Proceedings of the Design Society, Volume 5: ICED25
https://doi.org/10.1017/pds.2025.10216

Identifying measures to improve sustainability using the double diamond: a case study of industrial digital printers

Klemens Hohnbaum [1,✉], **Philipp Schröder** [1], **Andreas Fill** [1,2], **Markus Mörtl** [1] and **Markus Zimmermann** [1]

[1] *Technical University of Munich, Germany,* [2] *Forschungsstelle für Energiewirtschaft (FfE), Germany*

✉ klemens.hohnbaum@tum.de

ABSTRACT: Various methods, such as LCA, LCC, or circularity indicators, are used to integrate sustainability into product development. However, these approaches often require extensive expertise in both processes and sustainability, which is not always available in combination. This paper introduces a framework based on the double diamond model, structured into (1) a preliminary assessment, (2) a collaborative workshop, and (3) a prioritization process. It aims to help engineers identify sustainability improvements without requiring prior expertise. A case study on an industrial digital printing system identified five opportunities for enhancing sustainability. Three measures were validated using LCA and the RPR metric. The study resulted in seven principles for sustainable printer design, with a lightweight door design, reduced number of rivets, and logistical improvements as key outcomes.

KEYWORDS: sustainability, design methods, digital printing, LCA, circular economy

1. Introduction

Among other challenges, a significant shift toward sustainability is experienced across industries: Companies are challenged to reduce environmental impacts, conserve resources, and align with regulations (CSRD, 2022; Fetting, 2020). This is particularly relevant for industrial digital printing, where material efficiency, recyclability, and circularity present key sustainability challenges (Kariniemi et al., 2010). Addressing these challenges may seem overwhelming for engineers or designers who have no sustainability knowledge or are not trained in using sustainability tools or methods, eventually leaving them frustrated and preventing them from unlocking sustainability potential in their specific field of expertise (Boks & Diehl, 2006; De Eyto et al., 2008; Mengistu et al., 2024).

2. State of the art

2.1. Sustainable product design and the double diamond model

Sustainable Design of Products (SDP) emerged in the 1990s, emphasizing environmental optimization and equitable resource distribution across nations and generations (Van Weenen, 1995). Since then, various guidelines, principles, and evaluation methods have been developed to support SDP. For instance, Jawahir et al. (2006) introduced six design principles focusing on environmental and social impact, recyclability, functionality, manufacturability, and resource utilization. Similarly, Hallstedt (2017) and Wiesner (2022) propose comprehensive frameworks incorporating stakeholder perspectives and evaluation methods.
Eco-design guidelines emphasize lifecycle impacts and offer detailed suggestions across pre-manufacturing, manufacturing, use, and end-of-life stages. While these provide over 200

recommendations, their implementation only sometimes guarantees greener solutions, leading to revisions for higher-level usability (Russo, Rizzi, & Spreafico, 2017). Frameworks like the Product Lifecycle Matrix identify sustainability priorities across lifecycle phases (Lindemann et al., 2001).

Broader Approaches that are more generally applicable, like those by Oh (2017), emphasize actionable strategies with examples to guide users, while the principles by Caldeira et al. (2022) focus on material efficiency, renewable resources, and design for end-of-life. Circularity-focused guidelines typically provide general and specific strategies, including reuse and remanufacturing, but vary in applicability (Bauer et al., 2017; Lindemann et al., 2000, 2002). Other approaches offer frameworks to identify sustainability hotspots but note the need for more product-specific guidance (Byggeth et al., 2007).

A widely applicable framework in product design is the double diamond model. It is a structured design framework that visually represents the problem-solving process through four key phases: (1) Discover, (2) Define, (3) Develop, and (4) Deliver. It provides a clear, iterative approach to exploring challenges, identifying key issues, generating solutions, and refining them into implementable outcomes. Recognized for its accessibility and versatility, the model supports collaboration across disciplines and has been widely applied in product development, innovation, and sustainability improvements. (Design Council, 2004)

2.2. Lifecycle assessment and circular economy

Lifecycle assessment (LCA) is a widely used methodology for evaluating sustainability criteria across social, ecological, and environmental dimensions (Guinée, 2016). It is guided by several standards, such as the Greenhouse Gas Protocol (2023) or ISO 14040:2006, which outline structured assessment processes from boundary definition to data collection and evaluation. Various databases provide ecological information on materials and processes to support LCA, while digital tools streamline workflows by integrating these resources.

