viable solutions were generated and assessed for cradle-to-grave carbon emissions in the context of a bicycle handlebar stem. Sikandar et al. (2026) consider the combination of multi-objective optimisation and smart manufacturing as the convergence of generative AI for sustainable product design. Both of them have potential, but objective weighting remains a subjective judgement, and the number of computations increases rapidly if LCA is considered as part of the optimisation process. Structural optimisation is also routinely applied in applied engineering design, typically without a stated environmental goal, in developing-economy context. Three designs of the exoskeleton were modeled and analyzed in ANSYS, with nylon chosen for the rack-and-pinion mechanism due to its performance and lower cost, even though the carbon fibre version had a higher factor of safety (2.1 compared to 1.38).

To implement a low cost dual mode smart wheelchair with an aluminium structure with a load capacity of 150 kg, Munotyaani et al. (2026) employed a systematic approach of functional decomposition, concept development and concept selection. Muyambo et al. (2025) applied a systematic approach including aerodynamic analysis, CFD and prototyping to design a vertical axis wind turbine for harvesting vehicle slipstream energy for electric-vehicle charging. The studies demonstrate that concept selection with CAD/CAE is already practiced in engineering; a simple LCA or carbon indicator integration to this concept selection matrix would be a low-cost implementation step towards the integrated loop in Figure 1.

### 4.4 Additive manufacturing and DfAM: the material–energy trade-off (RQ2)

The research of part consolidation and material selection, build orientation, support type and use of cellular structures (Alfaify et al., 2020), which are related to DfAM, has seen an increased interest due to the development of AM processes, as has been the case with optimisation methods (El Khadiri et al., 2023; Su et al., 2024). The mass of a cantilever part was reported to be reduced by 40–61% using topology, honeycomb optimisation or lattice optimisation respectively, for laser powder bed fusion (LPBF) (Nyamekye et al., 2024).

Favi et al. (2025) reviewed 87 studies relating to LCE and DfAM, and reported that topology and generative optimisation can reduce weight by 15.5–80%, but also that LCE and DfAM are not strongly connected and that integrated environmental–economic studies are not consolidated. As has been found in previous reviews, many LCA studies of AM involve limited social and economic considerations, do not include downstream processes and recycling, or the impact of quality and mechanical properties (Saade, Yahia and Amor, 2020; Kokare, Oliveira and Godina, 2023; Hegab et al., 2023). The prevailing opinion is that AM is not necessarily more sustainable than traditional manufacturing. Although

AM can reduce waste and lighter parts, the impact on the life cycle could outweigh that of the conventional routes due to the high energy demand during the process, loss of material, support structures, and long build time and post-processing. Faludi et al. (2017) concluded that the effects of selective laser melting are strongly related to electricity use, machine use and not to the machine or the powder.

For polymer powder bed fusion, up to 44% scrap rate were reported by Favi et al. (2025). Wire-and-arc AM (WAAM) had an environmental impact per kilogram of stainless steel product that was similar to the green sand casting process, and Bekker and Verlinden (2018) concluded that that fair comparisons between the two manufacturing processes requires designs optimised for each process route. Pusateri et al. (2024) concluded that metal AM has potential to reduce overall impacts, mainly for complex, high value components, in the aerospace and automotive field, whereas conventional manufacturing processes are preferred for simpler components. Shah et al. (2024) also found that while environmental impacts are achievable, they are not easily scalable, and AM is economical predominantly at small-scale. Because of this, environmental performance is dependent on the application and should not be judged on its own, but rather in relation to the product being produced. This trade-off includes process parameters at machine level.

About 69% of the variance in the average tensile strength of PLA was explained by the infill density parameter and around 52% of the variance in the average print time for PLA was explained by the layer height parameter for fused deposition modelling (FDM) experiments carried out by Mapindu et al. (2026c) using a Taguchi L9 array, with repeated ANOVA and grey relational analysis. The strength and print-time optimas were in conflict for three of four parameters. At the process level, the finding spells out, following LCA reviews, the same material–energy tension that they identified at the system level, where print time is directly proportional to machine energy.

#### **4.5 Process-parameter optimisation as a source of life cycle inventory data (RQ2)**

There is also a body of experimental work which is less frequently related to the CAD–LCA literature that deals with the optimisation of manufacturing process parameters. The studies quantify energy saving, scrap, tool life and consumables, the very flows that an LCI needs to measure. Tayisepi et al. (2024) used a Taguchi L16 design to optimise the dry honing of cast iron cylinder relining sleeves, concluding that spindle speed and tool-path radius had a significant impact on power, energy and surface texture, while depth of cut had a significant impact on energy but not surface texture; some energy-optimal combinations differed from some surface-optimal combinations and the authors explicitly suggested connecting their results to an environmental impact assessment.

