

DECISION SUPPORT FRAMEWORK for CIRCULAR ADDITIVE MANUFACTURING: STAMPING DIE PRODUCTION and REPAIR

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Abstract: Additive Manufacturing (AM) holds significant potential for sustainability and circularity. Its near-net-shape production reduces material waste, enables the manufacturing of complex geometries, and extends product life through repair and remanufacturing. These capabilities make AM a key enabler of circular economy strategies such as reuse, repair, and remanufacture. However, current Life Cycle Assessment (LCA) methodologies are not fully adequate to capture AM's circular contributions. Most LCA models are designed for linear production systems and fail to incorporate AM-specific parameters such as powder reuse, repair frequency, and support structure recovery. Furthermore, data gaps in widely used databases limit the generalizability and reliability of LCA results, making it difficult to integrate AM into sustainability-driven decision-making frameworks in industry.

In this study, an industrial stamping die was evaluated by comparing conventional casting-based manufacturing with AM-based production and repair using Direct Metal Laser Sintering (DMLS) and Directed Energy Deposition (DED). The environmental impacts were modelled in SimaPro using ReCiPe Midpoint impact categories, and sensitivity analyses were conducted on critical parameters such as powder reuse rate, repair frequency, and transport distance. The results demonstrated that, compared with casting, AM significantly reduces material consumption and waste while extending die life and lowering the need for new die production.

Through this comparative assessment, the study provides a data-driven approach for monitoring circularity in real time and presents a decision-support framework that can be adopted by manufacturers to optimize repair strategies and material recovery in industrial tooling systems.

1. Introduction and Motivation

Global manufacturing industries are increasingly confronted with pressures to reduce environmental impacts while enhancing resource efficiency. Within this context, the circular economy (CE) provides a systemic alternative to the traditional linear production paradigm by seeking to preserve the value of products and materials throughout multiple life cycles [1].

AM, a production approach in which three-dimensional parts are fabricated layer by layer directly from digital models, has emerged as a central technological enabler of CE strategies due to its near-net-shape capabilities, the ability to fabricate highly complex geometries, and its potential to extend component lifetimes through repair and remanufacturing [2]. Additionally, it supports localized material recirculation and on-demand production, thereby reducing transportation needs, minimizing excess inventory, and enabling more agile and circular supply-chain configurations [3].

Despite these strengths, quantitatively assessing the sustainability and circularity performance of AM remains challenging within conventional Life LCA frameworks. Existing LCA models were largely developed for linear manufacturing systems and therefore fail to fully capture AM-specific characteristics such as powder reuse, multi-cycle repair loops, support-structure generation and removal, or powder degradation across reuse cycles [4]. Moreover, widely used LCA databases provide limited and sometimes inconsistent foreground data for metal AM processes, introducing uncertainty into environmental impact assessments and constraining the integration of AM into operational decision-support tools [3].

These limitations highlight the need for a more holistic and operationally grounded evaluation of AM processes. Addressing this gap, the present study systematically compares additive and conventional manufacturing routes with respect to their environmental and circularity performance. The analysis identifies key performance indicators (KPIs) that critically influence material and energy flows across the process, factory, and system levels—including powder efficiency and energy consumption at the process level, maintenance strategies and scrap recovery at the factory level, and transportation distances and repair-facility placement at the system level. Through this integrated multi-level perspective, the study underscores the importance of aligning operational decisions with system-level CE strategies when evaluating the circularity potential of AM. It demonstrates how AM-enabled repair can significantly contribute to lifecycle extension and resource efficiency, and provides practical insights into how manufacturers can incorporate CE principles more systematically into tooling and industrial component management.

2. Review of Related Work

CE has gained wide recognition as a systemic resource-management approach aimed at preserving the value of products and materials across multiple life cycles. AM, through its near-net-shape capabilities, potential for topology-optimized geometries, and opportunities for extending component life through repair and remanufacturing, plays an increasingly important role as a technological enabler of CE principles [5–9]. To implement CE strategies effectively within AM-enabled industrial operations, decision-support mechanisms that integrate circularity, sustainability, quality and cost indicators are essential. Prior studies have compared conventional and AM technologies across dimensions such as quality, processing time, cost, and environmental impacts [7]; evaluated manufacturing technologies through the R9 sustainability framework [10]; and proposed multi-criteria models that combine environmental, technical and economic assessment perspectives [11].

The development of such decision-support mechanisms requires the definition of measurable circularity and sustainability indicators. To this end, the literature proposes a wide range of frameworks—from macro-level policy instruments (e.g., CEAP, OECD CE Inventory), to system-level monitoring models (e.g., the Circularity Gap Framework, Eurostat CE monitoring), and product-level assessment tools (e.g., ReSOLVE, the Material Circularity Indicator), as well as the ISO 59000 series. These frameworks help identify inefficiencies in resource use and support the implementation of sustainability-aligned practices across supply chains. However, most existing indicators in the literature remain predominantly focused on material flows, exhibit limited integration with economic performance metrics, and fall short of providing the process-level data required to support operational decision-making [12].

While numerous studies have assessed the environmental performance of AM using LCA [10,13,14], the majority rely on linear production logic and therefore inadequately reflect AM-specific process characteristics such as powder reuse, powder degradation, multi-cycle repair strategies, support structure generation and recovery, or energy-intensive powder-atomization stages [3, 4]. Recognizing these gaps, several researchers have proposed methodological extensions. For example, [3] calls for expanding LCA databases with AM-specific foreground data, while [15] recommends integrating circularity indicators—such as Material Circularity Metrics—alongside multi-lifecycle scenarios within LCA modelling. In related work, [4] emphasizes the critical importance of representing powder reuse, post-processing steps, and end-of-life (EoL) strategies within AM system modelling. Furthermore, [16] argues for broadening LCA into a more comprehensive sustainability assessment by incorporating economic and social dimensions. These contributions collectively underscore the need for more dynamic, circularity-focused, and multi-dimensional evaluation approaches tailored to AM.