The circular economy concept aims at minimizing resource input, waste, emissions, and energy losses through regenerative systems that slow down, close, and restrict material and energy cycles (Geissdoerfer et al., 2017). While LCA effectively evaluates sustainability impacts, it does not address product disassembly or overall circularity. Indicators like the Material Circularity Indicator (MCI) and the Circularity Index (CI) have been developed to assess circularity (Hapuwatte et al., 2023), while the Relative Product-Inherent Recyclability (RPR) metric indicates whether a measure improves recyclability (Roithner et al., 2022). Martins et al. (2024) highlight that combining LCA with MCI enhances sustainability assessments, offering complementary insights for enterprises.

2.3. Industrial digital printing

The industrial printing sector faces sustainability challenges and opportunities similar to those of other industries. Companies like HP Inc. have implemented targeted measures, such as the High-Efficiency Drying (HED) technology in the HP PageWide A2200 printer, which reduces energy consumption and carbon footprint by recirculating hot air (HP Inc., 2022). Circular design principles are also applied more frequently: HP Inc. aims for 75% circularity in products and packaging by 2030 through initiatives like reselling pre-owned presses, which extend product lifespans and reduce waste (HP Inc., 2016).

Digital printing systems offer significant advantages over offset printing from an environmental perspective. By eliminating energy-intensive aluminum plate production, supporting short and customizable print runs, and reducing paper waste, these systems are well-suited to applications such as flexible packaging (Kodak, 2023). While the substrate and printing process account for the most significant environmental impacts across the lifecycle, the design of printers also presents opportunities for sustainability gains. For instance, optimizing material usage and recyclability in printer components can complement efforts to reduce the industry's environmental footprint (Kariniemi et al., 2010).

2.4. Research gap

The existing SDP approaches offer strategies for integrating sustainability into product development. They emphasize principles like recyclability, resource efficiency, and circularity (Byggeth et al., 2007; Russo, Rizzi, & Fayemi, 2017). However, many of these approaches assume expertise not always available in engineering teams, often requiring detailed data inputs or specialized knowledge, which limits their practical applicability.

The need for product-specific yet broadly applicable guidance remains a significant gap in achieving sustainability goals in product development. This limitation is particularly pronounced in digital printing systems, where tools like Life Cycle Assessment (LCA) and circularity indicators demand significant expertise and resources. Furthermore, existing voluntary eco-design guidelines for imaging equipment exclude high-speed industrial printers, leaving critical sustainability challenges in this sector yet to be addressed (European Commission, 2013).
Other frameworks focus on streamlined LCA at the organizational level, often leaving non-expert engineers needing the necessary tools to address sustainability at the product level (Clune & Lockrey, 2014; Russo & Spreafico, 2020).
This paper addresses the gap between general sustainability principles and their practical application in engineering. Specifically, it aims to:

1. Adapt the double diamond model to enable engineers to identify sustainability improvement opportunities using their domain knowledge, thus minimizing reliance on external experts.
2. Validate the approach through a case study on an industrial digital printing system, demonstrating its ability to guide the evaluation of improvement measures using LCA and circularity indicators.
3. Derive generally applicable, practical guidelines for sustainable printer design to be adapted and used within the industry.

This approach should provide engineers and designers with the tools to independently identify and address sustainability challenges without a need for profound sustainability knowledge.

3. Methodology

3.1. Literature review

A systematic literature review was conducted to identify relevant publications. As Blessing & Chakrabarti (2009) suggest, the keywords shown in Table 1 were logically linked and used for an advanced search within SCOPUS. Abbreviations were treated as synonyms on their own. The review excludes literature published before 2014, reduces the field of research to engineering, and only includes literature containing the keyword sustainability. Over 200 abstracts were screened for relevance. Technical white papers, special interest journals, basic literature, and regulatory documents from organizations like the European Union were additionally consulted.

Table 1. Research strategy plan for identifying existing methods for finding sustainability improvements in the context of digital printing

	Sustainability		Product Development	Digital Printing
OR	Ecodesign		Product Design	Industrial Printing
	Circularity		Design Thinking	Printing System
	Circular Economy	(CE)	Methodology	Digital Printer
	Triple Bottom Line	(TBL)	Framework	Industrial Printer
	Life Cycle Assessment	(LCA)		Imaging Equipment
	Life Cycle Costing	(LCC)		
	Life Cycle Inventory	(LCI)		
	AND			

3.2. The adapted double diamond model for sustainability improvements

The adapted double diamond for finding sustainability improvement potentials is shown in Figure 1. The focus is on the first diamond, as the Define phase should result in tangible requirements, i.e.,