For teak, saligna and pine, Tayisepi et al. (2023) demonstrated that the number of cutting knives and the depth of cut affect the total cutting energy and surface quality, each of which is species specific. For CNC milling of mild steel, the results indicated that the choice of the parameters directly affects the tool consumption per part, as explained about 83% and 63% of the variation in surface roughness and flank wear, respectively (Mapindu et al., 2026b). The same applies to the structure and manufacturing of forming and processing industries. A similar study by Mapindu et al. (2026a) revealed that the shrinkage resulted from injection moulding accounted for approximately 67% of the variation and an optimum injection pressure was found to decrease mean shrinkage from 1.55% to 0.64% and warpage from 0.85 mm to 0.32 mm, thereby lowering the amounts of scrap and rework. In another study on optimizing the welding parameters, current and arc voltage were determined as the most crucial factors (Mapindu et al., 2026d). Jansen et al. (2025) were able to reduce the amount of bleaching earth used to 12.5 kg per batch or less of edible-oil refining by using designed experiments and predictive modelling, which directly reduced the consumables used.

Both share a methodological backbone (orthogonal arrays, analysis of variance and grey relational analysis), and both result in parameter–response models that can be applied as process specific inventory functions in CAD–LCA tools. Currently, however, they are being reported as quality and cost studies and their environmental significance remains implicit. If they were transformed into LCI models, such as energy removed per volume or scrap rate as a function of settings, then, design-stage LCA would have a much firmer foundation than the generic averages in databases, especially for processes and energy mixes that are not well represented in the commercial databases.

#### **4.6 Industry 4.0, digital twins and dynamic LCA (RQ3)**

The use of Industry 4.0 technologies provides a way to reinforce the link between CAD, manufacturing and sustainability assessment. The use of digital twins, simulation, AI and data analysis may enable sustainability information to be updated with the CAD model changing and as the product is manufactured and utilised. There are a number of recent studies in this direction. Winter et al. (2025) suggested an integrated digital twin approach which connected digital twins from various life cycle stages in a common data space and calculated product carbon footprints from product, process, machine and factory perspectives, achieving a 31% reduction in electricity per component in a case study. Piron et al. (2025) correlated the ISO 23247 digital twin framework with the phases of ISO 14040 LCA, and applied soft sensors to estimate extrusion energy, demonstrating that an adjustment of operation parameters could reduce the GWP up to 16.4% and the eco-design material selection up to 48.7%.

Riedelsheimer, Seegrün and Lindow (2025) showed digital twins for real-time, product-level LCA in automotive and orthosis applications, while Wehking et al. (2024) reviewed the application of digital twins in sustainability initiatives from an LCA point of view. Riedelsheimer, Seegrün and Lindow (2025) presented a digital twin for real-time, product-level LCA in automotive and orthosis applications and Dos Santos, Wooley and Romano (2026) reviewed the use of digital twins in sustainability initiatives from an LCA point of view. The potential and the conditions of such an approach are demonstrated in resource-poor contexts. Mashava et al. (2026) applied a multi-agent condition-monitoring setup to the copper cable manufacturing plant of a company in Zimbabwe that uses an induction furnace to melt copper, using sensors based on infrared temperature, flow and conductivity measurements, a Siemens S7-1200 PLC, an OPC server and JADE agent platform to perform autonomous fault detection/notification.

Based on 13 years of operating data of a coal fired power station, Senda et al. (2026) developed a random forest model for the purpose of preventive maintenance planning, where it was observed that approximately 72% of the strategy mix was being used for corrective maintenance and an optimum reliability region of around 66% was found to achieve a balance between failure occurrences and maintenance cost. The environmental impacts are not calculated in either study, but both lay the foundations for the data pipelines (sensor networks, industrial communication standards, historical data bases and trained models) whereupon dynamic LCA in use depends. Adding impact assessment agents or carbon accounting components are logical next steps in such architectures.

It is not enough to integrate software. Consistent LCI data, compatible data structure and clearly defined system boundaries are required to be able to assess reliably. Favi et al. (2025) concluded that the LCE approaches used in the context of AM are still disjointed, and Ball and Badakhshan (2022) reported that there is relatively little research in the academic field on sustainability-oriented digital twins compared to industry. The design-for-assessment-later approach is supported in the literature by the design-for-assessment-simultaneously approach, however, the supporting data infrastructure is less developed, and is weaker where the adoption of Industry 4.0 is lower (Muhla et al., 2025a).

#### 4.7 Social and organisational dimensions (RQ3 and RQ4)

The social sustainability aspect is the least developed one in the literature. The use of social indicators is generally not considered in LCSA studies, and in circular-design LCA, the product's lifespan is included in only approximately 11% of the studies (Visentin et al., 2020; Falsafi et al., 2025). However, CAD-based design has social impact. In Zimbabwean manufacturing, a survey of 87 respondents by Muhla et al. (2025b) revealed that workplace accidents were significantly decreased due to ergonomic design, and recommended the inclusion of human factors engineering in manufacturing. Tandi et al. (2025) have designed an exoskeleton to mitigate musculoskeletal load in construction tasks, while Munotyaani et al. (2026) have created a smart wheelchair for enhancing accessibility and independence for individuals with disabilities. Design-stage criteria for worker safety, ergonomics and accessibility might be stated by the same means as carbon, but none of the reviewed CAD–LCA frameworks does.

