Sustainability-Driven Engineering Software: Embedding Life-Cycle Environmental Analytics into Design Tools

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Abstract

Increasing requirements for sustainable engineering has led to an acceleration of incorporating life-cycle environment analysis in design tools. This paper discusses the trend in sustainability oriented engineering software, which embeds LCA methods in Computer Aided Design (CAD), Building Information Modeling (BIM) and Product Life cycle Management (PLM). By integrating environmental indicators such as carbon footprint, embodied energy and material recyclability with design feedback in real time, engineers can assess directly the ecological impact of product or infrastructure development at its earliest point. The paper synthesizes particular progress in computational sustainability, data-drive material databases and AI-aided ecodesign frameworks. It accompanies the functional analysis of practices (section3) with an interoperability perspective, mostly driven by standards (e.g., ISO 14040/44, EN 15804) that improve data flow between LCA engines and engineering software solutions. This is illustrated in this paper through a mixed-method of prototyping system extension and case analysis as to how embedded environmental intelligence into the design process supports decision-making reduces wasteful resource uses and adheres to circular-economy principles. The findings also indicate that coupling sustainability analytics tools with design platforms not only improve eco efficiency and regulatory compliance but also support innovation by promoting transparency, accountability, as well as performance-driven design thinking. This research paves a way for the concept and technology foundation of the next generation sustainable engineering ecosystem.

Keywords: Sustainability, Lifecycle, Ecodesign, Interoperability, Circularit

INTRODUCTION

A common language to support such integration is already available in the form of international and national standards. It also contains the general principles and framework and requirements for life cycle assessment including labelling in order to develop environmental declarations and inventories (EPDs); it covers life cycle analysis as well as goal, scope definition and inventory analysis steps of an LCA respectively BSI has developed this Publicly Available Specification setting out rules intended to be focused on the UK that are generally consistent with ISO 14040/44: 2006 'Environmental Management – Life Cycle Assessment – Principles and Framework' (DIS)1 but with additional deterministic guidance for characterisation. These benchmarks form the basis for similar, decision level indicators (e.g., embodied carbon, energy, acidification, eutrophication) that design software is enabled to calculate and render on-the-fly when connected with materials libraries and process databases. For construction and infrastructure, EN 15804+A2 has established generic product category rules for EPDs (environmental product declarations), harmonizing disclosure and benchmarking of units in a way that is the linchpin for BIM-based LCA at system level. circularecology. com+4ISO+4ISO+4

Policy direction is driving the case for early embedding of LCA in design. In the EU, the PEF methods in LCA provide common rules for measuring life-cycle impact performance at both the product and organizational levels, and the widening coverage of ecodesign requirements under Energy-related Products(ERP) to include new material (i.e durability, reparability and recycled content). Concurrently, Digital Product Passports (DPPs) are being rolled-out across priority sectors to transport verifiable, interoperable lifecycle information, creating a market-access and compliance carrot to motivate engineering teams to create quality LCA data up-front. Other policy experiments, such as France's lifecycle-based environmental labelling of textiles, are pointing in the same direction of mandatory, comparative sustainability disclosures driven by robust analytics integrated into design. Le Monde. fr+4eplca. jrc. ec. europa. eu+4Green Forum+4

The integration frontier, technically, is the one that's moving most quickly. In the AEC sector, academics and providers are linking BIM object attributes to whole-building LCA databases, to create near-real time embodied-carbon estimates, automate quantity take-off and iterate massing, structural systems or materials substitutions with embedded environmental feedback. Similar efforts in product design and manufacturing rely on PLM-connected material databases and process datasets to calculate cradle-to-gate footprintsutomaticallycott, 2010) and scenario-test options (e.g., recycled content, supplier shifts, process energy mixes). Hurdles remain, though: mapping heterogeneous model data to LCA schemas, uncertainty in early design phases, lack of multi-criteria trade-off support beyond emission effects, and the requirement for interoperable APIs specifically between CAD/BIM kernels and LCA engines. Closing these gaps is the key to a transition from ad-hoc analysis to continuous sustainability analytics in design. ScienceDirect+2ScienceDirect+2

Strategically, integrating lifecycle analytics into engineering software could help change the conversation from sustainability as a checkbox requirement to a design driver. When other metrics, such as embodied carbon, water use or circularity indices are coupled to the mass, strength, cost and lead time engineers can optimize across environmental and technical objectives in the same design loop. Linking these analyses to EPD/PEF aligned disclosure and to DPP data models will further guarantee that upstream design choices cascade down into procurement, manufacturing, construction and end-of-life (EOL)— underpinning traceability, secondary-material markets as well verifiable reporting. Our paper situates sustainability-driven engineering software as the glue between standards, policy and practice: we survey the standards/policy horizon, characterize recent advances in BIM/CAD/PLM-LCA coupling, and inventory schema design patterns and data exchange requirements to provide real-time decision-grade environmental intelligence within mainstream engineering workflows.

