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Life cycle assessment-guided design for sustainable microinjection molds

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Abstract. Integrating Life Cycle Assessment (LCA) into the microinjection mold design phase enables a comprehensive comparison between Conventional Injection Molding (CIM) and Topological Optimized Injection Molding (TOIM) approaches. By combining Topological Optimization (TO) with LCA, this research evaluates the environmental impacts across four phases: material production, mold manufacturing, use phase, and end-of-life. Results highlight that, while CIM demonstrates lower initial environmental impacts, TOIM achieves better overall performance when the mold's lifecycle is considered. The sustainable break-even point for TOIM is reached around 68.50% of the mold's lifespan, attributed to energy recovery during the use phase. Additionally, recycling scenarios underline the importance of material recovery in reducing Cumulative Energy Demand. This study demonstrates that integrating LCA into early design stages and employing TO can significantly enhance sustainability in microinjection molding, offering a practical framework for balancing environmental and operational efficiency.

Introduction

The injection molding and microinjection molding process is a widely used technology for the mass production of polymer components and products featuring complex geometries with high precision and surface quality. Due to the high surface-to-volume ratios, successfully filling small cavities and intricate features demands elevated temperatures and pressures to prevent premature solidification and incomplete parts. In this context, process simulation and mold optimization are essential for refining the design phase, effectively addressing potential issues and minimizing complications during the production phase.

The core focus of this work is the sustainable optimization of molds, initially based on Topological Optimization (TO). Indeed, it is essential to develop the process sustainably to align with the European Union's goal of achieving net-zero emissions by 2050. The TO technique is widely used in aerospace, automotive and bio-medical fields and has been developed to provide a mathematical tool to the designers helping them in minimizing the amount of material used in parts' production [1-3]. Ren et al. [4] provided a structural scheme optimization design for the stationary platen of a plastic injection molding machine. In particular, to reduce the deflection of the stationary platen, they used the Finite Element Method (FEM) to optimize its structure.

They found an optimal topology model by variable density method, then, they performed further structural Topology Optimizations (TOs) by removing 50, 60 and 70% of material. Finally, the two recommended optimization schemes are compared with the original structure. They show that by choosing the best alternative, the volume and the local maximal stress of the platen could be decreased, corresponding to cost-saving material and better mechanical properties. Indeed, by removing unnecessary material, it is possible to reduce mold mass, lowering heating times and energy consumption. Excess material is typically removed by conventional techniques such as milling. In this field, several researchers have analyzed the process both from a numerical [5] and experimental perspective, for conventional materials such as aluminum and steel [6] and even superalloys [7,8].

On the other hand, alternative manufacturing techniques, such as Additive Manufacturing (AM), are particularly advantageous in this context due to their capability to produce complex and highly optimized geometries. TO combined with AM has revolutionized lightweight design in metal forming and structural applications [9]. In addition, AM is a tool to prototype and debug the tooling that will be used to mold the desired part. This approach can significantly reduce material costs associated with the tooling validation and debugging phase, as well as save both engineering and equipment time. While the material properties and surface finish of parts molded with AM tooling may not match those of parts produced with machining technique, the method offers a cost-effective and time-efficient solution during the development phase [10].

On the other hand, from an environmental perspective, industrial emissions have increased by 60% worldwide between 1990 and 2023 due to the growing global demand for industrial goods [11]. Therefore, it is crucial to focus on mitigating pollutant emissions, given their impact on both the environment and human health, by incorporating the Life Cycle Assessment (LCA) methodology.

Research suggests that reducing the weight of components contributes to lowering environmental emissions [11,12]. However, as demonstrated by [13], accurately assessing the greenhouse gas benefits of lightweight requires a comprehensive LCA analysis. In this regard, the work aims to propose an LCA-guided design framework for sustainable microinjection molds, considering, at this stage, only machining operations. The research presents a comprehensive comparison between Conventional Injection Molding (CIM) and Topology Optimized Injection Molding (TOIM), through a three-stage methodological framework: (1) initial design space definition using computer-aided engineering tools with micro-molding specific requirements/constraints, (2) iterative TO process, and (3) final design refinement incorporating manufacturability constraints.