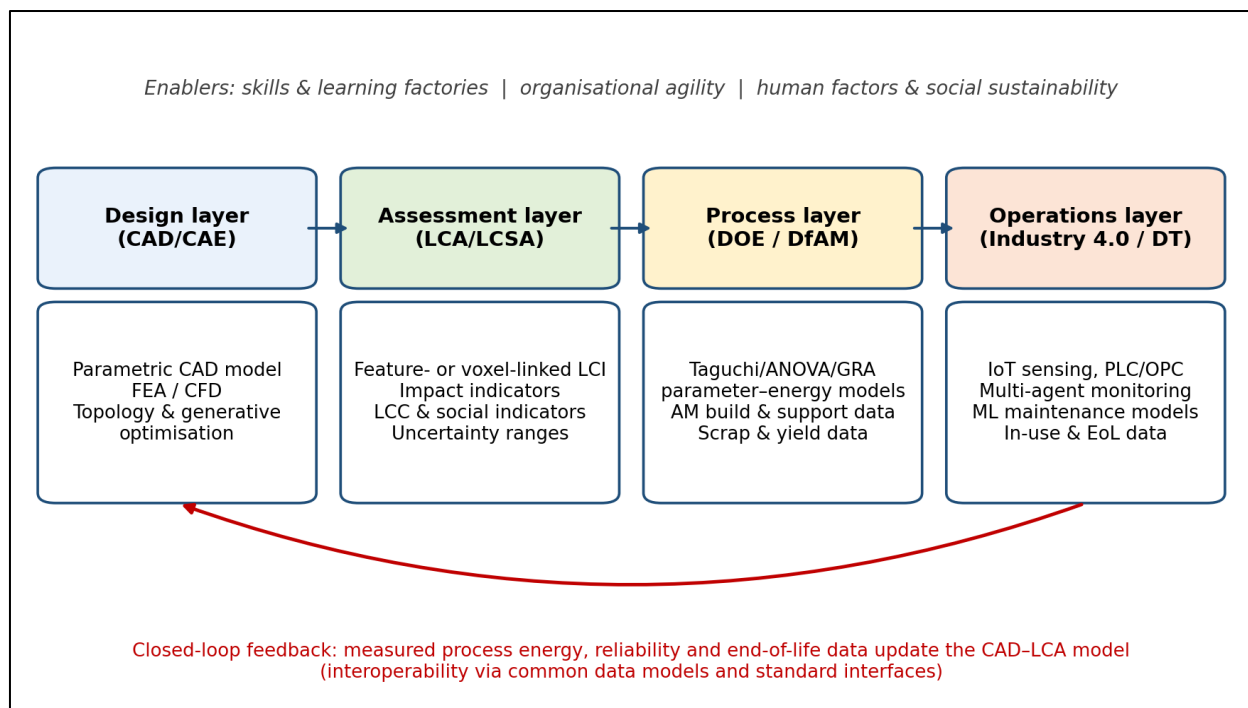
Whether sustainability-aware tools are adopted is determined by the organisational and skills factors. Muhla et al. 2025a found that shortage of skilled personnel, poor infrastructure and lack of commitment were the primary challenges for implementing Industry 4.0 in Zimbabwean manufacturing; while Muhla et al. 2023 indicated that agility, or the ability to adapt rapidly to evolving needs, is a strategic imperative for manufacturers in dynamic market environments like the COVID-19 pandemic. Another limitation is the capacity for skills development. Ndiyamba et al. (2026) found that only in South Africa there are learning factories in place and recommended a framework for the introduction of learning factories across the Southern Africa region that could ensure the transfer of knowledge between theory and industrial practice, especially in the fields of automation and digital manufacturing. CAD/CAE, AM, sensors and LCA software would be useful in a learning factory to give a practical environment in which designers become accustomed to using environmental data as a design variable.

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## 5 DISCUSSION

### 5.1 Cross-cutting insights

There are four insights that come out from all six streams. First, none of the strategies, whether lightweighting, topology optimisation or additive manufacturing, can ensure a reduction in environmental impact. Outcomes are dependent on the interaction of geometry, material, process energy, utilisation and product lifetime and hence CAD-based design processes should employ multi-objective optimisation based on geometry, material, structural performance, manufacturing energy, cost and life cycle impacts. Second, the weakest element in current CAD–LCA tools is not the impact-assessment method, but the inventory: the values in the generic databases do not account for the changes in energy and scrap with parameter choice for a specific machine.



**Figure 3: Proposed layered closed-loop framework for sustainability-aware CAD-driven design, synthesised from the reviewed literature (authors' own elaboration).**

This can be overcome by experimental process optimisation studies if they are presented in a consumable form by LCA tools. Third, digital twins and IIoT architectures provide the means to close the loop between design and use, but they are mainly oriented towards operational performance, and sustainability is seldom a primary, explicit objective. Fourthly, the social dimension and the organisational conditions for adoption are considered context instead of design variables. These learnings are combined into the cross-over closed loop system shown in Figure 3. The design layer creates and optimizes geometry, the assessment layer adds inventory and impact indicators such as cost and social indicators (with uncertainty ranges), the process layer provides inventory functions (based on designed experiments and DfAM build data) and the operations layer provides measured data on energy, reliability and end-of-life from sensors, multi-agent monitoring and machine learning models. Feedback to the design and assessment layers comes from the operations layer and the skills, organisational agility and human factors layers are present as enablers in all layers.