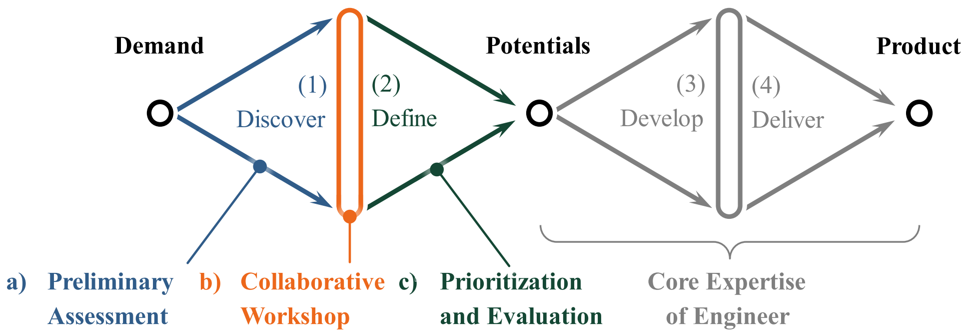


Figure 1. Double Diamond, adapted from the Design Council (2004), with essential phases for finding potential sustainability improvements

sustainability improvement potentials. From there onwards, the engineer can implement the identified potential according to their core expertise without a need for additional sustainability knowledge.
To enable engineers to find potential sustainability improvements, the following measures are considered during the first two phases of the Double Diamond:

a) **Preliminary Assessment:** The Discover phase is used to identify sustainability hotspots through surveys based on established sustainability principles and guidelines. This survey addresses all internal stakeholders, such as engineering, sales, quality assessment, etc. Participants are asked questions based on the categories (1) Using Standards and Guidelines for Sustainability, (2) Efficiencies, (3) Circularity, (4) Waste, (5) Longevity and Simplicity, (6) Renewable Resources, and (7) Over-exceeding Targets (Caldeira et al., 2022; Oh, 2017). Furthermore, participants are asked to rate the system regarding the Product Sustainability Index (Shuaib et al., 2014). Questions included open-ended responses and multiple-choice options. This process leverages the participant's knowledge and puts this into perspective regarding sustainability. To enhance the response rate, this process should be initiated internally and not by external consulting (Kraus & Kreitenweis, 2020).
b) **Collaborative Workshop:** During the transition between the Discover and Define phase, the survey results are evaluated by Qualitative Content Analysis (QCA) to identify specific areas for improvement (Mayring & Fenzl, 2014). Possible measures are then discussed, and promising ideas are developed further. Discussing these concretized topics with as many stakeholders as possible is crucial to enabling strategic decisions at an early design stage (Dewulf, 2013).
c) **Prioritization and Evaluation:** In the Define phase, QCA validates potential sustainability improvements according to the company's needs. Criteria may be mass, energy consumption, and material carbon footprint, but are not limited to them. This results in a weighted list of potential sustainability improvements.

Compared to other approaches, such as Clune and Lockrey's (2014) LCA-based framework, the presented approach focuses on the product level rather than organizational strategies. This makes it applicable to engineering contexts: No expertise in sustainability tools like LCA is needed, yet those tools may be used to validate the actual sustainability improvement of the proposed measures.

3.3. Case study setup

The study was conducted onsite at a digital printer manufacturer. Its objective was to identify and evaluate sustainability improvement potential that could lead to actionable design modifications. The decision-making process onsite focused on selecting feasible measures based on potential impact and implementation effort. To protect the manufacturer's interests, neither the printing system nor the manufacturer are stated here; part and unit names are changed and generalized. The employees involved in this study were engaged in developing, constructing, and manufacturing the printing system.

3.4. Process and evaluation

The process shown in Figure 2, according to the framework defined in Section 3.2, was presented and introduced in one of the manufacturer's department meetings.

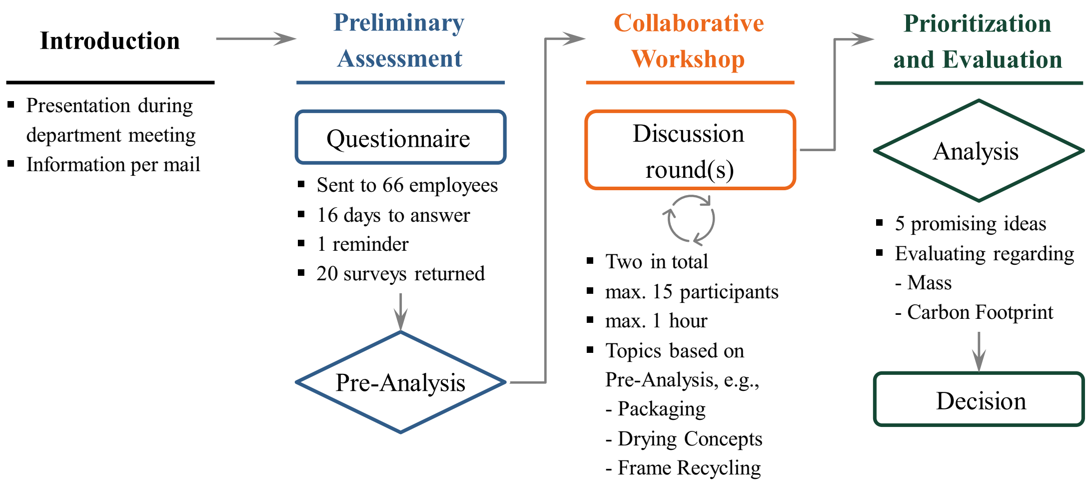


Figure 2. Case study setup showing the approach, including milestones and results

The preliminary assessment starts with a questionnaire initially tested with a small group of employees to ensure clarity and usability. The survey was then distributed digitally and in printed form to 66 employees, achieving a 30.3 % response rate after 16 days.