Besides, for KPIs to be monitored across the product lifecycle, consistent and standardized data flows are required. While enterprise systems such as ERP, MES, and PLM provide foundational capabilities for capturing process data, most existing platforms are not designed to support multi-cycle lifecycle tracking or dynamic circularity metrics [15, 17]. Moreover, manufacturing data are often fragmented across different functional units and digital platforms [1, 18, 19], creating significant barriers to CE implementation—especially in AM, where decisions related to component refurbishment, repair timing, and material reuse depend on accurate process history and material-quality data. Studies such as [20, 21] additionally note that data incompatibility and lack of interoperability across AM value-chain systems further hinder the adoption of circularity-driven operational strategies.

To summarize, the literature indicates that although AM clearly offers substantial opportunities for the circular economy, significant research gaps remain regarding the modelling of environmental performance from a multi-lifecycle perspective, the development of AM-specific circularity indicators, and the standardization of data flows. This study addresses these gaps by examining the environmental and circular impacts of AM-based repair strategies and by identifying the information-flow requirements necessary for CE-oriented decision-support frameworks.

3. Technology Approach

This study evaluates the environmental and circularity impacts associated with the production and operational life of an industrial stamping die used in metal-forming processes. The steel-based die, which requires high surface quality and geometric stability, is treated as a component that undergoes periodic wear during use and therefore necessitates scheduled repair interventions.

Within this scope, the process flows of three alternative production–repair strategies were modelled and examined comparatively: (i) conventional manufacturing of the die followed by full re-manufacturing at end-of-life – *CM Mold* (Figure 1); (ii) DED-enabled repair applied to a conventionally manufactured die – *CM Mold AM Repair* (Figure 2); and (iii) additive manufacturing of the die using DMLS, combined with DED-based repair throughout its entire service life – *AM Mold AM Repair* (Figure 3).

For each of these strategies, both Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) were conducted. Additionally, key circularity KPIs were evaluated, and a sensitivity analysis was performed to determine how critical process parameters influence overall.

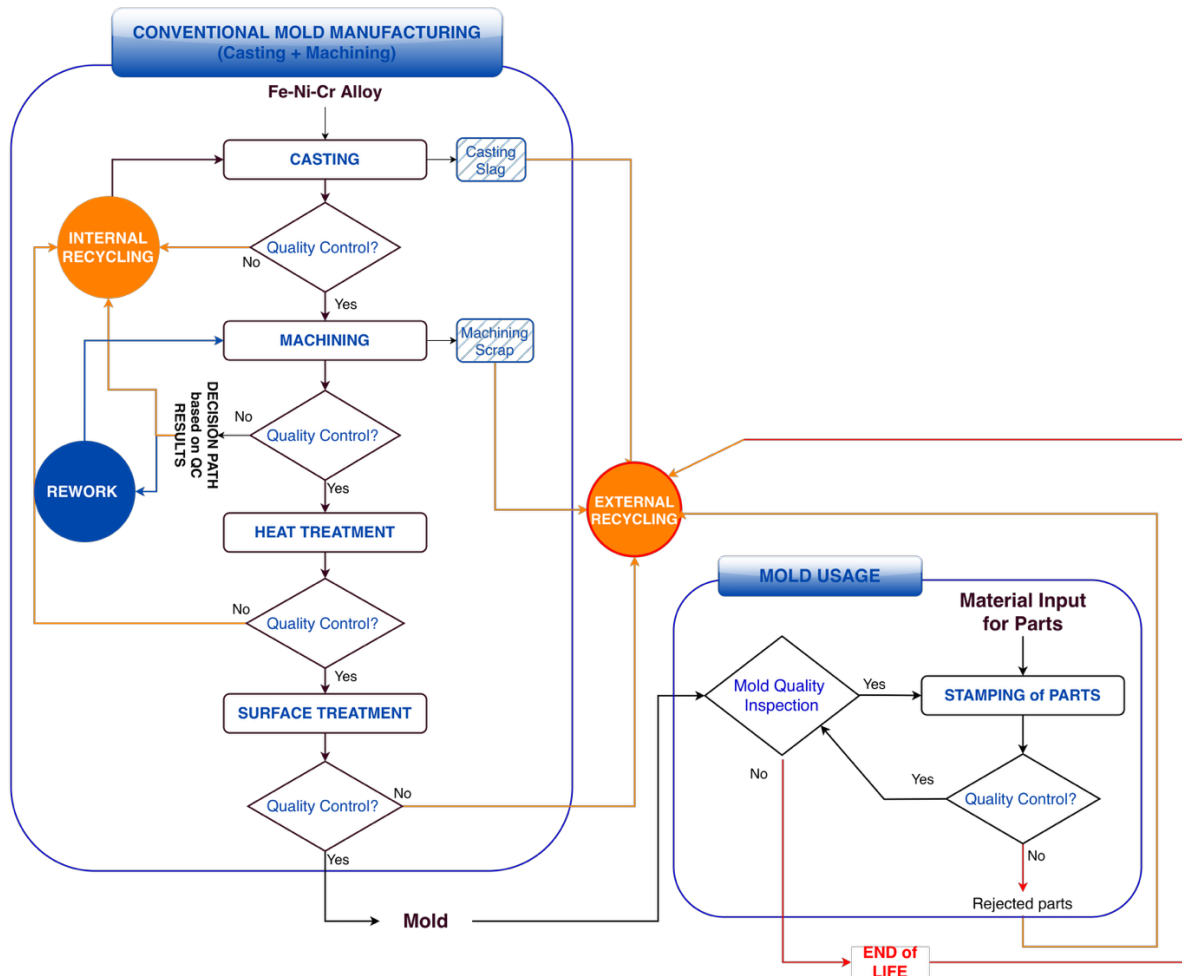


Figure 1. CM Mold - conventional manufacturing of the mold followed by re-manufacturing at end-of-life

3.1. Methodology

3.1.1 Sustainability Assessment

Due to the limited availability of detailed metal AM process data in existing LCA databases, the model was constructed using process parameters extracted from the literature, proxy values, and manually defined circularity assumptions. Processing times, energy consumption, powder efficiency, and post-processing steps for DMLS and DED were derived from published studies [22, 23], while parameters such as powder reuse rate, support-removal efficiency, rejection rate, and repair-cycle frequency were incorporated based on data reported in comparable AM studies and expert input from industry practitioners.