The LCA methodology [14] investigates three key aspects: the energy consumption during the operating life of the mold, the environmental impact of manufacturing processes in the production of the mold, and the potential for material recovery and recycling at the End-of-Life (EoL). In this manner, the optimization of material amount and distribution was simultaneously linked with the change in carbon footprint.

Materials and methods

The proposed methodology is applied to a specific case study in microinjection molding, considering the experimental equipment and process parameters described in [15]. The HASCO K20 molds analyzed in this study are made of AISI H13 stainless steel (X5CrNi18-10), whereas the material used during the injection process is Polyoxymethylene (POM) BASF Ultraform N2320 003. The densities of both materials are summarised in Table 1.

Table 1 – Mechanical properties of the investigated materials [16].

	Density [kg/m^3]	Young's Modulus [GPa]	Tensile Strength Yield [MPa]	Tensile Strength Ult. [MPa]	Elong. at break [%]
H13	7,848.00	210.00	1,650.00	1,990.00	9.00
POM	1,410.00	2.70	65.00	71.10	9.40

Case study design. The specific component to be molded is the input to start with the analysis. The process parameters were set as follows: melt temperature 200°C, mold temperature 90°C, holding pressure 180 bar, automatic filling control, velocity/pressure switchover, and pack/holding control. Fig. 1 (a) shows the geometry of the selected case study to be molded, a thin wall connector meshed with 183,069 tetrahedral elements in Autodesk Moldflow Adviser 2023. From the polymer filling simulation, a maximum of about 46.52 MPa is reached, with a clamping force equal to 0.24 tonnes. These data were considered as input for the structural analysis and TO using Ansys Finite Element (FE) software.

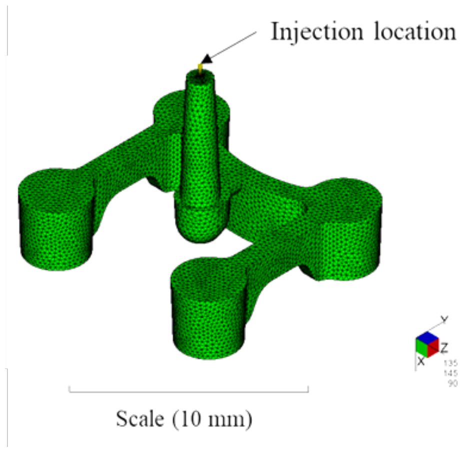

Figure 1 – Mesh of the selected case study to be molded.

The HASCO K20 molds mounted on the DESMA Tec formicaPlast® 1K injection machine [17,18] imported in Ansys are shown in Fig. 2 (a), while Fig. 2 (b) reports load and boundary conditions considering a safety factor of 1.5. Fig. 2 (c) highlights the injection pressure in the insert cavity. The assembly was meshed considering an average element size of 3 mm and a refinement parameter of 1 in the cavity of the object to be molded, obtaining 127,841 nodes and 75,328 elements. A frictionless behavior was set at the contact regions as it avoids introducing non-linearities that would increase the computational effort as there are small sliding involved. This makes it possible to estimate the mold opening, which would otherwise be impossible to achieve with a bonded contact.

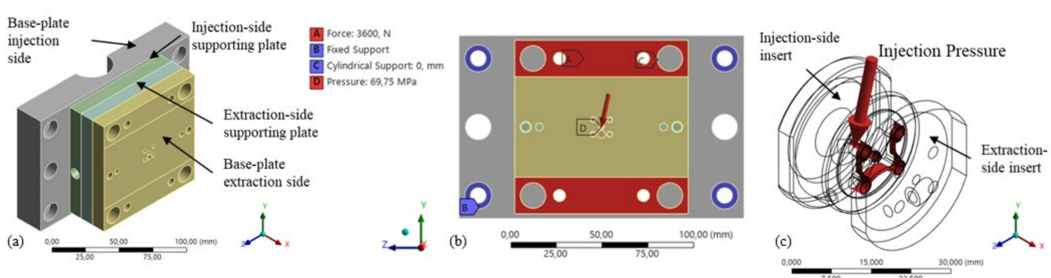

Figure 2 – (a) Geometry of the mold and setup, (b) Load and boundary conditions, (c) injection pressure in the cavity of the insert.