The data collected was reviewed during pre-analysis to prepare for discussion rounds. Most frequently, aspects related to efficiency during use, long lifetime and uncritical resources, and recycling occurred. Efficient manufacturing, reuse, and repairability also seemed essential to the participants. Responses were categorized based on themes such as parts, processes, materials, and sustainability principles. Categories frequently appearing or mentioned across departments were prioritized as potential improvement areas and discussed further during the discussion rounds.

Next, two discussion rounds were conducted. These sessions encouraged employees to expand on survey responses, explore additional topics, and share their perspectives on sustainability challenges. Topics discussed ranged from material usage and energy efficiency to logistics and packaging.

The insights from the questionnaire and the discussion rounds were analyzed using QCA regarding presumed cost, sustainable impact, and mass. This led to five discovered sustainability improvement potentials, three of which were selected for further investigation.

4. Results

4.1. Discovered sustainability potentials

As mentioned, the workshop identified five key topics with significant potential for sustainability improvement. Their assessment is shown in Table 2, which was based on QCA. The detailed topics are:

1. Recyclability of frame components: Improving recyclability by optimizing material selection, surface treatments, and disassembly.
2. Sheet metal offcuts: Reducing material waste during manufacturing by optimizing panel designs and cutting processes.
3. Reusing packaging components: Investigating the feasibility of returning and reusing transportation locks and angle brackets, reducing the need for new components.

Table 2. Evaluation results of identified potentials for sustainability improvement

Characteristic	**(1) Recycling frame components**	**(2) Sheet metal offcuts**	**(3) Reusing packaging components**	**(4) Drying concept efficiency**	**(5) Insulation material**
Mass	High	Medium	Medium	High	Low
Energy consumption	Low	/	/	High	Low
Carbon footprint	High	Medium	Medium	High	Low
Cost	High	Low	Medium	High	Low
Overall Potential	**High**	**Medium**	**Medium**	**High**	**Low**

4. Drying concept efficiency: Addressing energy consumption and emissions linked to drying processes and materials.
5. Insulation material: Using renewable insulation materials to reduce environmental impact.

Topic (5) insulation material showed lower overall improvement potential due to limited material usage and was not pursued further. In contrast, topic (4) drying concept efficiency was given a high sustainability potential; however, the opportunity for improvement mainly lay with process characteristics, such as the ink's chemical composition, and was not pursued further. This leaves the three topics (1) - (3) to explore in detail.

4.2. Implementation and validation of discovered potentials

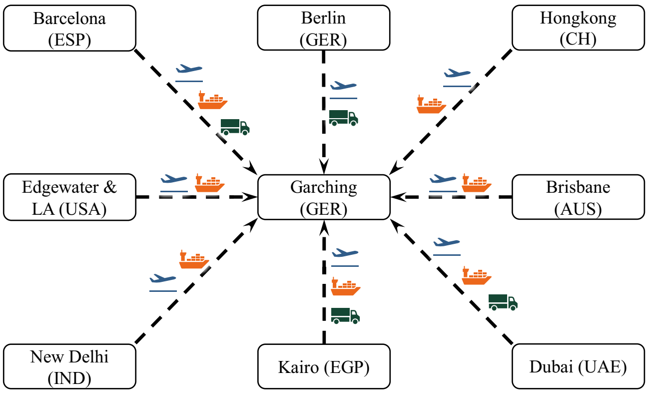
The three selected topics were investigated in agreement with the manufacturer. Their environmental impact was assessed using LCA and RPR. Based on the ReCiPe midpoint (H) method, LCA evaluated