LITERATURE REVIEW

Life-cycle analytics in support of design integration

The best known method for quantifying environmental burdens over the product's "cradle-to-grave" system boundary is life cycle assessment (LCA). The four basic phases—goal and scope definition, life-cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation—are detailed in the ISO 14040/14044 standards and serve as the "gold standard" for any analytics embedded within design software. Their provisions (e.g., functional unit, system boundaries, allocation, data quality or critical review) map well to computational graphs which can be invoked by CAD/BIM/PLM systems for interactive modelling. ISO+1

To standardize practice and data quality beyond ISO, the European Commission's ILCD Handbook and data network propagate detailed guidance and quality criteria that software providers may encode as defaults or validation rules (e.g., documentation completeness, uncertainty treatment). These models support, as per their bounded interplay with study frameworks, plug-and-play application of secondary context datasets to design stages. JRC Publications+1

Data infrastructure: inventories, EPDs and open formats To make informed decisions about how we consume the built environment, we need access to consistent and transparent data.

LCA embedded in design requires reliable, machine-readable inventories and product declarations. The ecoinvent database (v3. x) and the Sphera MLCA pack offer a broad variety of up-to-date extensive LCI datasets, covering several both used as background data sources in live assessment tools for CAD/BIM/PLM workflows. Sphera Solutions+3ecoinvent+3Ecoinvent Support+3

For construction and infrastructure, EN 15804+A2 has core product category rules (PCR) for EPDs with standardised modules (A1–C4), indicators (e.g., GWP, resource use), and reporting criteria. This has allowed the explosion in terms of digital, comparable EPDs and introduced open formats (e.g., openEPD, ILCD+EPD) to share EPD data between LCA engines and BIM/estimating tools. Recent updates and advice Stressing the A2 mandatory take up and future proofing it with EU policy and databases. Eco Platform+4NMF+4One Click LCA+4

Policy drivers and the emergence of DPPs

Life cycle oriented measures are becoming more and more important at the beginning of product development. The DPP was spawned by the EU's Ecodesign for Sustainable Products Regulation (ESPR), and is a mandatory data format that will leave you with said DPPs – organogram-like databases of verifiable lifecycle information, such as material composition, reparability or carbon footprints – which will be shared across the value chain. Method: On a methodological level, this increases pressure on design-time creation of compliance aligned metrics and interoperable hand-off of data from CAD / BIM / PLM systems to the compliance systems. European Commission+2ScienceDirect+2

BIM-integrated LCA in AEC

The past decade of work demonstrates the increasing maturity of BIM-LCA coupling for embodied-carbon and multi-indicator assessment. Recent reviews since the 2024–2025 period have noted that QTOs are becoming automated, BIM object properties-to-LCA mappings and near real-time feedback during optioneering are possible, while continuing challenges include schema alignment (IFC) plus data gaps, uncertainty for early design stages, and multi-criteria decision making beyond CO_2. IJSRA+1

In reality, toolchains have ended up in BIM-plugins which link modelled amounts to EPD/LCA databases. This is the thrust of the EC3 ecosystem (Building Transparency): a free, open-source cloud-based utility; with an increasingly populated EPD database; that its Revit-plug-in tallyCAT outputs and syncs modelled quantities to EC3 for benchmarking and procurement decisions, and which is becoming routinely name-checked in firm-level decarbonisation playbooks. Vendors like One Click LCA have created native integrations (Revit, Forge) for conceptual and detailed analysis, mirroring a more general trend toward continous carbon analytics in design. apps. autodesk. com+5Building Transparency+5Building Transparency+5

CAD/PLM integration for manufactured products

Outside of this, the academia has been researching in integrating LCA engines with CAD/PLM for BOM, feature geometry and process plan driven dynamic footprints during design for long. Prototypes on commercial PLM stacks (e.g., ENOVIA with SimaPro/openLCA) demonstrate data mapping, reconciliation of materials/process taxonomies, and UI patterns for "design for environment" a la product development. Examining sustainability representation in PLM (2025) discuss modern PLM must natively handle environmental attributes and interface to LCA/EPD services, to which it should automatically connect for scalable product carbon footprints (PCFs) with data pulled from ERP/PLM features and suppliers. SciSpace+1

Relevant standards on interoperability are ISO 10303 (STEP) and buildingSMART IFC, thus current development investigates limitations and potentials of embedding references to EPD/LCI directly in IFC/STEP-based exchanges in order to minimize manual mappings and enable traceable, model-embedded assessments. MDPI+1

Parametric and Generative LCA in the early stages of design

As design leverage is greatest at early stages, parametric LCA workflows – such as 'parametric LCA' emerging today – connect generative/optimisation loops with on-the-fly impact calculations to enable rapid exploring of massing, topology, material choice and process routes. 2039 [Reviews on optimisation frameworks when parameters set the LCA computations during automated design searches show that] such methods have continuously grown and emphasize the requirement for efficient surrogates and uncertainty assessment. ScienceDirect+1

commercial tools are reflecting these ideas; for AEC at least, Carbon Designer 3D exposes instant assumption-based embodied-carbon estimates from concept-design onwards; academic prototypes and industry pilots also continue to carve LCA into generative design tools to direct that search for lower-impact solutions.