LCA calculations were performed in SimaPro using the EcoInvent database. The model consisted of background processes—including raw material extraction, electricity production, transportation, steel recycling, and end-of-life treatment—represented through EcoInvent, and foreground processes defined in this study, namely casting, machining, DMLS, and DED. Environmental impact assessment was conducted using the ReCiPe 2016 Midpoint (H) method. Following categories highlighted as critical for AM in the literature [9], the analysis included global warming potential (GWP), ionizing radiation (IR), fine particulate matter formation (FPM), photochemical ozone formation, terrestrial acidification, fossil resource scarcity, and water consumption. Freshwater eutrophication was excluded due to its negligible contribution. For flows involving material recovery, a mass-based allocation approach was applied, and environmental credits from recovered materials—such as casting waste, DMLS support scrap, and unused DED powder—were incorporated using an avoided burden approach.

The LCC analysis was developed to cover the major cost elements in AM literature [5, 18, 24].

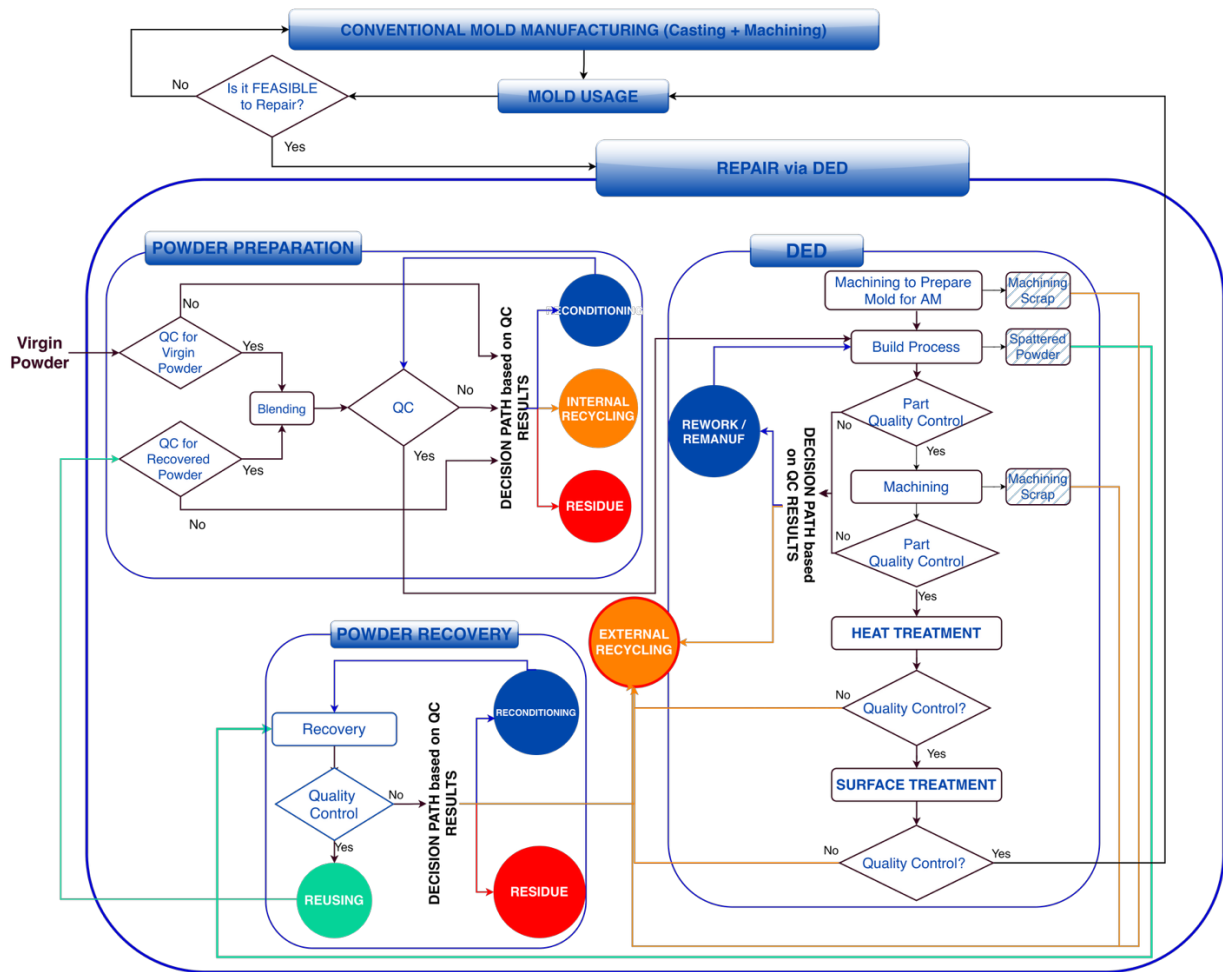


Figure 2. CM Mold AM Repair - DED enabled repair on the conventionally manufactured mold

3.1.2 Circularity and Sustainability Assessment Parameters

In this study, the key circularity and sustainability parameters governing the lifecycle performance of the stamping die were modelled using four primary variables. *Powder efficiency* and *powder reuse* represent the proportion of powder in DED that does not fuse to the part and can be recovered for subsequent use; both parameters exhibit wide variability in the literature [18, 25]. *Scrap recovery* refers to the reintegration of a defined fraction of support-structure scrap generated during DMLS production back into the powder-production cycle, and is considered a critical flow for material circularity in AM-based processes. *Transport distance* was included in the model due to its influence on logistics-related emissions, particularly in scenarios with frequent repair needs. Among these variables, *repair frequency* is one of the most influential parameters; it was defined by monitoring die wear through the rejected-part rate and reflects the relationship between quality performance and repair timing.

To ensure consistent comparison across scenarios, other input parameters—such as die weight, process energy consumption, and nominal die lifetime—were held constant. The model also generated dependent outputs including total number of repairs, quantity of rejected parts, and net material consumption after recovery.