Table 3. From idea to result of the examined sustainability potentials

	(1) Recyclability of Frame Components	(2) Sheet Metal Off-Cuts	(3) Reusing Packaging Components
Idea	Improve recyclability by increasing material purity	Reduce raw material demand by increasing material efficiency	Return and then reuse packaging material instead of manufacturing new ones
Implementation measure	Substitute blind rivets with different materials for the head and shaft with mono-material rivets (recycling-driven rivet selection)	Redesign stiffening structures for paneling doors so that they cause less waste material, e.g., by fitting better with standard steel panel sizes	After installation, return product-specific transportation locks (made of steel) by plane, ship, or truck
Functional constraints	No change in the assembly process	No significant downgrade regarding the doors' stability; No size or design changes	None
Validation: Investigated subject	Product structure of the printer's main module and its sub-modules	Four paneling concepts with reduced numbers of parts	Return scenarios from different locations and varying transportation
Validation: Method	RPR applied to the entire main module and its five sub-modules; Cost comparison of mono- and multi-material rivets	FEM: deformation and modal analysis of original and proposed designs; LCA: Compare impacts from raw material demand and jointing	LCA: Compare relevant life-cycle impacts of manufacturing and returning transportation locks; Cost comparison
Results	Utilization of up to 1.2 % of the remaining recyclability potential; Up to + 0.22 pp increase in RPR on sub-module level; Mono-material rivets are 2 – 4 times more expensive	Two acceptable concepts with slightly reduced mass and emissions, yet slightly worse stability	Returning is always more sustainable than manufacturing Returning by ship or truck is always cheaper; plane location dependent

carbon footprint, material efficiency, and metal depletion, while RPR used statistical entropy to compare recyclability before and after design changes. The results quantitatively validated each measure's sustainability potential. Table 3 summarizes the main concepts, constraints, and findings.

Firstly, to enhance the recyclability of the printer's frame components, blind rivets were substituted with mono-material variants made of steel for both the head and shaft. This change increases material purity and supports recyclability. Validation was conducted using the RPR metric applied to the printer's main module and sub-modules. The results indicate a utilization of up to 1.2 % of the remaining recyclability potential and an increase of 0.22 percentage points in the RPR metric on the sub-module level. However, mono-material rivets are more expensive, potentially impacting cost-effectiveness.



	Manu-facturing	Brisbane, via ship	New Delhi, via ship	Brisbane, via plane
Climate change	**100%** (ref.)	**6%**	**7%**	**44%**
	86%	*9%*	*12%*	*55%*
Particulate matter (PM) formation	**100%** (ref.)	**51%**	**39%**	**52%**
	86%	*64%*	*57%*	*66%*

Figure 3. Detailed results for Topic (3) reusing packaging components. Various reuse scenarios (left) in comparison to manufacturing (right); numbers represent the LCA midpoint impact

Next, raw material demand was reduced by aligning stiffening structures with standard sheet sizes, minimizing off-cuts. Finite Element Modeling (FEM) confirmed stability in some redesigns, leading to two concepts with lower mass and improved resource efficiency.

Finally, the reuse of transportation locks was evaluated as an alternative to manufacturing new locks. The proposed measure requires logistical adjustments, as the components must be returned and reused without additional processing. Different return scenarios are examined, incorporating locations and transportation modes like ships, airplanes, and trucks, as shown in Figure 3 (left). Results confirm that returning locks is consistently more sustainable than producing new ones. Figure 3 (right) shows those results, with the baseline scenario in **bold** and the comparison according to EU's JRC (2010) of the best-case manufacturing scenario with the worst-case transportation scenarios in *italics*. Even in worst-case scenarios, transportation is substantially more sustainable than a best-case manufacturing scenario. Additionally, transportation via ship or truck proved to be more cost-effective and environmentally friendly in general, while the viability of air transport is location-dependent.

5. Discussion

5.1. Validated sustainable impact

The three measures selected for detailed evaluation were chosen based on their assessed sustainability improvement potential, as indicated in Table 2. Replacing rivets with frame-compatible materials, such as steel for both the shaft and mandrel, supports closed-loop recycling processes. Concerns about the carbon footprint of materials like aluminum are irrelevant to the analyzed module due to the predominance of steel-based rivets. However, cost implications could limit adoption, as stated in Table 3. The assumption that all disassemblable components would be fully dismantled is likely impractical, making the results primarily theoretical regarding recyclability.

The evaluation of door paneling concepts identified two designs with improved material efficiency and acceptable stability. One concept reduced environmental impacts but had compromised stability due to its critical second natural frequency. At the same time, another concept met all stability criteria but required more raw material, resulting in higher environmental impacts. Further analysis is needed to evaluate the cost implications of these designs.

Returning transportation locks was shown to be more sustainable than manufacturing new ones, even in worst-case scenarios, as shown in Figure 3. The significant impact of raw materials on the environmental footprint highlights the importance of prioritizing reuse. However, broader sustainability considerations could have been assessed, including social aspects of international logistics such as labor conditions.

5.2. Practical implications

The following recommendations were extracted from the findings of this study and are aimed at improving the sustainability of industrial printer designs. Recommendations (1) - (3) were mainly derived from results of topics (1) and (2), while recommendations (4) - (7) were derived from topic (3).