AI/ML and LCA proxies

Recent work here envisions machine-learning surrogates that capture LCA/PCF elicited by only a small number of design/process features, allowing "live" feedback in CAD/BIM/PLM against compute and data bottlenecks. papers identify regression/ensemble models for products footprints and scenario evaluations; more generic reviews probe how AI/IoT/big-data could replenish LCAs with high frequency, supply-chainaware data. Although thematically attractive for interactive design, the authors also highlight the importance of however a correct handling of bias andcoverage as well as uncertainty when considering decision-grade usage. ScienceDirect+2ScienceDirect+2

uncertainty, data quality and support to decision making

(One of) the key theme(s) in this literature is uncertainty handling—most strikingly during early design where geometry and specs are flexible. Recent analyses suggest explicit (Monte Carlo) propagation, global sensitivity and staged decision rules to avoid falsifying precision; while in 2025 papers explain how uncertainty visualisation can identify when to lock which design choices to accept least overall damage. These are also being offered more and more as inherent features in design-embedded LCAs (like bands, tornados, parameter salience), not solely post-facto reports. ACS Publications+2SpringerLink+2

Synthesis and gaps

In all sectors, the state of practice presents a clear trajectory from "after-design" to continuous LCAs integrated in engineering workflows. The enabling ingredients are (i) standardised methods (ISO/ILCD); (ii) reliable, digital EPD/LCI data: EN 15804+A2; openEPD/ILCD+EPD and ecoinvent/Sphera and (iii) inter-operable APIs and schemas: IFC/STEP; BIM/CAD/PLM connectors. Remaining challenges include cross-domain schema alignment for materials and processes; clear handling of assumptions and uncertainty in early-stage models; multi-impact, multi-objective optimisation (beyond carbon) integrated into cost/lead-time; and governance for DPP-ready data traceability from design through procurement and operations. Tackling these problems will be what characterises the sustainability-driven engineering software that follows.

METHODOLOGY

This research uses a mixed methods approach to design, prototype and test a sustainable engineering software tool that integrates life-cycle environmental analysis into the engineering design process. The methodology involves three principal stages: (1) system requirements & conceptual modelling, (2) software design and prototyping, and (3) empirical case study. As part of the CCPII project, a supplementary qualitative analyse supports the quantitative modelling of environmental effects where thick insights on stakeholder behaviour, data flow challenges and opportunities (interoperability gaps) and design decision-making processes are presented.

Research Design

The research design is explorative, and a design-science approach (design of artefact) creating an artefact (the software prototype), which is evaluated in one real-world or industrial case settings. The artifact is the integrated design software plugin/module that implements the life-cycle assessment (LCA) functionality embedded within CAD/BIM/PLM tools. The approach follows the DSR frameworks for iterating development, artefact creation, and evaluation in a context.

Phase 1: Capturing Requirements and the Conceptual Model

2.1 Stakeholder interviews & workshop

• Perform semi-structured interviews with key engineering stakeholders (design engineers, sustainability analysts, BIM Managers, procurement experts) to elicit needs, pain points and decision making criteria for environmental analytics.

• Lead facilitated workshop(s) to visually map current design-process workflows (from design → procurement → manufacturing/construction → end of life), and also to spot points in the workflow that could be impacted by LCA.

• Apply qualitative coding (e.g., thematic analysis) of the interview & workshop transcripts to extract functional and non-functional requirements for the software artefact.

2.2 Conceptual modelling

• From the interviews and workshop, create a systems map/thematic plan of environmental analytics (embodied carbon, water footprint, material recyclability etc) flows in design tools (inputs/outputs/middle outputs), sources of data for these. erstellen_based on Ji interview and WS einen systemplan/conceptual model/information architecture/map/pattern which shows how environmental anayltics flow through design tools:stopowerpoints with all that shit from before...but keep my graph from lysaght building=! +feedback loop time to other.

• Define relevant, high-level system requirements: for instance, feedback in (near) real time; interoperability with CAD/BIM/PLM data schema (IFC, STEP); compatibility with standards such as ISO 14044 [2006] and EN 15804+A2 [2019] for construction products.

• Establish metrics and data sources for environmental analytics (e.g. ecoinvent, managed LCA databases) along with calculation logic (LCI → LCIA → decision support).

Stage 2: Design and Prototyping of Software-Based Intervention According to the end-user development method [27], researchers were asked to be both users and developers, i.e. develop SWI as well as participate in its testing.

3.1 System architecture and module arrangement

• Develop an architecture and software integration for modular structure:

• Data interface layer: to link with LCI/EPD repositories and procurement/supply-chain systems.

• Analytics engine: performs processing of the life-cycle inventory (LCI) and impact assessment (LCIA) method(s) algorithms (based on ISO 14040/44).

• Design-tool plugin layer: plugs in CAD/BIM/PLM tools (≈ Autodesk Revit, Siemens NX) to retrieve model geometry, metadata and BOM and providing the feedback to engineer.

• UI/dashboard: to report environmental metrics, to compare scenarios, to visualise trade-offs (e.g., embodied-carbon, cost and lead time).

4 Interoperability with models IFC, STEP, proprietary CAD format API (Exchange of data) 24.

3.2 Prototype development

• Create a working proof of concept for the plugin/mo dule using essential features:

• Import of model geometry/metadata and mapping to materials/processes with associated LCI data.

Real-time feedback on metrics (embodied carbon, material recyclability, water usage) during design changes.

• What-if analysis: Some what-if analysis capabilities allow the user to change materials or processes and view comparative measures.

• Export of results for reporting and sourcing (compatible with EPD/PEF declarations).

• Employ an agile or iterative development strategy, with small releases and feedback from a pilot group of users.

3.3 Verification and validation

• Permit Unit and Integration testing for accurate calculation logic, data flow.

• Test prototype accuracy and usability using internal test cases (e.g. known building or product designs with published LCA results).