Static structural simulations were performed with this FE model. Fig. 3 (a) depicts the Von Mises stress on the assembly, which served as the baseline for the subsequent TO process. The design regions considered in this work for optimization are highlighted in Fig. 3 (b), along with the excluded region at the boundary conditions location.

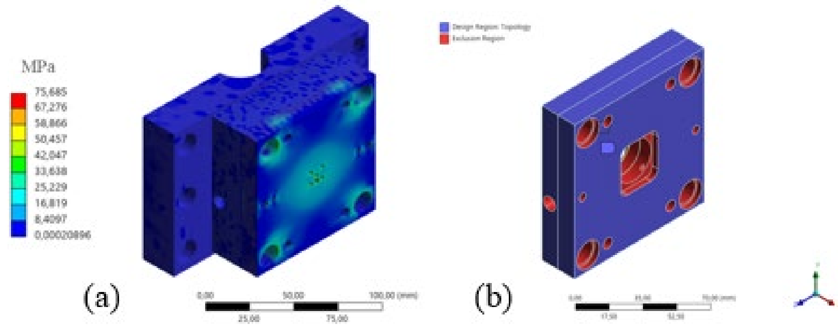

Figure 3 – (a) Von Mises stress on the assembly; (b) Design region for TO.

Density-based TOs were carried out with the objective of minimizing the compliance of the plate by redistributing 60% of the initial mass in the appropriate areas for the injection-side supporting plate and 20% for the extraction-side one. Fig. 4 shows the workflow from static structural results of the initial geometry of the designed mold to refined geometry for both the injection-side and extraction-side supporting plates.

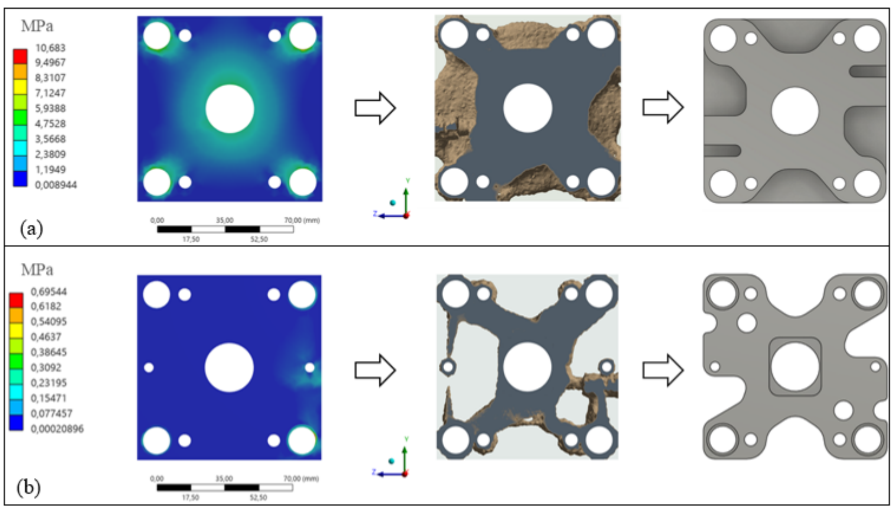

Figure 4 – Workflow from static structural results to refined geometry for: (a) Injection-side supporting plate, and (b) Extraction-side supporting plate.

The optimized geometries underwent Computer Aided Design (CAD) refinement for machining operations, maintaining the functional features, including thermocouple ports and cooling channels network. The final design achieved an average of 22% mass reduction across both plates compared to the conventional design. An important factor influencing the LCA analysis is the total weight of the material required for each mold, including the waste generated during the machining operation. Based on this, the initial volume of the billet used for machining was determined by calculating the volume needed to fully encompass the machined component. The main dimensions of the initial geometry of the molds are 95 mm x 95 mm x 12 mm for height, length and width, respectively. The weight of CIM and TOIM used in the study are provided in Table 2. Indeed, the analyzed case study comprises two molds, one for the injection side and one for the extraction side, with the same initial geometry. In the LCA analysis, the combined weight of both molds for conventional and topologically optimized mold is considered as a single aggregate value.