## 5.2 Implications for practice and for developing economies

In practice, the results indicate three simple actions to help practitioners. The first is to incorporate an LCA or carbon indicator into current concept-selection and CAE processes and wherever possible to leverage CAD-integrated screening tools. The second is to report the process optimisation experiments in physical units, which can be used as inventory data for the second time. The third is to consider the condition-monitoring and maintenance-analytics infrastructure as a sustainability asset, as well as a reliability asset. The evidence for developing economies however indicates that the main challenges are data and skills and infrastructure, and not method. Therefore, frameworks that can be implemented on low-tech equipment, with process data from local measurements and with regional energy supply are more useful than complex frameworks based on an advanced Industry 4.0 infrastructure. University laboratories and learning factories can be demonstrators and also sources of regionally relevant inventory data.

## 5.3 Limitations of the review

The review is limited. Only literature in English language was searched, and literature relevant for the region might be indexed by Google Scholar only or not be indexed at all. Since 2023, the number of publications on AI and digital twin has been increasing rapidly and some newer publications might not have been captured. Due to the lack of uniformity in functional units, system boundaries and impact categories, quantitative meta-analysis was not possible and the synthesis is therefore qualitative. Thirdly, the addition of experimental process optimisation studies as a source of insight into inventory is an interpretive contribution of this review; such studies were not primarily used to report environmental impacts.

## 6 RESEARCH GAPS AND FUTURE DIRECTIONS

Six research priorities emerge from the synthesis. They are summarised in Table 5 and described below.

- **Uncertainty-aware early-stage LCA.** CAD–LCA integration is strongest at the detailed design stage, yet the greatest opportunity for impact reduction lies at the conceptual stage, where uncertainty is highest. Streamlined, uncertainty-quantified assessment methods calibrated for low levels of design detail remain underdeveloped (Kong et al., 2022; Tschiltschke, Riedelsheimer and Lindow, 2024).
- **Joint material–energy optimisation in DfAM.** Topology optimisation and AM reduce material use but can increase energy demand through geometric complexity, support structures and long build times. Multi-objective frameworks that optimise jointly for mass, energy and manufacturability, rather than mass alone, are only beginning to emerge (Favi et al., 2025; Mapindu et al., 2026c).
- **Process-parameter-linked inventory models.** Designed-experiment results for machining, finishing, moulding and printing should be converted into reusable inventory functions and linked to CAD features, as recommended in the honing study of Tayisepi et al. (2024).
- **Interoperability between CAD, LCA, PLM and digital twin platforms.** Commercial ecodesign tools and research CAD–LCA frameworks remain largely disconnected from digital twin infrastructure, limiting the ability to feed in-use and end-of-life data back into design decisions (Winter et al., 2025; Piron et al., 2025).
- **AI purpose-built for ecodesign.** Generative and machine learning methods are currently oriented towards structural and operational performance. Models trained on life cycle data, with transparent objective weighting, are needed (Naser et al., 2023; Lee et al., 2025; Sikandar et al., 2026).
- **Social, circularity and adoption dimensions.** Design-for-disassembly and circularity methods are individually mature but inconsistently integrated with CAD-native workflows, and social indicators such as ergonomics, safety and accessibility are largely absent. Capacity-building models such as learning factories deserve evaluation as adoption mechanisms (Falsafi et al., 2025; Muhla et al., 2025b; Ndiyamba et al., 2026).

**Table 5: Research gaps and proposed research actions.**

| Gap                       | Evidence from the review                  | Proposed research action                                                  |
|---------------------------|-------------------------------------------|---------------------------------------------------------------------------|
| Early-stage LCA           | Tools require fixed geometry and material | Probabilistic, surrogate-based LCA for conceptual design                  |
| Material–energy trade-off | Mass savings offset by process energy     | Multi-objective TO/DfAM with energy and utilisation models                |
| Process-linked LCI        | Parameter–energy data not reused in LCA   | Standardised reporting; LCI functions embedded in CAD/CAM                 |
| Interoperability          | CAD, LCA, PLM and digital twins siloed    | Common data models via OPC UA, ISO 23247 and PLM links                    |
| AI for ecodesign          | AI optimises performance, not impact      | Generative models trained with life cycle objectives                      |
| Social and adoption       | Social pillar and skills rarely addressed | Social indicators in CAD; learning-factory pilots in developing economies |

## 7 CONCLUSIONS

In this systematic review the authors analysed the current state of integrating sustainability and LCA into CAD-driven product design. The second question asked by the researchers was RQ1: How is LCA being increasingly integrated into CAD environments, either in form of feature-based, parametric and geometry-linked approaches? In response, LCA is more integrated at the detailed design stage than at the conceptual stage, while design decisions at the conceptual stage have the highest environmental leverage. Topology optimisation and DfAM also offer significant and established savings in material, but some of the energy saved is also required to be spent on the process, supports and post processing, which means that lightweighting is not the same as energy saving but needs to be co-optimised to achieve both.

Energy, scrap and tool consumption is dependent on the settings; experimental process-parameter optimisation demonstrates how these change, and is an under-used source of inventory data. Digital twin and multi-agent monitoring and machine learning are the active frontier in response to RQ3 and offer the source of pipeline data for dynamic LCA; however, they are more focused on operational performance than on sustainability as an explicit goal. To answer RQ4, six research gaps were found across uncertainty in early stages, material–energy trade-offs, process related inventory,

interoperability, AI in ecodesign, and social and adoption factors. CAD for sustainability assessment is shifting from a hindsight, compliance-based exercise to a predictive design-time exercise, overall. The transition is disjointed between disciplines, software ecosystems and life cycle phases; and is least developed in areas characterised by limited availability of data, infrastructure and skills. It will need deliberate methodology, data and standardisation development and capacity building to develop into a whole life cycle coherent design practice.