1. To minimize offcuts and material waste, large sheet metal parts should be designed with dimensions that align with standard material panel sizes (e.g., divisions by 2, 3, or 4).

2. Rivets should be selected with shafts and mandrels made from the same material, ensuring compatibility with joint materials to facilitate recycling.
3. Stitch welding should be replaced with riveting for sheet steel joints whenever possible to reduce the carbon footprint.
4. Designers should familiarize themselves with the supplier's processes and efficiencies when designing externally manufactured parts to identify sustainability improvements.
5. Painted steel components should be returned and reused whenever feasible, as this is more sustainable than manufacturing new ones, provided quality and performance are maintained.
6. Returning parts for reuse should prioritize trucking within Europe and shipping (cargo) for international logistics to minimize environmental impact.
7. If galvanized steel requires additional protective painting, stainless steel should be evaluated as a potential replacement to reduce lifecycle environmental impacts.

While these recommendations are specific to the industrial printer sector and partly the manufacturer involved, similar recommendations can be easily obtained by applying the presented approach to other products or processes. Organizations can systematically address sustainability vulnerabilities and develop actionable improvements by adapting the framework to different fields.
Its accessibility to non-expert users ensures that a wide range of industries can integrate sustainability considerations into their product development processes, advancing circular economy principles and reducing environmental impact at a systemic level.

5.3. Limitations and future research

This study is limited in scope, as the approach was tested exclusively on digital printers. While the results demonstrate their potential for identifying sustainability vulnerabilities and proposing improvement measures, their applicability to other industries has yet to be examined. Future research should expand the framework's scope to different use cases to provide empirical evidence of its impact (Hohnbaum et al., 2024) and ideally include a benchmarking comparison with an established approach to further validate its effectiveness.
Furthermore, the Life Cycle Assessment (LCA) validation was conducted on specific components rather than the entire printer system, potentially overlooking broader environmental impacts and interdependencies. Incorporating a standardized circularity indicator into the process could further enhance its ability to assess resource efficiency.
Next, the reliance on survey-based data presents a vulnerability to biases. Differences in participants' sustainability knowledge and interpretations could introduce individual biases, as experts might overestimate their professional background and experience (Stylidis et al., 2020).
Additionally, the framework lacks a standardized circularity indicator, limiting resource efficiency assessment. LCA uncertainties in modeling and software algorithms also affect result accuracy, requiring cautious interpretation (De Oliveira et al., 2021).
Ultimately, while the proposed measures reduce environmental impact, quantifying the overall improvement remains challenging, as this study lacked comprehensive data to assess the full impact of the examined printing system. Although the results indicate a positive effect, these measures alone are unlikely to make industrial printers fully sustainable.

6. Conclusion

Sustainability is multifaceted and challenging, particularly when measuring impacts requires specialized expertise. Established tools like LCA or circularity indicators often must be made available to non-experts, presenting a barrier to broader adoption. This may hinder engineers from finding potential for sustainability improvements. To address this, the presented framework based on the double diamond model offers a practical, accessible solution for identifying sustainability improvement potentials.
A case study applied the presented framework to an industrial digital printer, leading to the development of three sustainability measures: (1) Enhancing the recyclability of frame components, (2) reducing sheet metal offcuts, and (3) reusing packaging materials. Validation through LCA and the RPR metric confirmed that all these measures would improve the printer's sustainability, demonstrating the framework's effectiveness in identifying impactful improvements.

Based on the case study, seven general recommendations for designing more sustainable printers were derived. The presented approach offers engineers and designers a simple and collaborative approach to detect sustainability improvement potentials.

Acknowledgment

This research was conducted as part of the TuWAs (FKZ: 16THB0007E) research project, funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

References

Bauer, T., Brissaud, D., & Zwolinski, P. (2017). Design for High Added-Value End-of-Life Strategies. In R. Stark, G. Seliger, & J. Bonvoisin (Eds.), *Sustainable Manufacturing* (pp. 113–128). Springer International Publishing. https://doi.org/10.1007/978-3-319-48514-0_8

Blessing, L. T. M., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. Springer London. https://doi.org/10.1007/978-1-84882-587-1

Boks, C., & Diehl, J. C. (2006). Integration of sustainability in regular courses: Experiences in industrial design engineering. *Journal of Cleaner Production*, 14(9–11), 932–939. https://doi.org/10.1016/j.jclepro.2005.11.038

Byggeth, S., Broman, G., & Robèrt, K.-H. (2007). A method for sustainable product development based on a modular system of guiding questions. *Journal of Cleaner Production*, 15(1), 1–11. https://doi.org/10.1016/j.jclepro.2006.02.007