Table 2 – Weight of the investigated components.

Manufacturing Process	Overall employed material [kg]	Mold [kg]
CIM	2.07	1.24
TOIM	2.07	1.02
Deviation	-	-22%

Life Cycle Assessment methodology

Comparative LCA of two different process configurations, namely CIM and TOIM processes, in manufacturing a component in POM was conducted. The comparison included the TO of molds, developed in the case study design section, versus a non-optimized mold inherited by HASCO [18]. The midpoint assessment focusing on Global Warming Potential (GWP) and endpoint damage to human health and ecosystems were reported, in addition, the Cumulative Energy Demand method was used in the study. Specifically, the LCA study involves four main phases detailed as follows.

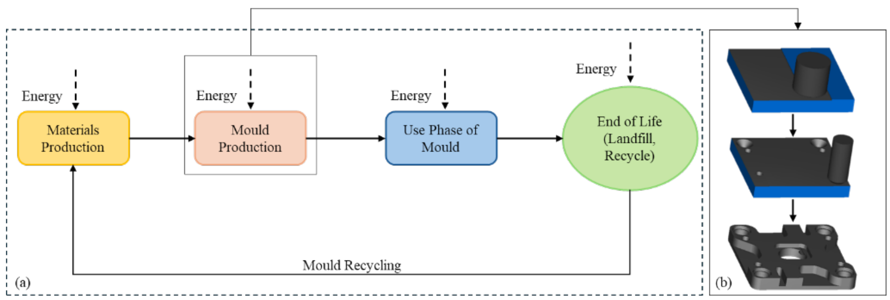

Figure 5 – (a) System boundary of the injection molding process;(b) FeatureCam simulation setup.

Goal & Scope. The product system under investigation comprises molds used in the microinjection molding process, manufactured and optimized through machining technologies. The functional unit selected for this study is a yield stress-constrained formulation within these molds, as detailed in case study design section. The yield strength is constrained by a specific limit determined by the material properties of the mold. The system boundary includes all relevant unit processes, including raw material extraction, mold manufacturing, use phase, and EoL scenarios, as described in Fig. 5 (a). The study does not account for the environmental impacts of transportation between these unit processes. Recycling of materials is considered within a closed-loop system, where the avoided impacts are allocated to the corresponding manufacturing processes [6].

Life Cycle Inventory. Life Cycle Inventory (LCI) consists of an inventory list of data collected for all the processes indicated in the system boundaries [6]. In this work, the analysis focuses on the energy quantification for the material production energy; in this case, the Ecoinvent database was used. Once extracted, the material is manufactured (i.e., casting and tempering) to obtain a billet to be machined. The required energy and process time were extracted from the literature [6], while simulations were performed using FeatureCam Ultimate software [19]. Regarding the simulation setup, as shown in Fig. 5 (b), it was configured with one main phase comprising four sub-phases and two elementary operations, which involve contouring and drilling processes. The simulation objective was defined to optimize the process time by reducing the number of tool changes. Specifically, nine tools were used, including a planer, end mill, center drill, and twist drill. Moreover, the product manufacturing was simulated to obtain the process energy for CIM and TOIM, whose masses result from the optimization analysis, as detailed in the case study design section. The energy consumption during the use phase of both molds was included in the analysis. The energy required for POM injection and auxiliary operations by the compressor was measured using the Efergy E2 device, while the energy for heating and moving the molds was calculated analytically. The heating thermal energy was estimated by considering the specific heat and the mass of the molds for a temperature change (ΔT) from 25°C to 90°C. The handling energy was calculated considering the machine specifications, namely a 40 mm opening and closing stroke of the molds on linear ball bearing slides with a friction coefficient of 0.02. In detail, the handling energy was estimated by calculating the work done by the equipment with both CIM and TOIM. The cycle time for injection operations was extracted from DESMA TEC formicaPlast® 1K [17] and resulted in 10.5 sec. During the EoL phase, two different scenarios were investigated. Firstly, the energy associated with the landfilling of EoL molds and chips from machining operations was considered. Secondly, the energy required for remelting and recycling the chips and molds at the end of their life was taken into account. These assumptions were made to obtain a quantification of the worst- and best-case scenarios. The recycling rate for steel and chips used during the recycling operations was 98% and 90%, respectively, according to the literature [6,20]. The energy consumption considered in the LCA analysis was modeled based on the electricity market in Italy. The Ecoinvent V3.10 data provided by SimaPro 9.6.0.1 software and information extracted by experimental setup and literature were combined and calculated for the two investigated processes, e.g., detailed values of energy and masses, as summarized in Table 3.