A sensitivity analysis was conducted to evaluate the influence of these parameters on model behaviour. Considering the broad ranges reported in the literature, DED powder efficiency was examined between 15–90% [26–28], and powder reuse between 0–100% [29, 30], with a baseline reuse rate of 50%. The maximum allowable rejection rate used to trigger a repair was varied between 0.1% and 1.0%, with a baseline value of 0.5% representing a moderate maintenance strategy. Under this baseline assumption, the model corresponds to approximately four repair cycles over the functional lifetime of the mold, and repeated repair interventions contribute directly to the observed lifetime extension in the AM-based scenarios relative to conventional mold manufacturing. Transport distance was evaluated over a 0–500 km range to reflect industrial practice, incorporating both on-site and remote-repair scenarios. This analysis was used to define the boundary conditions of the circularity KPIs established in the study and to assess the model's sensitivity to key process parameters.

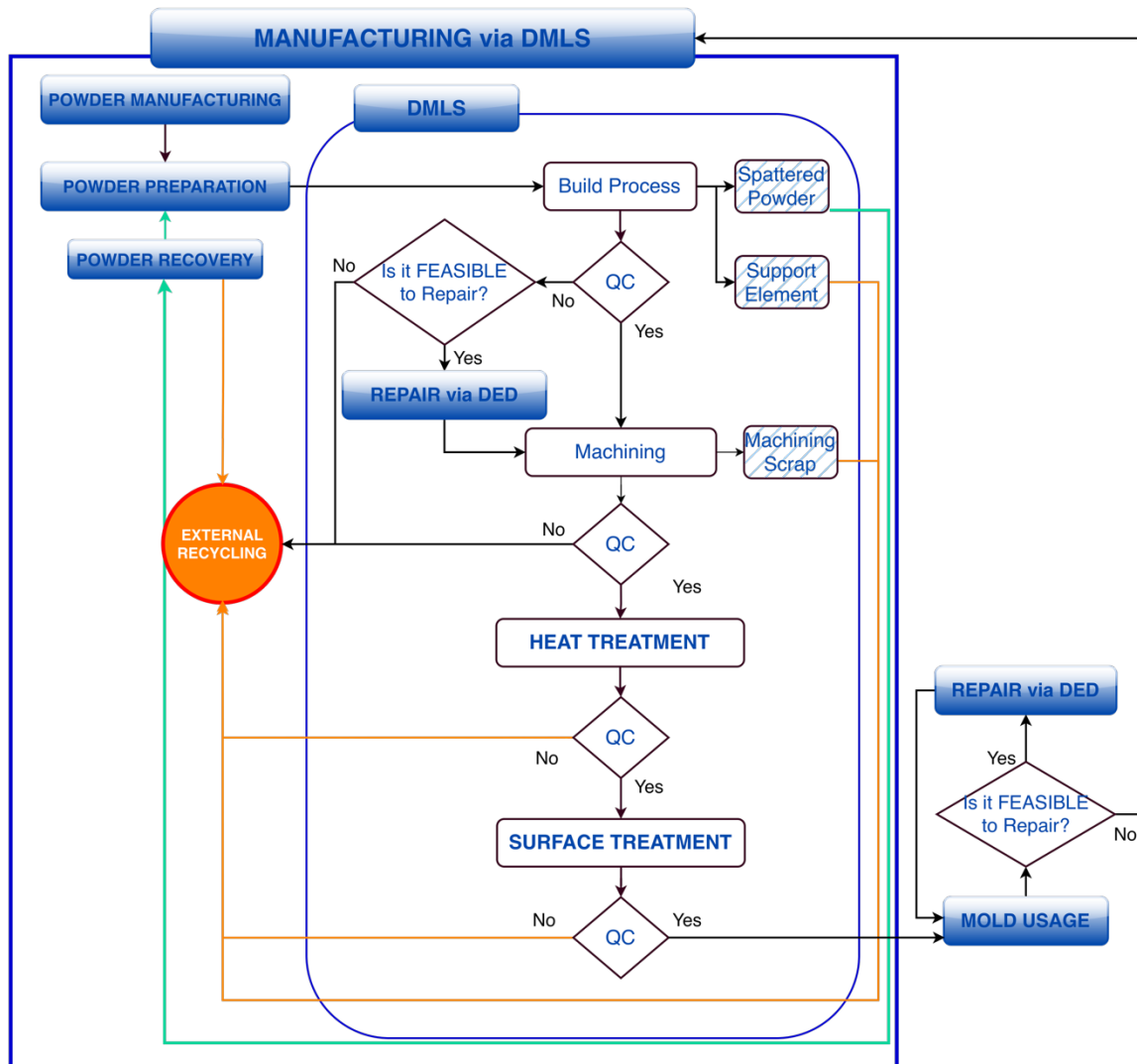


Figure 3. AM Mold AM Repair - manufacturing of the mold using DMLS and repairing with DED throughout its entire service life

3.2. Results of Circularity and Sustainability Assessment

3.2.1 Environmental Impact & Material Consumption Comparison

The LCA results indicate that among the three production–repair scenarios, the highest environmental impact occurs in the conventional mold manufacturing route (Figure 4).