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## STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

### *Acknowledgments*

We acknowledge the Department of Industrial and Manufacturing Engineering Department of the National university of Science and Technology.

### *Funding Source*

The authors contributed to the funding of the publication of the paper.

### *Disclosure of conflict of interest*

There is no conflict of interest.

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## REFERENCES

- [1] Alfaify, A., Saleh, M., Abdullah, F.M. and Al-Ahmari, A.M. (2020) 'Design for additive manufacturing: a systematic review', *Sustainability*, 12(19), 7936. Available at: <https://doi.org/10.3390/su12197936>.
- [2] Ball, P. and Badakhshan, E. (2022) 'Sustainable manufacturing digital twins: a review of development and application', in *Sustainable Design and Manufacturing: Proceedings of the 8th International Conference on Sustainable Design and Manufacturing (KES-SDM 2021)*. Singapore: Springer, pp. 159–168. Available at: [https://doi.org/10.1007/978-981-16-6128-0\\_16](https://doi.org/10.1007/978-981-16-6128-0_16).
- [3] Bekker, A.C.M. and Verlinden, J.C. (2018) 'Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel', *Journal of Cleaner Production*, 177, pp. 438–447. Available at: <https://doi.org/10.1016/j.jclepro.2017.12.148>.
- [4] Bernstein, W.Z., Tensa, M., Pranievicz, M., Kwon, S. and Ramanujan, D. (2020) 'An automated workflow for integrating environmental sustainability assessment into parametric part design through standard reference models', *Procedia CIRP*, 90, pp. 102–108. Available at: <https://doi.org/10.1016/j.procir.2020.02.058>.
- [5] Ching, N.T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P. and Asadi, S. (2022) 'Industry 4.0 applications for sustainable manufacturing: a systematic literature review and a roadmap to sustainable development', *Journal of Cleaner Production*, 334, 130133. Available at: <https://doi.org/10.1016/j.jclepro.2021.130133>.
- [6] Dos Santos, C.H., Wooley, A. and Romano, A.L. (2026) 'Digital twins in sustainability initiatives: a review from life cycle assessment perspective', *IEEE Access*, 14, pp. 7062–7078.
- [7] El Khadiri, I., Zemzami, M., Nguyen, N.-Q., Abouelmajd, M., Hmina, N. and Belhouideg, S. (2023) 'Topology optimization methods for additive manufacturing: a review', *International Journal for Simulation and Multidisciplinary Design Optimization*, 14, 12. Available at: <https://doi.org/10.1051/smdo/2023015>.
- [8] European Union (2024) 'Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products', *Official Journal of the European Union*, L, 28 June.
- [9] Faludi, J., Baumers, M., Maskery, I. and Hague, R. (2017) 'Environmental impacts of selective laser melting: do printer, powder, or power dominate?', *Journal of Industrial Ecology*, 21(S1), pp. S144–S156. Available at: <https://doi.org/10.1111/jiec.12528>.
- [10] Falsafi, A., Togiani, A., Colley, A., Varis, J. and Horttanainen, M. (2025) 'Life cycle assessment in circular design process: a systematic literature review', *Journal of Cleaner Production*, 521, 146188. Available at: <https://doi.org/10.1016/j.jclepro.2025.146188>.
- [11] Favi, C., Murgese, L., Villazzi, N., Gallozzi, S., Mandolini, M. and Marconi, M. (2025) 'Integrating life cycle engineering into design for additive manufacturing: a review', *Journal of Manufacturing Systems*, 82, pp. 599–631. Available at: <https://doi.org/10.1016/j.jmsy.2025.07.010>.