Table 3 – LCI literature data and calculated data for the entire life cycle.

Material Production [MJ/kg]		Product manufacturing [kWh]			Use phase [kWh]			EoL [MJ/kg]	
Material extraction	26.42 [21] (CIM/TOIM)	Machining	15.37 [calc.] (CIM)	34.79 [calc.] (TOIM)	Injection	0.67 [det.] (CIM/TOIM)		Land-fill	0.39 [21] (CIM/TOIM)
Material casting	2.90 [22] (CIM/TOIM)	Tempering	33.00 [23]		Compressor operation	1.42 [det.] (CIM/TOIM)		Recycling*	24.90 [21] (CIM/TOIM)
					Heating	37.69 [kJ] [det.] (CIM)	30.99 [kJ] [det.] (TOIM)		
					Molds movement	4.93E-04 [Wh] [calc.] (CIM)	3.60E-04 [Wh] [calc.] (TOIM)		

Life Cycle Impact Assessment (LCIA). To assess the impact of conventional and topologically optimized mold used in the microinjection molding process IMPACT World+ Midpoint and Endpoint methods version 1.04 were used, all available in the SimaPro 9.0.6.1 software [21]. The analysis focuses on the quantification of GWP required for the material extraction used in mold manufacturing by using the Ecoinvent database. Consequently, according to the literature [22], the material was utilized to produce a billet through a casting process. The energy used in the manufacturing processes from mold manufacturing to the use phase was quantified from simulations and energy measuring. Lastly, at the EoL two different scenarios were considered, i.e., landfill and recycling through material remelting.

Results and Discussion

The GWP results are schematized in the networks of Fig. 6, which outline the unit processes involved in mold manufacturing. Looking at Fig. 6, the output of networks for the best scenario accounted for 12.00 and 20.20 kg CO_2 eq for the CIM and TOIM process, respectively. The GWP analysis reveals a trade-off between the two manufacturing approaches. It highlights that the mold optimization phase increases the overall GWP value, whereas the use phase allows for a slight energy recovery. However, this recovery is almost negligible when considering only a single cycle. This underlines the importance of evaluating the entire life cycle rather than focusing on single phase.