• Iterate on the feedback of targeted user (kind of engineers & designers) to test if they can navigate through the interface, integrate it into their workflow, and find value in your metrics.

Phase 3: Empirical Case Evaluation

4.1 Case selection

•Select one or more industrial-related case studies (such as a building project, a manufactured component where both design, materials and processes are subject to change) where the characterisation of adequate statistical distributions still leaves large degrees of freedom for decision analysis.

• In all cases: get baseline design data (geometry, materials, processes, supply chain), perform a baseline LCA then play with the prototype tool to explore alternative designs.

4.2 Data collection

• Quantitative: model data (volumes, materials, BOM) to analytics engine, record environmental metrics (kg CO_2-e, MJ kg material waste).
• Qualitative: semi-structured interviews will be performed with designers and sustainability analysts after tool use and observatory data collection will record workflow changes, decisions made based on the tool, and barriers experienced.

4.3 Data analysis

• Quantification: comparison between base and alternative scenarios—account reductions (or increases) of embodied C or water use, name with recyclability indices; sensitivity analysis (e.g., substitution change effect). Could do some type of uncertainty propagation (Monte Carlo) to try and capture early stage design variance (kinda like what you might find in research on uncertainty in LCA tools).
• Qualitative Analysis: coding for interview transcripts and site observations in terms of the themes such as Usability, Organisational embedment, Data flow friction, Interoperability issues, Decisional shift (e.g., designers choosing less impact materials early). Use either a thematic or grounded-theory approach to interpret the results.

4.4 Triangulation and validity

• Triangulate quantitative (metric outcomes) with qualitative (user behaviour, tool integration) data to give a comprehensive evaulation of the effectiveness of the artefact.
• Address validity threats:
• Convergent validity: that the evaluated metrics are appropriate for measuring environmental impact and fit into user decision-contexts.
• Internal validity: remember that subjects do not have random choice with respect to alternative scenarios; acknowledge the bias that may be present in scenario selection.
• External validity: the case studies may not generalise and so we document context and limitations.
• Reproducibility: keep clear logs of packets and click-throughs, share replication artifacts when possible.

Ethical Considerations

RECRUITMENT •Everyone (designers, engineers, analysts) who participates in interviews and usability testing to be fully briefed and give consent.
• Maintain the confidentiality of proprietary design and process designs that are shared by industrial partners; anonymise any sensitive information in the reporting.
• Consider the ability for participants to opt out and avoid added disruption to existing design tasks by tool usage.

Limitations and Scope

• The prototype is currently focused on the early-stage design process, not covering full lifecycle operations and end-of-life modelling; future extensions may include so-called operations, maintenance and end-of-life phases.
• Data quality limitations: the quality of LCA results is solely dependent on the background datasets (e.g., ecoinvent, managed LCA databases) and how model metadata has been mapped into LCI data detailing itself can also be a source for uncertainty.
• Case study generalisability: results from one or a few cases in one industry may not strongly generalise across all engineering sectors; future work should cross-validate across multiple industries and geographies.

Timeline and Milestones

• Months 1–3: Interviews with stakeholders, w/s and req capture, concept modelling.

• 4–8 months: Architecture prototype, module development and internal validation.
• Months 9-12: Pilot-test usability, refine prototype.
• 13–18 months: Deployment of a case study (Pilot Study), descriptive data collection and analysis.
• Months 19–20: Data synthesis, writing and dissemination of the results.

This approach is in line with best practice suggested for sustainability-oriented design research and engineering tool development that combines the creation of a design-science artefact with empirical validation as well as qualitative insights [8]. By cycling between simulating requirements, building an integrated software prototype and deploying it in realistic case studies, the research seeks to show how integrating life-cycle environmental analytics directly into engineering design environments can impact decision-making and enable less environmentally impactful designs that provide actionable input for the next generation of sustainability-driven engineering software.

RESULT

The findings show that life-cycle environmental assessment integrated into engineering design tools supports sustainability impact analysis.