Caldeira, C., Farcal, L. R., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (with Europäische Gemeinschaften). (2022). Safe and sustainable by design chemicals and materials: Framework for the definition of criteria and evaluation procedure for chemicals and materials. *Publications Office of the European Union*. https://doi.org/10.2760/487955

Clune, S. J., & Lockrey, S. (2014). Developing environmental sustainability strategies, the Double Diamond method of LCA and design thinking: A case study from aged care. *Journal of Cleaner Production*, 85, 67–82. https://doi.org/10.1016/j.jclepro.2014.02.003

De Eyto, A., Mc Mahon, M., Hadfield, M., & Hutchings, M. (2008). Strategies for developing sustainable design practice for students and SME professionals. *European Journal of Engineering Education*, 33(3), 331–342. https://doi.org/10.1080/03043790802088681

De Oliveira, C. T., Dantas, T. E. T., & Soares, S. R. (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. S*ustainable Production and Consumption*, 26, 455–468. https://doi.org/10.1016/j.spc.2020.11.024

Design Council. (2004). *The Double Diamond—Design Council*.https://www.designcouncil.org.uk/our-resources/the-double-diamond/

Dewulf, K. (2013). Sustainable Product Innovation: The Importance of the Front-End Stage in the Innovation Process. *In Advances in Industrial Design Engineering. IntechOpen*. https://doi.org/10.5772/52461

Directive on Corporate Sustainability Reporting, Directive (EU) 2022/2464 (2022). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:22016A1019(01)

European Commission. (2013). *Report from the Commission to the European Parliament and the Council on the Voluntary Ecodesign Scheme for Imaging Equipment*.https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013DC0023

European Commission. Joint Research Centre. Institute for Environment and Sustainability. (2010). International Reference Life Cycle Data System (ILCD) Handbook?:general guide for life cycle assessment: Detailed guidance. *Publications Office*. https://data.europa.eu/doi/10.2788/38479

Fetting, C. (2020). The European Green Deal. *ESDN Report*.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Guinée, J. (2016). Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges? In R. Clift &A. Druckman (Eds.), *Taking Stock of Industrial Ecology* (pp. 45–68). Springer International Publishing. https://doi.org/10.1007/978-3-319-20571-7_3

Hallstedt, S. I. (2017). Sustainability criteria and sustainability compliance index for decision support in product development. *Journal of Cleaner Production*, 140, 251–266. https://doi.org/10.1016/j.jclepro.2015.06.068

Hapuwatte, B. M., Mathur, N., Last, N., Ferrero, V., Reslan, M., & Morris, K. C. (2023).Optimizing Product Life Cycle Systems for Manufacturing in a Circular Economy. In H. Kohl, G. Seliger, & F. Dietrich (Eds.), *Manufacturing Driving Circular Economy* (pp. 419–427). Springer International Publishing. https://doi.org/10.1007/978-3-031-28839-5_47

Hohnbaum, K., Martins Pacheco, N. M., Ponn, J. C., & Zimmermann, M. (2024). Do Methods Work: On the Correlation of Method Application, Effort, and Product Quality. *Proceedings of NordDesign* 2024, 333–341. https://doi.org/10.35199/NORDDESIGN2024.36

HP Inc. (2016). Low environmental impact printing with HP Indigo Digital Presses. *For production of flexible packaging. HP Development*. h20195.www2.hp.com/V2/GetDocument.aspx?docname=4AA7-5259ENW

HP Inc. (2022). Go Beyond. 2022 *HP Sustainable Impact Report. HP Development*. https://www8.hp.com/h20195/v2/GetPDF.aspx/c08636600.pdf

Jawahir, I. S., Dillon, O. W., Rouch, K. E., Joshi, K. J., Venkatachalam, A., & Jaafar, I. H. (2006). *Total Life-Cycle Considerations in Product Design for Sustainability: A Framework for Comprehensive Evaluation.*

Kariniemi, M., Nors, M., Kujanpää, M., Pajula, T., & Pihkola, H. (2010). Evaluating Environmental Sustainability of Digital Printing. *NIP & Digital Fabrication Conference*, 26(1), 92–96. https://doi.org/10.2352/ISSN.2169-4451.2010.26.1.art00025_1

Kodak. (2023). KODAK PROSPER Presses. *Unlock the power of digital print. Eastman Kodak Company*.https://www.kodak.com/content/products-brochures/KODAK-PROSPER-Press-Platform-Brochure-EN.pdf

Kraus, R., & Kreitenweis, T. (2020). Führung messen: Inklusive Toolbox mit Messinstrumenten und Fragebögen. *Springer Berlin Heidelberg*. https://doi.org/10.1007/978-3-662-60518-9

Lindemann, U., Hessling, T., Hutterer, P., & Mörtl, M. (2001). Applicable methods for sustainable development for small and middle-size companies. *Proceedings Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 180–183. https://doi.org/10.1109/ECODIM.2001.992342

Lindemann, U., Mörtl, M., Hessling, T., & Hutterer, P. (2002). The Guideline "Design for Upgrading " as a Medium for Sustainable Design. Proceedings of DESIGN 2002, *the 7th International Design Conference*, 1331–1338.