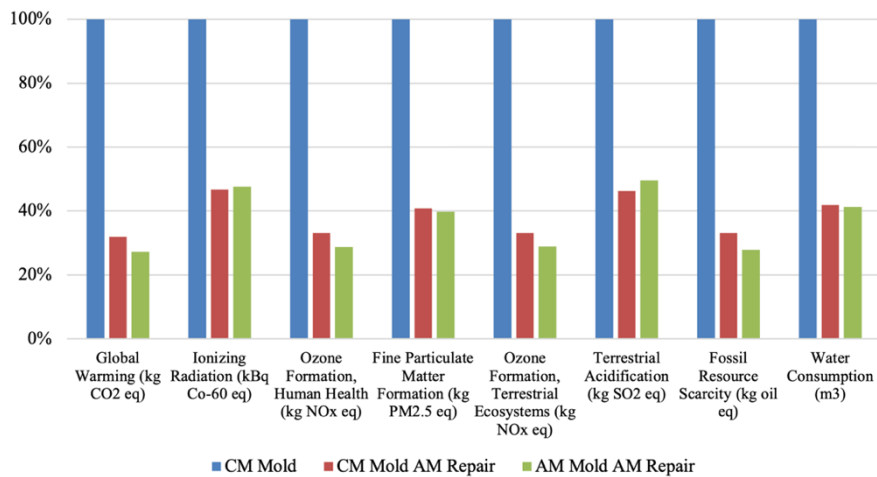


Figure 4. Environmental Impacts of All Scenarios

Because this scenario lacks any repair possibility, the mold must be fully remanufactured at the end of its service life, leading to more than a twofold increase in material and energy consumption and generating substantial burdens across all impact categories. In contrast, scenarios incorporating AM-based repair significantly reduce raw-material use and rejected-part-related impacts by extending the mold’s service life. Among these, the “AM Mold + AM Repair” option yields the lowest impacts in most environmental categories. The only exceptions are ionizing radiation and terrestrial acidification, where slightly higher values are observed due to the energy-intensive nature of laser-based AM processes.

The impact categories that most clearly differentiate the scenarios are GWP, IR, and FPM, as illustrated in Figure 5. In the conventional scenario, the majority of the environmental burden stems from rejected-part generation, whereas AM-based repair strategies substantially reduce the rejected-part rate. Although the energy demand associated with AM repair introduces additional load in the IR category, the environmental benefits gained from avoiding raw-material production clearly outweigh this increase. Consequently, both AM repair scenarios deliver a significant improvement in overall environmental performance compared with conventional manufacturing.

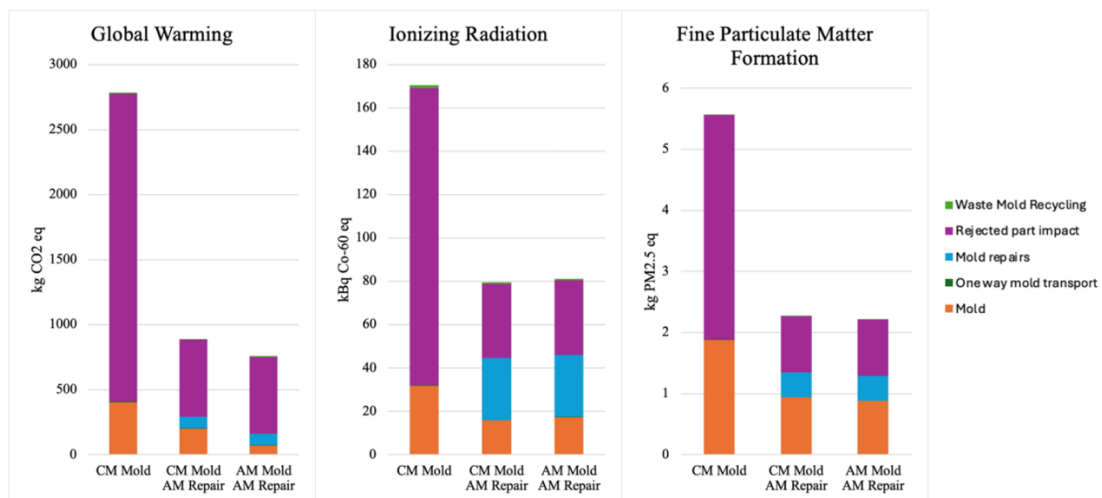


Figure 5. Comparison of Lifecycle Impact Contributors

When the mold is produced with AM, the distribution of environmental impacts across contributing processes is shown in Figure 6a, while Figure 6b further details the impact contributors within the DMLS process. The results indicate that the majority of the environmental burden arises from the DMLS process, and in particular from metal powder production. Powder atomization is the dominant contributor to the GWP and FPM categories, whereas electricity consumption during laser sintering is the primary driver in the IR category. In Figure 6a, minor contributions are also associated with auxiliary post-processing steps, such as electrical discharge machining, used for local finishing operations. Conversely, the high level of recovery achieved for support-structure scrap generates an avoided-burden effect, which serves as an important mechanism for reducing the total environmental impact.

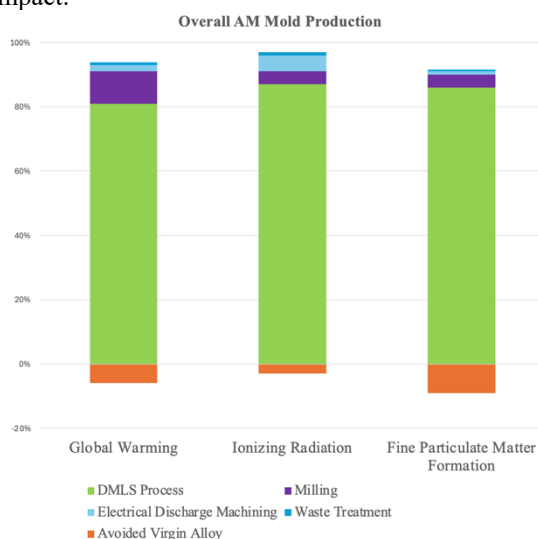


Figure 6a. Impact Contributors for Overall AM Mold Production

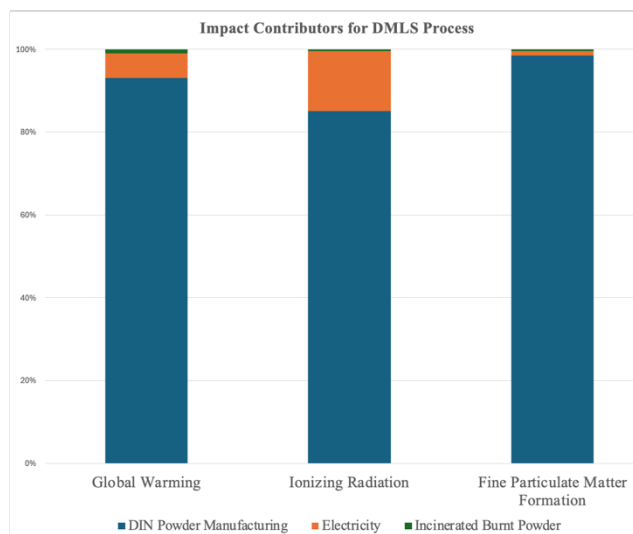


Figure 6b. Impact Contributors for DMLS Process

The contributions associated with the mold repair process are presented in Figure 7. The DED operation is the dominant contributor across all impact categories due to its high energy demand and the long duration of laser-based deposition; the use of metal powder and argon gas further amplifies this burden. However, improvements in powder efficiency and the recovery of milling scrap reduce net material consumption, creating an avoided-burden effect that enhances the environmental performance of the repair process. Although increasing repair frequency raises both energy consumption and transportation requirements, the avoidance of primary material production ensures that AM-based repair strategies still offer a clear environmental advantage compared with conventional remanufacturing.