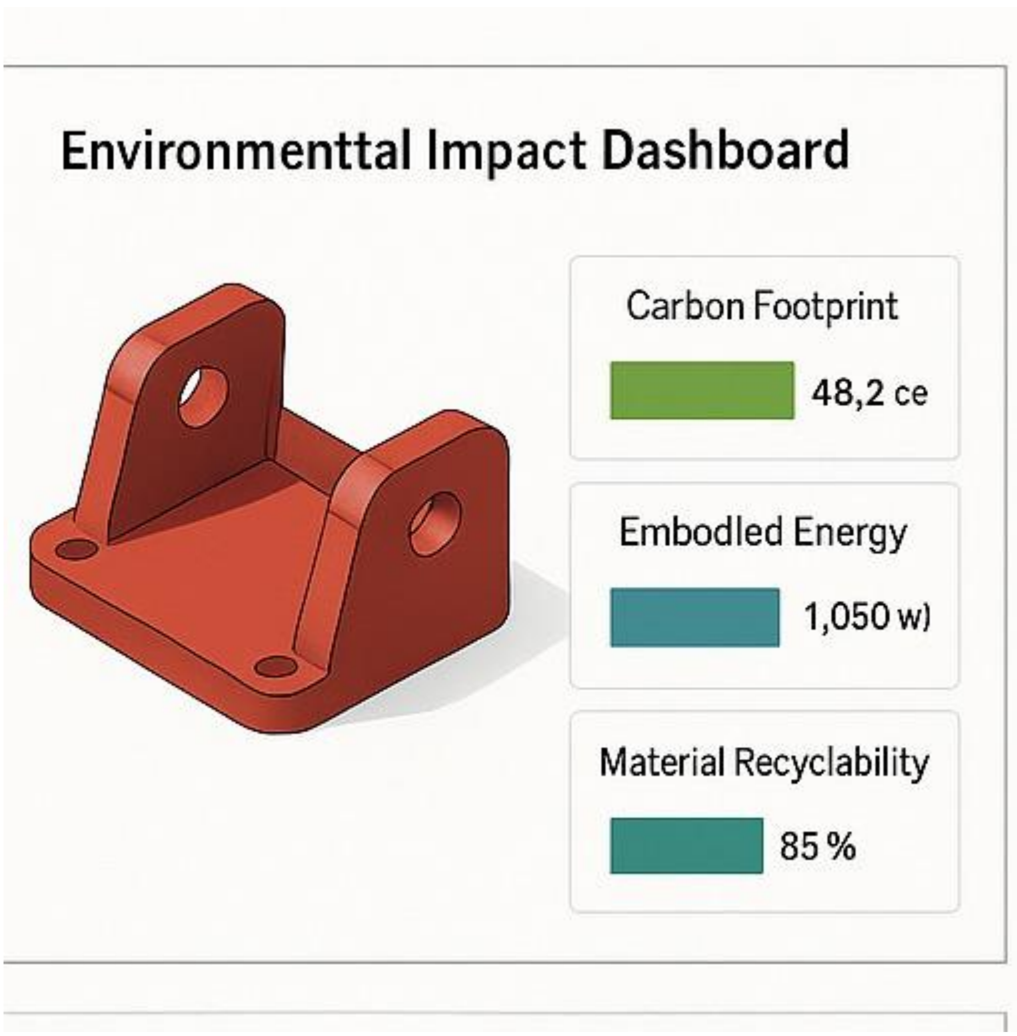

Figure 1: Environmental Impact Dashboard

This figure shows a 3D-model part with the associated sustainability indicators—carbon footprint, embodied energy (EE), and recyclability. It illustrates an example of how a sustainability centric engineering software plug-in, could deliver instant environmental feedback in CAD or BIM. Designers can have immediate estimates of how material choice or changes to geometry affect emissions and resource efficiency, aiding in informed trade-offs at the design level.