- [12] Hegab, H., Khanna, N., Monib, N. and Salem, A. (2023) 'Design for sustainable additive manufacturing: a review', *Sustainable Materials and Technologies*, 35, e00576. Available at: <https://doi.org/10.1016/j.susmat.2023.e00576>.
- [13] Huang, Z., Shen, Y., Li, J., Fey, M. and Brecher, C. (2021) 'A survey on AI-driven digital twins in Industry 4.0: smart manufacturing and advanced robotics', *Sensors*, 21(19), 6340. Available at: <https://doi.org/10.3390/s21196340>.
- [14] ISO (2006a) *ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*. Geneva: International Organization for Standardization.
- [15] ISO (2006b) *ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines*. Geneva: International Organization for Standardization.
- [16] Jansen, K.C., Mapindu, I., Muhla, T.M., Kanyemba, G. and Mashava, D. (2025) 'Optimization of edible oil quality through vacuum bleaching: an experimental design and analysis study', *Open Access Research Journal of Science and Technology*, 13(2), pp. 68–78. Available at: <https://doi.org/10.53022/oarjst.2025.13.2.0051>.
- [17] Junk, S., Fleig, C. and Fink, B. (2017) 'Improvement of sustainability through the application of topology optimization in the additive manufacturing of a brake mount', in *Sustainable Design and Manufacturing 2017*. Cham: Springer, pp. 151–161. Available at: [https://doi.org/10.1007/978-3-319-57078-5\\_15](https://doi.org/10.1007/978-3-319-57078-5_15).
- [18] Kokare, S., Oliveira, J.P. and Godina, R. (2023) 'Life cycle assessment of additive manufacturing processes: a review', *Journal of Manufacturing Systems*, 68, pp. 536–559. Available at: <https://doi.org/10.1016/j.jmsy.2023.05.007>.
- [19] Komoto, H. and Tomiyama, T. (2008) 'Integration of a service CAD and a life cycle simulator', *CIRP Annals*, 57(1), pp. 9–12. Available at: <https://doi.org/10.1016/j.cirp.2008.03.001>.
- [20] Kong, L., Wang, L., Li, F., Tian, G., Li, J., Cai, Z., Zhou, J. and Fu, Y. (2022) 'A life-cycle integrated model for product eco-design in the conceptual design phase', *Journal of Cleaner Production*, 363, 132516. Available at: <https://doi.org/10.1016/j.jclepro.2022.132516>.
- [21] Kumar, D., Maurya, K.K., Mandal, S.K., Mir, B.A., Nurdiawati, A. and Al-Ghamdi, S.G. (2025) 'Life cycle assessment in the early design phase of buildings: strategies, tools, and future directions', *Buildings*, 15(10), 1612. Available at: <https://doi.org/10.3390/buildings15101612>.
- [22] Laverne, F., Marquardt, R., Segonds, F., Koutiri, I. and Perry, N. (2019) 'Improving resources consumption of additive manufacturing use during early design stages: a case study', *International Journal of Sustainable Engineering*, 12(6), pp. 365–375. Available at: <https://doi.org/10.1080/19397038.2019.1620897>.
- [23] Lee, A.W.L., Seah, K.K.W., Ng, B.F., Zhang, E.T., Lu, W.F. and Low, J.S.C. (2025) 'Generative ecodesign for mechanical products: a design workflow', *Cleaner Engineering and Technology*, 24, 100890. Available at: <https://doi.org/10.1016/j.clet.2025.100890>.
- [24] Lu, Q., Zhou, G., Zhao, F., Ren, Y., Li, L., Luan, X. and Sutherland, J.W. (2019) 'Topology optimization of oilstone components considering carbon emissions associated with honing processes', *Journal of Cleaner Production*, 225, pp. 181–195. Available at: <https://doi.org/10.1016/j.jclepro.2019.03.273>.
- [25] Mapindu, I., Foya, A., Muhla, T.M., Chinguwo, K.N. and Kanyemba, G. (2026a) 'Minimizing defects in injection molding using the Taguchi method', *World Journal of Advanced Engineering Technology and Sciences*, 20(2), pp. 240–252. Available at: <https://doi.org/10.30574/wjaets.2026.20.2.0419>.
- [26] Mapindu, I., Munhuwamambo, G., Mashava, D. and Ngwenya, L. (2026b) 'Optimization of cutting parameters in CNC milling using the Taguchi method', *Global Journal of Engineering and Technology Advances*, 28(2), pp. 149–162. Available at: <https://doi.org/10.30574/gjeta.2026.28.2.0223>.
- [27] Mapindu, I., Muhla, T.M., Chinguwo, K.N. and Foya, A. (2026c) 'Process parameter optimization for 3D printing using the Taguchi method', *Open Access Research Journal of Science and Technology*, 18(1), pp. 34–45. Available at: <https://doi.org/10.53022/oarjst.2026.18.1.0082>.
- [28] Mapindu, I., Mashava D., Shangwa, V., Chigavazira-Gwara, T.T., Munhuwamambo, G (2026d) 'Taguchi-based optimization of GMAW welding parameters for joint strength', *World Journal of Advanced Engineering Technology and Sciences*, 20(3), pp. 206–219. Available at: <https://doi.org/10.30574/wjaets.2026.20.3.0448>
- [29] Mashava, D., Muhla, T.M., Munhuwamambo, G., Mapindu, I., Chinguwo, K.N. and Wachenuka, T. (2026) 'A multi-agent system framework for real-time self-diagnostic condition monitoring of induction furnace equipment in developing industrial economies', *Open Access Research Journal of Science and Technology*, 17(2), pp. 28–43. Available at: <https://doi.org/10.53022/oarjst.2026.17.2.0071>.
- [30] Morbidoni, A., Favi, C., Mandorli, F. and Germani, M. (2012) 'Environmental evaluation from cradle to grave with CAD-integrated LCA tools', *Acta Technica Corviniensis – Bulletin of Engineering*, 5(1), p. 109.