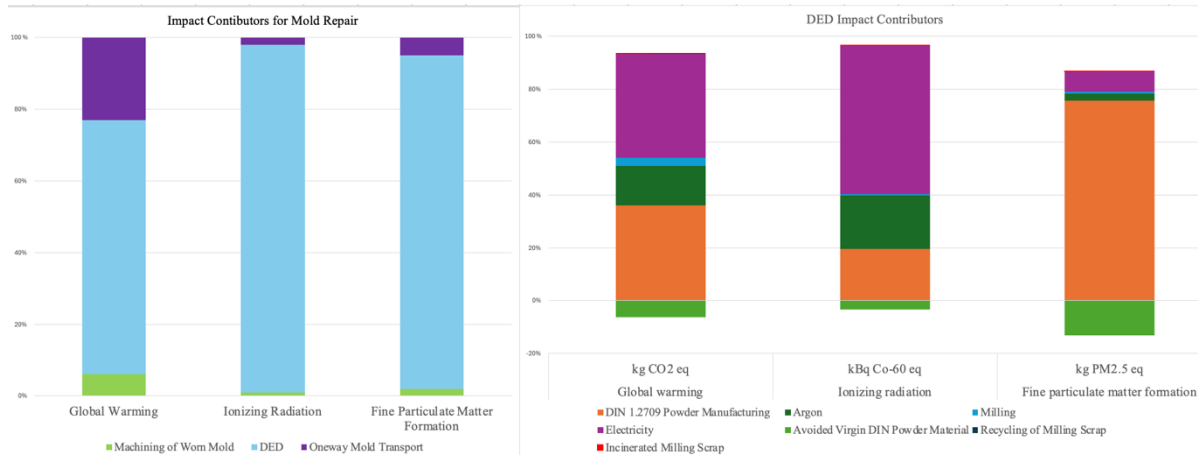


Figure 7a. Impact Contributors for Mold Repair

Figure 7b. Impact Contributors for DED Process

Overall, the results demonstrate that despite the energy-intensive nature of DMLS and DED processes, AM-based repair strategies significantly reduce total environmental impacts through material circularity, support-scrap recovery, and the closure of raw-material loops. This finding confirms that AM repair methods can play a critical role in the sustainable management of metal tooling systems.

3.2.2 Interpretation of LCC Results

The LCC results show that costs are predominantly concentrated in the repair stages (Figure 8). While the conventional “CM Mold” scenario exhibits the lowest total cost, the “AM Mold + AM Repair” scenario results in the highest overall cost due to both the elevated manufacturing cost of additively produced molds and the cumulative cost of repeated AM-based repair operations. This cost difference is primarily driven by the high unit price of metal powder used in additive manufacturing and the energy- and time-intensive nature of laser-based processes.

The disaggregated cost distribution for the repair process is presented in Figure 9. More than 80% of the total repair cost originates from process-related expenditures, particularly energy consumption. Material costs account for a comparatively smaller share, and transportation and waste-management expenses remain minimal within the overall cost structure.

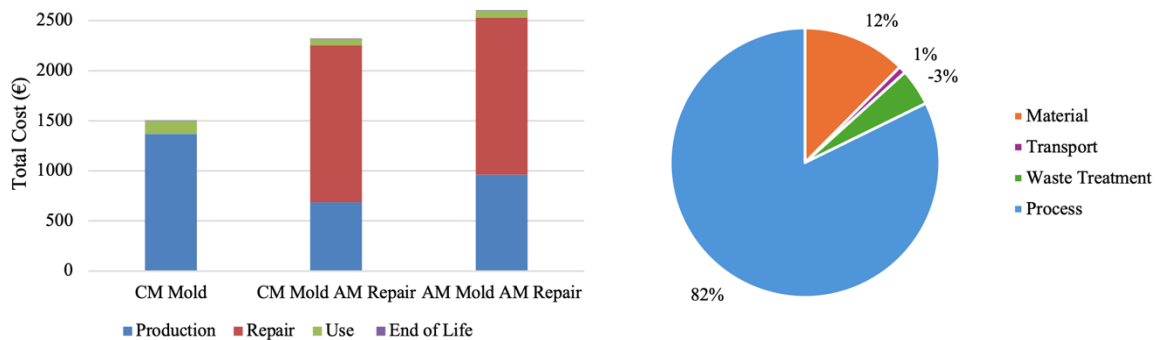


Figure 6. Comparison of Total Lifecycle Cost

Figure 7. Cost Breakdown of Repair

Overall, the LCC findings indicate that although AM-based manufacturing and repair strategies offer notable environmental advantages, they still entail relatively high economic costs. Therefore, improving process efficiency, enhancing powder-utilization effectiveness, and optimizing repair frequency are essential for achieving a balance between circularity benefits and economic feasibility.

3.2.3 Sensitivity Analysis Outcomes

Within this study, the influence of circularity parameters on the model's environmental performance was examined in detail. The most critical determinant was repair frequency: more frequent, small-volume repairs were found to substantially reduce overall environmental impacts by lowering both material consumption and energy use. Improvements in powder efficiency and powder reuse similarly contributed to reduced impacts by decreasing the upstream energy burden associated with metal powder production, resulting in notable reductions in the GWP and IR categories. Scrap recovery provided an additional avoided-burden benefit by enabling the reintegration of DMLS support structures into a closed-loop material cycle, thereby further mitigating total environmental impact. In contrast, transport distance partially diminished the advantages of AM-based repair—particularly beyond the 250–400 km range—due to increased logistics-related emissions. Collectively, these findings demonstrate that the environmental and circularity performance of AM-enabled repair strategies is highly sensitive to process efficiencies and supply-chain conditions.