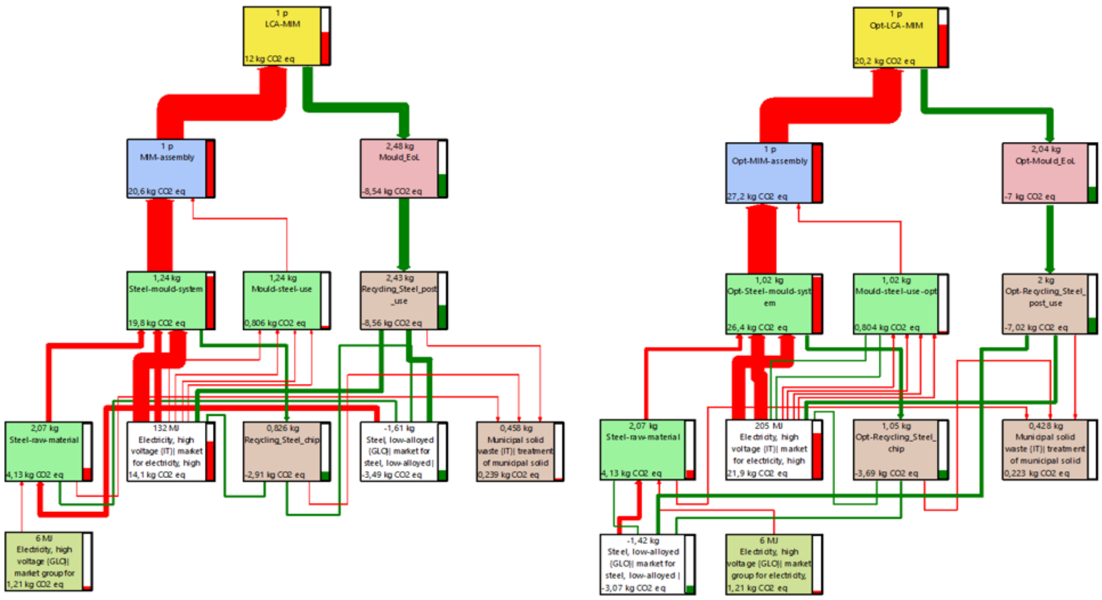

Figure 6 – On the left is CIM's GWP network and on the right is TOIM's.

The CED outcomes are summarized in Fig. 7, detailing the contributions of the four phases under investigation. Considering Fig. 7 (a), the cradle-to-grave CED can be evaluated in detail. The starting configuration of molds used in the investigated process resulted in a more environmentally friendly process within the system boundary analyzed. However, this observation changes if the overall lifespan is taken into account. Making explicit the CED subdivision, the following insights emerge: the CED attributed to both CIM and TOIM processes in the material production phase accounted for 51.30MJ, considering the whole material used during billet production processes. In the mold manufacturing phase, the CED is strictly linked to the required time for machining.

The optimized shape of molds results in an increased CED for TOIM compared to CIM, with values of 581.00MJ and 425.00MJ, respectively. The CED ascribable to the use phase is related to the mass of the molds. Specifically, regarding TOIM, an energy recovery related to the heating and moving phase for each cycle is provided, due to the reduced mass resulting from the TO phase. The resulting CED values for this phase are 18.30MJ and 18.40MJ for TOIM and CIM, respectively. Looking at the EoL phase, the best-case scenario, where materials are remelted, accounted a CED reductions of -118.00MJ for TOIM and -144.00MJ for CIM. This difference arises from the varying recycling efficiencies for chips and steel. The Cradle-to-Grave analysis provide a comprehensive view of the CED impact for each process, considering conventional and optimized designs, shows that the CIM process is 30.80% more environmentally friendly if one cycle time was considered.

The LCA analysis was therefore extended to consider the contribution of the use phase based on the typical number of cycles a mold undergoes during the injection process. The energy used to heat and move the molds was reused in the mold's lifecycle. According to this assumption, the energy contribution of the use phase was added to the analysis, as detailed in Fig. 7 (b). Notably, the sustainable-break-even point (S-BEP) is achieved around 68.50% of the mold’s lifespan.

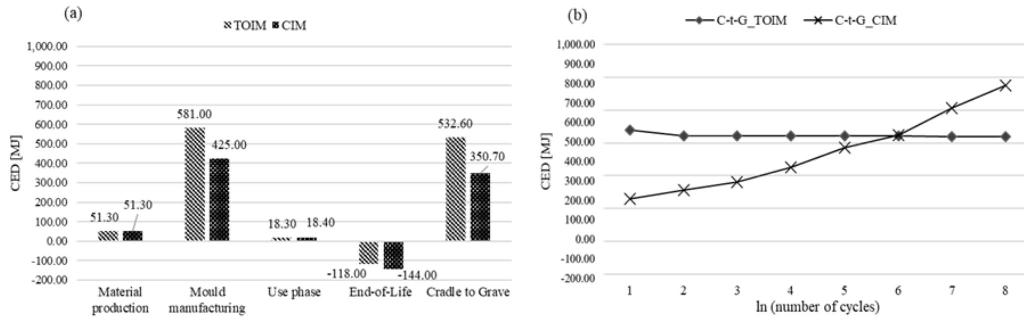

Figure 7 – (a) The CED weight of the investigated processes for each LCA phase; (b) CED increment for each manufacturing solution at changing the number of cycles.