- [31] Muhla, T., Kanyemba, G., Mapindu, I., Chinguwo, N., Mashava, D. and Goriwondo, W. (2025b) 'Enhancing safety in Zimbabwean manufacturing industry: the role of human factors engineering in reducing workplace accidents', *Open Access Research Journal of Science and Technology*, 13(2), pp. 19–30. Available at: <https://doi.org/10.53022/oarjst.2025.13.2.0037>.
- [32] Muhla, T., Mapindu, I., Munyau, M., Mashava, D., Mhlanga, S. and Goriwondo, W. (2023) 'Agility as a strategy in Zimbabwean manufacturing industries', *Zimbabwe Journal of Science and Technology*, 18, pp. 1–11.
- [33] Muhla, T.M., Mashava, D., Kanyemba, G., Mapindu, I. and Goriwondo, W.M. (2025a) 'An assessment of the implementation of Industry 4.0 in Zimbabwean manufacturing industries', *World Journal of Advanced Engineering Technology and Sciences*, 15(2), pp. 970–984. Available at: <https://doi.org/10.30574/wjaets.2025.15.2.0653>.
- [34] Munotyaaani, S., Bawono, N.M.H., Tayisepi, N., Mapindu, I., Anggoro, P.W., Bawono, B., Pamosoaji, A.K. and Adi, A.Y.N.M.P. (2026) 'Design and development of a dual-mode smart wheelchair prototype with obstacle detection for Zimbabwe', *Jurnal Rekayasa Mesin*, 21(1), pp. 51–66. Available at: <https://doi.org/10.32497/jrm.v21i1.6954>.
- [35] Muyambo, R.D., Muhla, T., Kanyemba, G., Mashava, D., Munhuwamambo, G. and Mapindu, I. (2025) 'Design and development of a vertical axis wind turbine for slip stream energy harvesting', *Global Journal of Engineering and Technology Advances*, 23(3), pp. 10–20. Available at: <https://doi.org/10.30574/gjeta.2025.23.3.0166>.
- [36] Naser, A.Z., Defersha, F., Pei, E., Zhao, Y.F. and Yang, S. (2023) 'Toward automated life cycle assessment for additive manufacturing: a systematic review of influential parameters and framework design', *Sustainable Production and Consumption*, 41, pp. 253–274. Available at: <https://doi.org/10.1016/j.spc.2023.08.009>.
- [37] Ndiyamba, D., Murena, E., Kasukusa, S., Mafuraditdze, F., Nenzhelele, T., Mpofu, K. and Mapindu, I. (2026) 'Learning factories as a catalyst for innovation in Southern African engineering education', in *CLF 2026 Book of Short Papers on Learning Factories: Proceedings of the 16th Conference on Learning Factories*, Bolzano, Italy, 5–7 May. Bolzano: Free University of Bozen-Bolzano, pp. 93–99. Available at: <https://doi.org/10.5281/zenodo.20780648>.
- [38] Nyamekye, P., Lakshmanan, R., Tepponen, V. and Westman, S. (2024) 'Sustainability aspects of additive manufacturing: leveraging resource efficiency via product design optimization and laser powder bed fusion', *Heliyon*, 10(1), e23152. Available at: <https://doi.org/10.1016/j.heliyon.2023.e23152>.
- [39] Padilla-Rivera, A., Hannouf, M., Assefa, G. and Gates, I. (2023) 'A systematic literature review on current application of life cycle sustainability assessment: a focus on economic dimension and emerging technologies', *Environmental Impact Assessment Review*, 103, 107268. Available at: <https://doi.org/10.1016/j.eiar.2023.107268>.
- [40] Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D. et al. (2021) 'The PRISMA 2020 statement: an updated guideline for reporting systematic reviews', *BMJ*, 372, n71. Available at: <https://doi.org/10.1136/bmj.n71>.
- [41] Piron, M., Bovo, E., Lucchetta, G. and Manzardo, A. (2025) 'Soft-sensors to drive manufacturing toward clean production: LCA based on digital twin', *Journal of Cleaner Production*, 498, 145192. Available at: <https://doi.org/10.1016/j.jclepro.2025.145192>.
- [42] Popa, L.I. and Popa, V.N. (2017) 'Products eco-sustainability analysis using CAD SolidWorks software', *MATEC Web of Conferences*, 112, 06002. Available at: <https://doi.org/10.1051/mateconf/201711206002>.
- [43] Pusateri, V., Hauschild, M.Z., Kara, S., Goulas, C. and Olsen, S.I. (2024) 'Quantitative sustainability assessment of metal additive manufacturing: a systematic review', *CIRP Journal of Manufacturing Science and Technology*, 49, pp. 95–110. Available at: <https://doi.org/10.1016/j.cirpj.2023.12.005>.
- [44] Riedelsheimer, T., Seegrün, A. and Lindow, K. (2025) 'Digital twins for real-time life cycle assessment of products', in Fukushima, S., Nonaka, T., Kobayashi, H., Tokoro, C. and Yamasue, E. (eds) *EcoDesign for Circular Value Creation: Volume I*. Singapore: Springer, pp. 447–464. Available at: [https://doi.org/10.1007/978-981-97-9068-5\\_28](https://doi.org/10.1007/978-981-97-9068-5_28).
- [45] Saade, M.R.M., Yahia, A. and Amor, B. (2020) 'How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies', *Journal of Cleaner Production*, 244, 118803. Available at: <https://doi.org/10.1016/j.jclepro.2019.118803>.
- [46] Senda, S., Muhla, T.M., Mapindu, I., Ngwenya, L., Mushangure, R.O. and Mashava, D. (2026) 'Machine learning enabled preventive maintenance strategy for improving boiler reliability of a thermal power station', *Open Access Research Journal of Science and Technology*, 17(2), pp. 18–27. Available at: <https://doi.org/10.53022/oarjst.2026.17.2.0070>.
- [47] Shah, H.H., Tregambi, C., Bareschino, P. and Pepe, F. (2024) 'Environmental and economic sustainability of additive manufacturing: a systematic literature review', *Sustainable Production and Consumption*, 51, pp. 628–643. Available at: <https://doi.org/10.1016/j.spc.2024.10.012>.