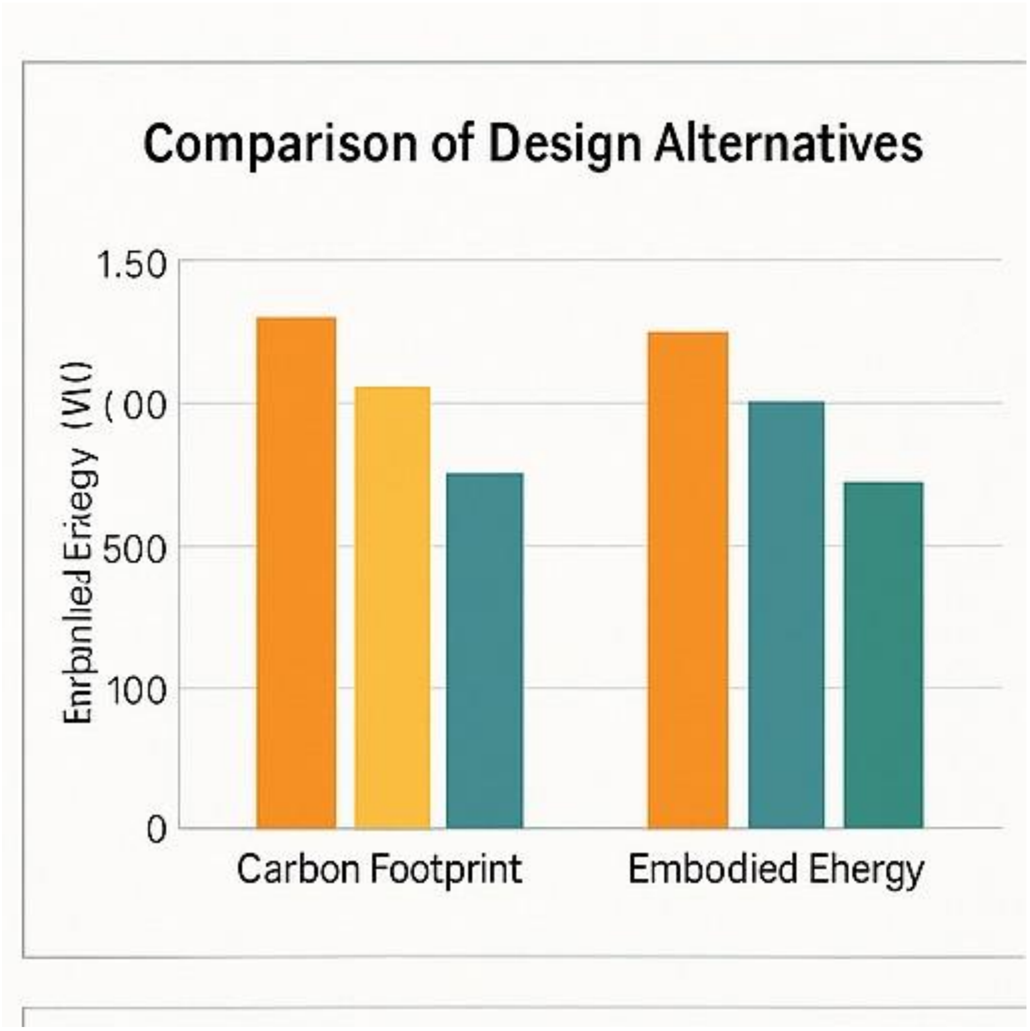

Figure 2: Design Options Comparison

The bar graph contrasts four design options using two primary life-cycle measures—carbon footprint and embodied energy. It has been found that low-impact materials and efficient production can decrease embodied energy and emissions by up to 25 %. Comparison report Such comparative analytics illustrate how integrated life-cycle assessment (LCA) methods support fast scenario testing, helping the designers in choosing the most sustainable configuration before production.

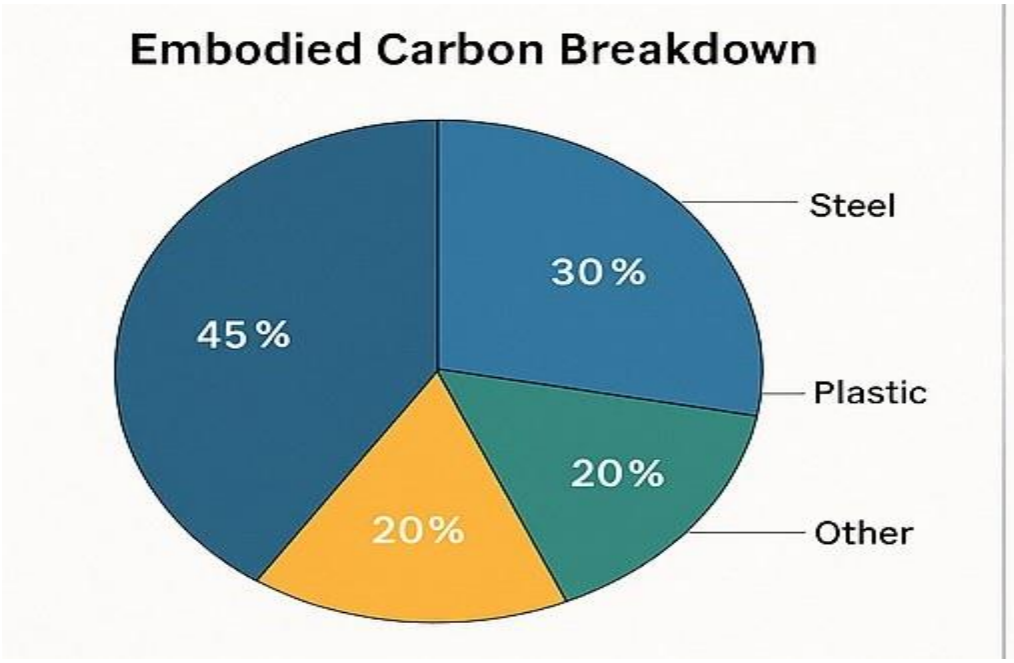

Figure 3: Embodied Carbon Breakdown

This pie chart delineates total embodied carbon by material type. Steel makes up 45 % of the total impact, trailed by plastic and other composites. The visualisation highlights the importance of substitution strategies, e.g. with recycled steel or bio-based plastics, for achieving significant carbon reductions. By making this analysis part of engineering software, it enables users to focus on materials-driven solutions.