Lindemann, U., Mörtl, M., & Rath, S. (2000). A Design Methodology for the Recycling of simple and complex Products. *R'2000-Recovery, Recycling, Re-Integration, 5th World Congress on Integrated Resources Management and Envirotech Trade Show*.

Martins, M. G., Nunes, A. O., Mancini, S. D., Belli, C., Rocha, T. B., & Moris, V. A. S. (2024). Comparative analysis of life cycle assessment and material circularity indicator: Study applied to smart electricity meter polycarbonate parts. *Journal of Material Cycles and Waste Management*, 26(6), 3777–3786. https://doi.org/10.1007/s10163-024-02077-4

Mayring, P., & Fenzl, T. (2014). Qualitative Inhaltsanalyse. InN. Baur & J. Blasius (Eds.), *Handbuch Methoden der empirischen Sozialforschung* (pp. 543–556). Springer Fachmedien. https://doi.org/10.1007/978-3-531-18939-0_38

Mengistu, A. T., Dieste, M., Panizzolo, R., & Biazzo, S. (2024). Sustainable product design factors: A comprehensive analysis. *Journal of Cleaner Production*, 463, 142260. https://doi.org/10.1016/j.jclepro.2024.142260

Oh, S. (2017). From an Ecodesign Guide to a Sustainable Design Guide: Complementing Social Aspects of Sustainable Product Design Guidelines. *Archives of Design Research*, 30(2), 47–64. https://doi.org/10.15187/adr.2017.05.30.2.47

Ranganathan, J., Corbier, L., Bhatia, P., Schmitz, S., Gage, P., Oren, K., Dawson, B., Spannagle, M., McMahon, M., Boileau, P., Frederick, R., Vanderborght, B., Thomson, F., Kitamura, K., Woo, C. M., Pankhida, N., Miner, R., Segalen, L., Koch, J., . . . Cook, E. (2023). *GHG Protocol Initiative Team.*

Roithner, C., Cencic, O., Honic, M., & Rechberger, H. (2022). Recyclability assessment at the building design stage based on statistical entropy: A case study on timber and concrete building. *Resources, Conservation and Recycling*, 184, 106407. https://doi.org/10.1016/j.resconrec.2022.106407

Russo, D., Rizzi, C., & Fayemi, P.-E. (2017). An Industrial Application of a TRIZ Based Eco-Design Approach.In G. Campana, R. J. Howlett, R. Setchi, & B. Cimatti (Eds.), *Sustainable Design and Manufacturing* 2017 (Vol.68, pp. 909–918). Springer International Publishing. https://doi.org/10.1007/978-3-319-57078-5_85

Russo, D., Rizzi, C., & Spreafico, C. (2017). How to Build Guidelines for Eco-Improvement. In G. Campana, R. J. Howlett, R. Setchi, & B. Cimatti (Eds.), *Sustainable Design and Manufacturing* 2017 (Vol. 68, pp. 879–887.). Springer International Publishing. https://doi.org/10.1007/978-3-319-57078-5_82

Russo, D., & Spreafico, C. (2020). TRIZ-Based Guidelines for Eco-Improvement. *Sustainability*, 12(8), 3412. https://doi.org/10.3390/su12083412

Shuaib, M., Seevers, D., Zhang, X., Badurdeen, F., Rouch, K. E., & Jawahir, I. S. (2014). Product Sustainability Index (ProdSI): A Metrics-based Framework to Evaluate the Total Life Cycle Sustainability of Manufactured Products. *Journal of Industrial Ecology*, 18(4), 491–507. https://doi.org/10.1111/jiec.12179

Stylidis, K., Wickman, C., & Söderberg, R. (2020). Perceived quality of products: A framework and attributes ranking method. *Journal of Engineering Design*, 31(1), 37–67. https://doi.org/10.1080/09544828.2019.1669769

Van Weenen, J. C. (1995). Towards sustainable product development. *Journal of Cleaner Production*, 3(1–2), 95–100. https://doi.org/10.1016/0959-6526(95)00062-J

Wiesner, M. (2022). Nachhaltige Produktentwicklung. In S. Vajna (Ed.), *Integrated Design Engineering: Interdisziplinäre und ganzheitliche Produktentwicklung* (pp. 387–428). Springer. https://doi.org/10.1007/978-3-662-60439-7_12