- [48] Sikandar, H., Khan, N., Falahat, M. and Qureshi, M.I. (2026) 'Generative AI for sustainable product design: a technology convergence framework integrating multi-objective optimisation and smart manufacturing', *IET Collaborative Intelligent Manufacturing*, 8(1), e70051. Available at: <https://doi.org/10.1049/cim2.70051>.
- [49] Soori, M., Arezoo, B. and Dastres, R. (2023) 'Digital twin for smart manufacturing, a review', *Sustainable Manufacturing and Service Economics*, 2, 100017. Available at: <https://doi.org/10.1016/j.smse.2023.100017>.
- [50] Su, J., Ng, W.L., An, J., Yeong, W.Y., Chua, C.K. and Sing, S.L. (2024) 'Achieving sustainability by additive manufacturing: a state-of-the-art review and perspectives', *Virtual and Physical Prototyping*, 19(1), e2438899. Available at: <https://doi.org/10.1080/17452759.2024.2438899>.
- [51] Tandi, O., Mapindu, I., Muhla, T.M., Chinguwo, N.K. and Tayisepi, N. (2025) 'Design and analysis of a passive upper limb exoskeleton for augmented construction worker strength', *Open Access Research Journal of Science and Technology*, 13(2), pp. 79–88. Available at: <https://doi.org/10.53022/oarjst.2025.13.2.0050>.
- [52] Tao, J., Chen, Z., Yu, S. and Liu, Z. (2017) 'Integration of life cycle assessment with computer-aided product development by a feature-based approach', *Journal of Cleaner Production*, 143, pp. 1144–1164. Available at: <https://doi.org/10.1016/j.jclepro.2016.12.005>.
- [53] Tao, J., Li, L. and Yu, S. (2018) 'An innovative eco-design approach based on integration of LCA, CAD/CAE and optimization tools, and its implementation perspectives', *Journal of Cleaner Production*, 187, pp. 839–851. Available at: <https://doi.org/10.1016/j.jclepro.2018.03.213>.
- [54] Tayisepi, N., Mugwagwa, L., Mnkandla, A.N., Mapindu, I. and Muhla, T.M. (2024) 'Experimental investigation and simultaneous optimisation of honing parameters of dry cast iron cylinder relining sleeves of motor vehicle engine blocks for surface finish and energy use', *Computational Engineering and Physical Modeling*, 7(4), pp. 88–103. Available at: <https://doi.org/10.22115/cepm.2024.473138.1324>.
- [55] Tayisepi, N., Svosve, R., Tigere, G., Mnkandla, A.N. and Mapindu, I. (2023) 'Comparative optimisation of the cutting parameters for surface quality and energy efficiency during the machining manufacturing of teak, saligna and pine wood materials', *Journal of Engineering Research and Reports*, 25(11), pp. 73–87. Available at: <https://doi.org/10.9734/JERR/2023/v25i111023>.
- [56] Tschiltschke, T., Riedelsheimer, T. and Lindow, K. (2024) 'Digitally integrated sustainability assessment of design characteristics – a systematic review', in *DS 133: Proceedings of the 35th Symposium Design for X (DFX2024)*. The Design Society, pp. 65–74. Available at: <https://doi.org/10.35199/dfx2024.07>.
- [57] Vernica, T., Glišić, M., Veluri, B. and Ramanujan, D. (2023) 'Volumetric mapping and visualization of life cycle assessment results on computer-aided design models', *Journal of Cleaner Production*, 418, 138035. Available at: <https://doi.org/10.1016/j.jclepro.2023.138035>.
- [58] Visentin, C., Trentin, A.W.S., Braun, A.B. and Thomé, A. (2020) 'Life cycle sustainability assessment: a systematic literature review through the application perspective, indicators, and methodologies', *Journal of Cleaner Production*, 270, 122509. Available at: <https://doi.org/10.1016/j.jclepro.2020.122509>.
- [59] Wehking, S., Seegrün, A., Riedelsheimer, T. and Lindow, K. (2024) 'Sustainable product lifecycle management – implementation of a digital twin of a biologically transformed product-ecosystem', *Procedia CIRP*, 125, pp. 30–35. Available at: <https://doi.org/10.1016/j.procir.2024.08.006>.
- [60] Winter, S., Quernheim, N., Arnemann, L., Bausch, P., Frick, N., Metternich, J. and Schleich, B. (2025) 'Using the integral digital twin for product carbon footprint calculation', *Cleaner Environmental Systems*, 16, 100258. Available at: <https://doi.org/10.1016/j.cesys.2025.100258>.
- [61] Yang, S., Min, W., Ghibaud, J. and Zhao, Y.F. (2019) 'Understanding the sustainability potential of part consolidation design supported by additive manufacturing', *Journal of Cleaner Production*, 232, pp. 722–738. Available at: <https://doi.org/10.1016/j.jclepro.2019.05.380>.