3.3. Decision Support Framework

The proposed decision-support framework determines the optimal production–repair strategy for stamping dies by comparing new manufacturing options (CM or DMLS) with DED-based repair alternatives in terms of quality performance, circularity indicators, and environmental impacts. The framework integrates an LCA–LCC structure that incorporates a rejection-rate–based repair-trigger mechanism and holistically evaluates the influence of four critical parameters—*powder efficiency*, *powder reuse*, *scrap recovery*, and *repair frequency*—on lifecycle performance. In doing so, it provides decision-makers with a dynamic roadmap that identifies, under varying operational and supply-chain conditions, which approach offers superior environmental performance, higher circularity, and improved economic viability.

4. Discussion

This study systematically compared new production routes (CM or DMLS) with DED-based repair strategies for stamping dies, revealing the conditions under which each pathway provides a more sustainable and circular solution. The findings show that DED-enabled repair can extend die lifetime by a factor of two to three, significantly reducing raw-material demand and yielding substantial improvements in impact categories such as GWP, FPM, and fossil resource scarcity. These results confirm that lifecycle extension serves as a critical leverage point for environmental sustainability in material-intensive manufacturing systems.

Although DMLS-produced dies initially exhibit higher energy demand, this burden is offset during use by repeated DED repair cycles. The recovery of support-structure scrap and the reuse of unfused powder further strengthen material circularity within the AM production–repair chain by mitigating the high upstream impacts associated with powder atomization. The results demonstrate that material recovery is a central mechanism for enhancing the environmental performance of AM processes.

The proposed decision-support framework indicates that system performance is highly sensitive to powder efficiency, powder reuse rate, scrap recovery, and repair frequency. Among these parameters, repair frequency is the most influential, as it governs both energy and material flows. Frequent, small-scale repairs triggered by the rejection rate effectively control wear progression and reduce environmental impacts, whereas delayed, large-volume repairs lead to higher energy consumption due to extended DED processing. Transport distance, on the other hand, diminishes the benefits of AM-based repair beyond the 300–400 km range, underscoring the importance of regionalizing repair services.

Despite its contributions, the study has certain limitations. First, due to the limited availability of detailed foreground data for AM processes in LCA databases, several parameters were estimated using literature values and expert judgement. This introduces uncertainty, particularly regarding energy consumption in DMLS powder production and DED process efficiency. Second, regional variations in electricity mixes and emission factors restrict the generalizability of the results to other geographical contexts. Third, the repair-trigger mechanism is based on the rejected-part rate, while real industrial environments often rely on more complex multi-sensor wear-monitoring systems, which fall outside the scope of this model. Finally, the economic model includes only direct manufacturing and repair costs, excluding indirect cost drivers such as production planning, downtime, or operational logistics.

Overall, the study demonstrates that AM-based repair holds strong potential to improve circularity and sustainability in industrial tooling, though these benefits are highly dependent on process efficiency, supply-chain characteristics, and maintenance strategies. Methodologically, the presented decision-support framework integrates a rejection-rate-based repair trigger with circularity parameters, LCA/LCC results, and operational considerations, providing a coherent and condition-dependent basis for determining whether new manufacturing or repair should be preferred in stamping-die applications. In doing so, AM is positioned not merely as an alternative manufacturing route, but as a strategic enabler of circularity when deployed under appropriate conditions.

5. Conclusions & Recommendations

This study demonstrates that integrating additive manufacturing into the lifecycle of industrial stamping molds can enable substantial gains in circularity and resource efficiency, provided that repair processes are triggered at the right intervals and supported by effective material recovery practices. The comparative analysis shows that DED-based repair, when applied within appropriate operational conditions, offers a clear reduction in material consumption and environmental burden, while DMLS-based mold production becomes advantageous only when its higher initial energy demand is compensated by multiple repair cycles. These findings underscore that the benefits of AM are not inherent but conditional, emerging when process efficiencies, powder reuse and localized repair operations align within a repair-centric lifecycle strategy.

The decision support framework developed in this work provides a structured basis for determining whether a mold should be repaired or newly produced, combining rejection-rate monitoring with AM-specific circularity parameters and lifecycle performance indicators. This framework offers a practical starting point for manufacturers seeking to integrate circularity principles into tooling decisions and highlights that the environmental and economic value of AM lies in its ability to support extended use rather than simple substitution of conventional production routes.

Future work should focus on validating the framework with real-time production data, expanding AM-specific databases, and integrating advanced wear monitoring to refine repair timing decisions. Broader system-level studies, including logistics, downtime and region-specific energy mixes, will further enhance the decision-making robustness for industrial deployment.