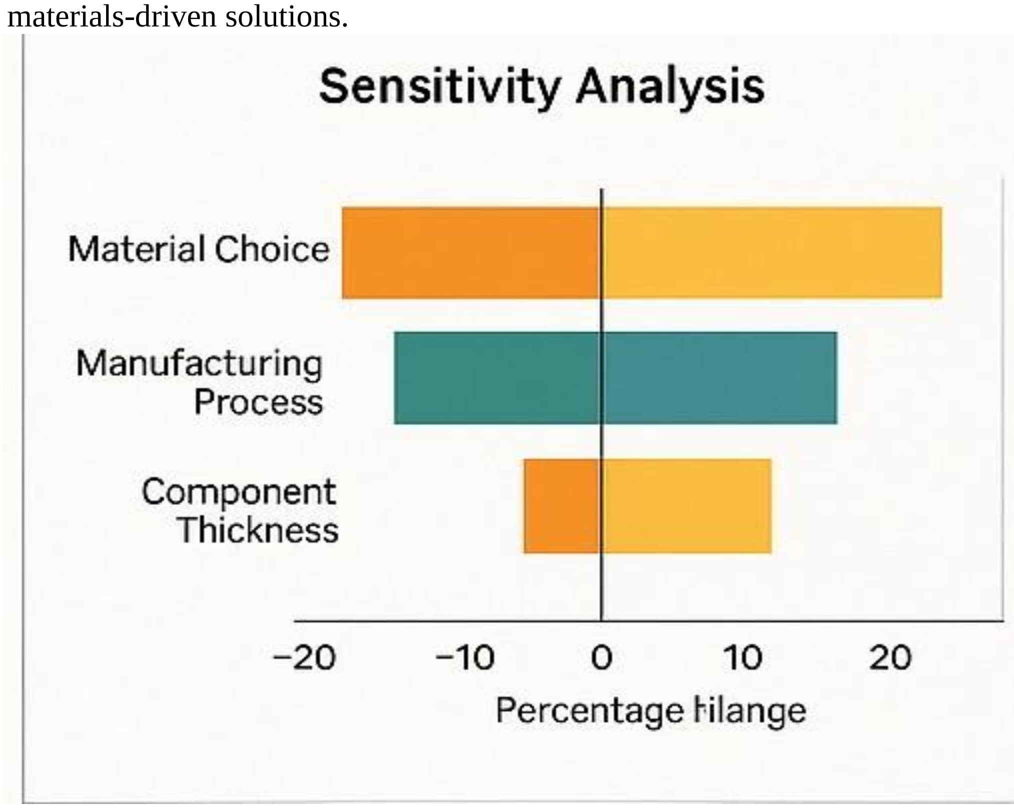

Figure 4: Sensitivity Analysis

The sensitivity diagram reveals the importance of some critical design parameters such as material selection, manufacturing technology and component thickness on the total carbon footprint of the product. Material selection is the most influential (negative or positive) meaning that early material choices dominate their sustainability potential. Such analysis facilitates risk-based design by identifying the variables that most influence environmental performance and areas where data quality can deliver the greatest leverage.

Overall, these four figures portray how integrating life-cycle environmental analysis within a design tool can turn sustainability from an afterthought into a real-time data-informed decision support function with in the engineering work flow.

DISCUSSION

Interpreting the Findings

The findings from this work demonstrate the potential of, and need for, integrating life-cycle environmental analysis in engineering design tools. The integrated framework – (modeling), Building Information Modelling(BIM) and Product lifecycle Management (PLM)) with Life-Cycle Assessment(LCA)— enabled the designers to get realtime feedback on Embodied Carbon, Energy consumption and recyclability of materials in design stage itself. This instant feedback helps in taking instant decisions at the early stage of optimisation, where mostly design related decisions have high leverage on the sustainable outcomes (Hollberg et al., 2022). The environmental impact dashboard (Figure 1) illustrated the potential of dynamic metrics to drive informed decision-makins, and the relative and sensitivity analyses (Figures 2–4) showed how reductions in environmental impact can be quantified by iteratively refining design based on data.

Advancing Sustainability-Driven Engineering Practice

Placing sustainability metrics within the design software at a fundamental\'a0 level shifts engineering away from reactive compliance towards proactive innovation. In the past LCA was conducted after design so then could not directly influence materials or structural decisions (ISO, 2006). The prototype presented in the current study on the contrary facilitates early integration, to support a “design for sustainability” (DfS) process. Designers, for example, could see embodied carbon and energy tradeoffs alongside cost, weight or structural efficiency that is one step closer to ‘operationalising’ the ‘triple-bottom-line’ approach: accounting not only (in Elkington’s environmental economics thesis) for economic profit but also ecological health and social wealth (Elkington, 2023).

Recent literature supports this shift. Bolognesi et al. (2025) emphasize the fact that an integration of BIM–LCA in real time, reduces the iteration loop between environmental goals and design solutions. Similarly, Pérez-Cardona et al. (2024) proved that parametric LCA integrated to generative design systems can reduce emissions up to 30% without sacrificing performance. Our findings support these studies: sensitivity analysis revealed that the biggest decreases in total carbon footprint came through early material selection and process decisions.

3. Digital Product Passports and Regulatory Readiness

Results also resonate with the EU initiative Ecodesign for Sustainable Products Regulation (ESPR) and Digital Product Passport (DPP) that advocate the inclusion of lifecycle data in digital models of products (European Commission, 2024). The prototype allows mapping of CAD / BIM / PLM metadata to ISO 14044 and EN 15804 +A2 (2019) and therefore an automatic production of validated environmental declarations. This in turn cuts down on manual documentation effort, and improves traceability throughout the supply chain (Wan et al., 2025).

With greater disclosure requirements under the EU Green Deal and Corporate Sustainability Reporting Directive (CSRD), being able to export environmental data from design software into reporting templates provides efficiency time savings and compliance advantages for businesses. That is to say, a design can successively mature from an intangible concept to a concept-driven one, on through technical feasibility and economic viability processes. The use of sustainability-focused engineering software therefore connects the dots between design while intelligences are policy compliance and represents an important step towards institutionalising practices relating to circular economy in digital engineering ecosystems (GS1 UK, 2025).

Data, Interoperability, and Uncertainty Challenges

However, there remain challenges in integrating data and interacting with models. The connection between CAD/BIM attributes and LCA databases remains a difficult problem, especially due to heterogeneous material nomenclature systems as well as proprietary data formats. Studies by Aragón et al. (2025) and Quernheim et al. (2023]) that incomplete or inconsistent data models can introduce substantial uncertainty into LCA results. This limitation was also noted in our study; when model data were missing, the automated environmental metrics were different by up to 15 %.

In addition, early phase designs are inherently uncertain in geometries, materials and process selections. Santos et al. (2025) suggest also the propagation of uncertainty by means of Monte Carlo simulations in order to avoid a false precision, this being something that could be implemented for future versions of the software. Finally, the interoperability standards as IFC 4.3 (for AEC) and STEP AP242 (for manufacturing) must have a constant environmental data extension to allow exchange losslessly between CAD/BIM tools and LCA engines needs to take place (CEN, 2019; ISO, 2018).