Finally, taking into account the impact assessment conducted using the IMPACT World+ Endpoint V1.04 method, the damage assessment of each analyzed scenario was evaluated in detail, as presented in Fig. 8.

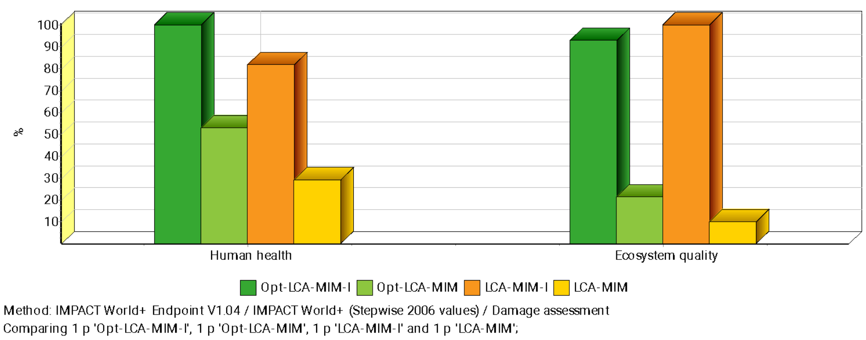

Figure 8 – Damage categories for each analyzed scenario.

Conclusion

This study has demonstrated the significant benefits of integrating LCA into the design and manufacturing processes of microinjection molds. By comparing CIM and TOIM, several key findings were identified:

- Environmental Impact: while CIM initially showed lower environmental impacts due to reduced manufacturing process time, TOIM achieved better performance over an extended lifespan, emphasizing the importance of life cycle assessment.
- Cumulative Energy Demand: the TOIM process exhibited higher CED during mold manufacturing due to extended machining times. However, the energy saved due to the reduced mass to be moved and heated during the use phase, contributed to reducing the overall energy consumption, with the S-BEP reaching about 68.50% of the mold life.
- EoL efficiency: recycling scenarios revealed that TOIM and CIM processes both benefit from high material recovery rates. TOIM demonstrated potential for further impact reductions through improved recycling strategies.
- Design Optimization: incorporating TO reduced material use and mold mass, leading to a decrease in movement energy during the use phase.

Finally, integrating LCA early in the design process enables more sustainable decision-making, balancing initial environmental costs with long-term benefits. The findings of this study reinforce the value of topology optimization combined with lifecycle analysis as a framework for advancing sustainability in microinjection molding. This methodology was applied only on support plates, but it can be extended to all injection mold components to further increase the related benefits and positive impacts. Future research could explore the scalability of these findings to other manufacturing processes and materials. Furthermore, the mold turnover rate during production planning has to be integrated into future developments to provide a clear and comprehensive framework for the sustainability of the microinjection molding process.

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References

[1] Ananthasuresh, G.K., in *Comprehensive Microsystems* (Elsevier, 2008), pp. 559–583.

[2] Saffioti, M.S., Rotella G., Umbrello D., Superfinishing Processes Applied on the Biomedical Implants Surface to Improve Their Performance., May 25 2023, pp. 1341–1346. https://doi.org/10.21741/9781644902479-145

[3] Sanguedolce, M., Rotella, G., Saffioti, M.R., Filice, L. Burnishing of AM Materials to Obtain High Performance Part Surfaces. *Journal of Industrial Engineering and Management* 2022, *15*, 92. https://doi.org/10.3926/jiem.3608

[4] Ren, B., Zhang, S., & Tan, J. (2014). Structural scheme optimization design for the stationary platen of a precision plastic injection molding machine. Chinese Journal of Mechanical Engineering, 27(4), 714–721.