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7. References

- [1] Lindahl, E., Dahlin, J.-E., Bellgran, M. A framework on circular production principles and a way to operationalise circularity in production industry. *Cleaner Production Letters*, 4, 100038, 2023.
- [2] Khalid, M., Peng, Q. Sustainability and environmental impact of additive manufacturing: A literature review. *Computer-Aided Design and Applications*, 18(6), 1210–1232, 2021.
- [3] Ribeiro, I., et al. Framework for life cycle sustainability assessment of additive manufacturing. *Sustainability*, 12(3), 929, 2020.
- [4] Rahmani, R., Bashiri, B., Lopes, S.I., Hussain, A., Maurya, H.S., Vilu, R. Sustainable additive manufacturing: An overview on life cycle impacts and cost efficiency of laser powder bed fusion. *Journal of Manufacturing and Materials Processing*, 9(1), 18, 2025.
- [5] Bahuriddin, N.S., Mat Saman, M.Z., Mohamad-Ali, N., Ngadiman, N.H.A., Mohd Maulana, M.I.I. State of sustainability assessments of metal additive manufacturing: Literature review and triple-bottom-line perspectives. *Environmental Science and Pollution Research*, 32, 20825–20843, 2025.
- [6] Bhatt, V., Roy, S. Sustainable manufacturing through additive manufacturing and recycled materials. *Journal of Advance Manufacturing System and Technology*, 10(1), 35–46, 2025.
- [7] Catalano, A.R. The role of wire-based additive manufacturing processes in the 6Rs sustainability framework. Doctoral dissertation, Politecnico di Torino, 2022.
- [8] Chiriță, A.-P., Borș, A.-M., Benescu, A.-A. New trends and developments of additive manufacturing in the field of hydraulic drive systems according to the circular economy concept. *Hidraulica – Magazine of Hydraulics, Pneumatics, Tribology, Ecology, Sensorics, Mechatronics*, (2), 37–47, 2023.
- [9] Mani, M., Lyons, K.W., Gupta, S.K. Sustainability characterization for additive manufacturing. *Journal of Research of the National Institute of Standards and Technology*, 119, 419–428, 2014.
- [10] Ikonen, M. Sustainability analysis for microwave receiver for maritime radar repeater using the R9 strategies. Master's thesis, Lappeenranta–Lahti University of Technology (LUT), 2025.
- [11] Yosofi, M., Kerbrat, O., Mognol, P. Framework to combine technical, economic and environmental points of view of additive manufacturing processes. *Procedia CIRP*, 69, 118–123, 2018.
- [12] Sherif, Z., Sarfraz, S., Jolly, M., Salonitis, K. Identification of the right environmental KPIs for manufacturing operations: Towards a continuous sustainability framework. *Materials*, 15(21), 7690, 2022.
- [13] Sandberg, C., Tinglöv, E. Business model innovation for additive manufacturing: A case study of an established actor in the metal manufacturing industry. Master's thesis, Lund University, Faculty of Engineering LTH, Division of Innovation Engineering, 2021.
- [14] Agnusdei, L., Del Prete, A. Additive manufacturing for sustainability: A systematic literature review. *Sustainable Futures*, 4, 100098, 2022.

- [15] Farooq, A., Chairat, S., Gheewala, S.H. Application of life cycle assessment for evaluating circular product systems. *Circular Economy and Sustainability*, 4(3), 1937–1959, 2024.
- [16] Taddese, G., Durieux, S., Duc, E. Sustainability performance indicators for additive manufacturing: A literature review based on product life cycle studies. *The International Journal of Advanced Manufacturing Technology*, 107(7–8), 3109–3134, 2020.
- [17] Anjaria, K. Enhancing sustainability integration in sustainable enterprise resource planning (S-ERP) system: Application of transaction cost theory and case study analysis. *International Journal of Information Management Data Insights*, 4(2), 100243, 2024.
- [18] Syu, F.-S., Vasudevan, A., Despeisse, M., Chari, A., Turanoglu Bekar, E., Gonçalves, M.M., Estrela, M.A. Usability and usefulness of circularity indicators for manufacturing performance management. *Procedia CIRP*, 105, 835–840, 2022.
- [19] Schmitt, T., Wolf, C., Lennerfors, T.T., Okwir, S. Beyond “leanear” production: A multi-level approach for achieving circularity in a lean manufacturing context. *Journal of Cleaner Production*, 318, 128531, 2021.
- [20] El Haouat, Z., Essalih, S., Bennouna, F., Ramadany, M., Amegouz, D. Environmental optimization and operational efficiency: Analysing the integration of life cycle assessment (LCA) into ERP systems in Moroccan companies. *Results in Engineering*, 22, 102131, 2024.
- [21] Brändström, J., Saidani, M. Comparison between circularity metrics and LCA: A case study on circular economy strategies. *Journal of Cleaner Production*, 371, 133537, 2022.
- [22] Stieberova, B., Broumova, M., Matousek, M., Zilka, M. Life cycle assessment of metal products produced by additive manufacturing: A metal mold case study. *ACS Sustainable Chemistry & Engineering*, 10(16), 5163–5174, 2022.
- [23] Gouveia, J.R., Pinto, S.M., Campos, S., Matos, J.R., Sobral, J., Esteves, S., Oliveira, L. Life cycle assessment and cost analysis of additive manufacturing repair processes in the mold industry. *Sustainability*, 14(4), 2105, 2022.
- [24] Shanawad, A. Cost estimation, budgeting, and OEE analysis for binder jetting at Sandvik Additive Manufacturing Division. Master’s thesis, KTH Royal Institute of Technology, Department of Production Engineering and Management, Stockholm, Sweden, 2023.
- [25] Ponis, S., Aretoulaki, E., Maroutas, T.N., Plakas, G., Dimogiorgi, K. A systematic literature review on additive manufacturing in the context of circular economy. *Sustainability*, 13(11), 6007, 2021.
- [26] Liu, Z., Jiang, Q., Cong, W., Li, T., Zhang, H.-C. Comparative study for environmental performances of traditional manufacturing and directed energy deposition processes. *International Journal of Environmental Science and Technology*, 15(11), 2273–2282, 2017.
- [27] Böckin, D., Tillman, A.-M. Environmental assessment of additive manufacturing in the automotive industry. *Journal of Cleaner Production*, 226, 977–987, 2019.
- [28] Svozilova, S., Zetková, I., Santa Marin, J.F., Torres Garay, J.A. Evaluation of recycled and reused metal powders for DMLS 3D printing. *Materials*, 17, 6184, 2024.
- [29] Morrow, W.R., Qi, H., Kim, I., Mazumder, J., Skerlos, S.J. Environmental aspects of laser-based and conventional tool and die manufacturing. *Journal of Cleaner Production*, 15, 932–943, 2007.
- [30] Müller, V., Fasselt, J. M., Kruse, T., Klötzer, C., Kleba-Ehrhardt, R., Choma, T., Biegler, M., Rethmeier, M. Using ultrasonic atomization to recycle aluminium bronze chips for additive laser directed energy deposition. *IOP Conf. Ser.: Mater. Sci. Eng.*, 1296, 012036, 2023.

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