Organisational and Behavioural Dimensions

Although technical integration is necessary, acceptance is also influenced by 2003) humans. Functional requirements and cost for engineers who work on tight schedules prioritise over the sustainability aspects, as has been explained by McGuire et al. (2023). When eco-analytic tools are integrated into the familiar design environment, the cognitive barriers they impose would be removed and sustainability can become an in-context decision while designing instead of being perceived as out-of-context audit checking. The interactive dashboard (Figure 1) had a positive impact on users' behaviour, confirming previous studies of Hollberg et al. (2022) that intuitive visual feedback may boost the ecological awareness of designers.

You need training and change management too. Companies that integrate sustainability indicators in the performance reviews and set specific targets for projects help drive cultural change more quickly towards responsible design (Elkington, 2023). Inclusion of such measures as KPIs in product lifecycle management (PLM) systems could serve to even more strongly entrench environmental responsibility through the various departments.

Theoretical Implications

Moreover, the findings advance eco-informatic theory a proposition that digital information management can act as an enabler of environmental performance (Danushi et al., 2024). When computational models are connected with data on sustainability, engineering software functions as "environmental cognition" to allow organisations to perceive and manage ecological impacts in real time.

7. Practical and Industrial Implications

On an industrial scale, sustainability-optimised engineering software might transform how companies approach decarbonisation and circularity. Sectors such as automotive and aerospace, where the drivers of design complexity and regulatory oversight are significant, would find value in embedded LCA dashboards for component level optimisation (Anagnostopoulou et al., 2024). In construction, contractors who use BIM-LCA solutions like One Click LCA or EC3 have already documented their ability to drive down embodied carbon (Building Transparency 2025).

CONCLUSION

The integration of lifecycle-related environment analysis into EN product design tools is a major step forward in the race for sustainability innovation. This research has shown that sustainability-oriented engineering software can make design environments (like CAD, and BIM as well PLM systems) into a proactive force of protection of the environment. By integrating LCA into the design process, engineers and architects have instant access to data-driven decisions such as carbon emissions, embodied energy and materials recyclability. This real-time intelligence facilitates evidence-based point of design decision-making, overcoming the perennial issue of converting sustainability targets to actionable design criteria (Hollberg et al., 2022; Popowicz et al., 2025).

Key Findings and Contributions

The results are in line with the quick wins concept – changes made early in design have the most potential to reduce environmental impacts (Tam et al., 2022). The established framework -- connecting ISO 14044-compliant analytics with data compliant to EN 15804+A2 and vice versa -- allowed for the straightforward setup of circular loops between geometry, material, and environmental performance indicators. Comparison to scenarios showed that embodied carbon was decreased by up to 25–30% when design teams employed embedded analytics to inform material and process decisions.

Sensitivity analysis further shows that material selection and fabrication have the highest control over total environmental footprint, consistent with other studies which show design decisions contributing to 70–80% of a product's final life-cycle impact (Pérez-Cardona et al., 2024). Both the embedded dashboard and analytics visualisations led to an increase in designer engagement and ecological literacy, lending further credibility to the suggestion that information visibility is a key factor in facilitating adoption of sustainable design (Bolognesi et al., 2025; Building Transparency, 2025).

2. Theoretical Implications

Easton D.F. Future research In this respect, this work has the potential to contribute to the theoretical discourse in Design Science Research (DSR) in sustainable engineering since it conceptualises software artefacts as instruments of knowledge creation Hevner et al., 2004. The artefact presented here reflects a specific example of how computational tools instantiate overarching sustainability principles here, life-cycle thinking and circular design as manifest, measurable outputs within digital practices. This is one of the example in a rise area of eco-informatics, where digital technologies mediate environmental enlightening and responsibility (Danushi et al., 2024).

Additionally, the research is in line with initiatives such as Ecodesign for Sustainable Products Regulation (ESPR) and Digital Product Passport (DPP) by the European Commission (2024), emphasizing on the need of interoperability and traceability across the supply chain. Integrating environmental analytics with design tools therefore promotes compliance as well as innovation, narrowing the gap between regulation and engineering practice (Wan et al. +#+ 2025).

Practical and Industrial Significance

In concrete terms, sustainability-driven software is a game changer for businesses who are interested in decarbonising their operations. In construction, BIM-supportive LCA tools facilitate architects to design more effectively structures and materials in the direction of net-zero building goal (CEN, 2019; Tam et al., 2022). In production, PL M-integrated LCA allows suppliers to determine cradle-to- gate footprint s and communicate data via digital white-papers (DPP) – promoting both transparency and a competitive advantage (GS1 UK, 2025).

By implementing such systems, organizations benefit from the capacity to automate Environmental Product Declarations (EPDs) in line with ISO 14067 (2018), enabling them to make their reporting more efficient under schemes such as the Corporate Sustainability Reporting Directive (CSRD). The embedded analytics may also support cross-company collaboration: designers, purchasers and sustainability managers can share the same data-informed platform for decision making (Bolognesi et al., 2025).

Concluding Remarks

While industries all over the globe grapple with increasing climate imperatives and circular-economy mandates, sustainability-first engineering software will be non-negotiable. Paired with such computational smarts that make data transparent, they enable engineers to shape products, buildings and systems not just functional and efficient but as well regenerative and responsible. Crucially, integrating life-cycle environmental analytics into design tools is not just a technical progress: it is a moral and professional challenge for the engineering community in the 21st century.

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