[5] Caruso, S., Imbrogno, S., Rotella, G., Ciaran, M.I., Arrazola, P.J., Filice, L., Umbrello, D. Numerical Simulation of Surface Modification During Machining of Nickel-Based Superalloy. Procedia CIRP 2015, 31, 130–135. https://doi.org/10.1016/j.procir.2015.03.053

[6] Borda, F., La Rosa, A.D., Filice, L., Gagliardi, F. Environmental Comparison of Opposing Manufacturing Strategies at Changing of Energy Sources, EoL Approaches and Shape Peculiarity for an Automotive Component. Advances in Materials and Processing Technologies 2024, 1–21. https://doi.org/10.1080/2374068X.2024.2432724

[7] Rotella, G., Cosco, F., Saffioti, M.R., Umbrello, D. Evaluation of Fretting Corrosion Fatigue in Burnishing of Ti6Al4V Component for Artificial Hip Joint. CIRP Annals 2023, 72, 509–512. https://doi.org/10.1016/j.cirp.2023.04.010

[8] Caruso, S., Sgambitterra, E., Rinaldi, S., Gallone, A., Viscido, L., Filice, L., Umbrello, D. Experimental Comparison of the MIG, Friction Stir Welding, Cold Metal Transfer and Hybrid Laser-MIG Processes for AA 6005-T6 Aluminium Alloy., 2016, p. 100004. https://doi.org/10.1063/1.4963498

[9] Ribeiro, T. P., Bernardo, L. F. A., & Andrade, J. M. A. (2021). Topology optimisation in structural steel design for additive manufacturing. Applied Sciences, 11(5), 2112.

[10] Gohn, A. M., Brown, D., Mendis, G., Forster, S., Rudd, N., & Giles, M. (2022b). Mold inserts for injection molding prototype applications fabricated via material extrusion additive manufacturing. Additive Manufacturing, 51, 102595.

[11] International Energy Agency. Energy System of EUROPE. 2023. Available online: https://www.iea.org/energy-system (accessed on 31 January 2025).

[12] Campos-Romero, H., Rodil-Marzábal, Ó., Gómez Pérez, A.L. Environmental asymmetries in global value chains: The case of the European automotive sector. J. Clean. Prod. 2024, 449, 141606. https://doi.org/10.1016/j.jclepro.2024.141606

[13] Kirchain, R.E., Jr., Gregory, J.R., Olivetti, E.A. Environmental life-cycle assessment. Nat. Mater. 2017, 16, 693–697. https://doi.org/10.1038/nmat4923[14] M. Radovanović, in *Sustainable Energy Management* (Elsevier, 2023), pp. 35–94.

[15] Trotta, G., Basile, V., & Fassi, I. (2015). A Novel Setup for Cavity Pressure and Temperature Measurements in Microinjection Moulding. Proceedings of the 4M/ICOMM2015 Conference, 287–290. https://doi.org/10.3850/978-981-09-4609-8_073

[16]ASM Specialty Handbook - Carbon and Alloy Steels, edited by J.R. Davis, Davis & Associates, ASM International, Metals Park, OH, (1996).

[17] Trotta, G., Cacace, S., & Semeraro, Q. (2022). Process optimization via confidence region: a case study from microinjection molding. Journal of Intelligent Manufacturing, 33(7), 2045–2057. https://doi.org/10.1007/s10845-022-01955-8

[18] HASCO. "Moulding Systems." Accessed January 20, 2025. https://www.hasco.com/en/Product-catalogue/K/Moulding-systems/c/PIM0103.

[19] Autodesk. FeatureCAM Ultimate 2024, Version 7.27, Autodesk Inc.: San Rafael, CA, USA, 2024. Available online: https://www.autodesk.com/products/featurecam/overview (accessed on 4 January 2025).

[20] Borda, F., Adduci, R., Mundo, D., Gagliardi, F. Cumulative Energy Demand Analysis of Commercial and Hybrid Metal-Composite Gears at Different End-of-Life Strategies. Journal of Manufacturing and Materials Processing 2025, 9, 14. https://doi.org/10.3390/jmmp9010014.

[21] PRÉ Sustainability, Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., Wernet, G. Ecoinvent, SimaPro 2020.

[22] Ashby, M.F. *Materials and the Environment: Eco-Informed Material Choice*, Elsevier, 2021.

[23] Agarski, B., Budak, I., Micunovic, M.I., Vukelic, D. Life Cycle Assessment of Injection Moulding Tools and Multicomponent Plastic Cap Production. J Clean Prod 2023, 413, 137450, doi:10.1016/j.jclepro.2023.137450