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Sustainability-Driven Business Model in Mold Manufacturing: A Multi-Criteria Comparison between Conventional and Additive Technologies

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Abstract. The growing demand for high-performance, sustainable micro-moulded components requires integrated approaches to material and process selection. The study presents a Life Cycle Engineering (LCE) framework for the integrated selection of materials and manufacturing technologies for micro-injection molds, combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and multi-criteria decision models. The methodology implements multicriteria cost impact maps and ternary LCA–LCC–technical performance model, allowing for result normalization and sensitivity analysis with respect to criterion weighting. The framework is applied to molds fabricated from steel, aluminium alloy, polyether-ether-ketone (PEEK), and high-temperature resin, using both subtractive and additive processes, with topological optimization. Mass reductions of up to 22% achieved through optimization translate into cost and environmental impact savings of 30–45% during production and use phases, although with potential service life reductions of up to 50% for polymeric materials. LCA and LCC analyses highlight production and use as the dominant life cycle phases, with end-of-life (EoL) impacts being comparatively minor. Sensitivity analysis shows that: (i) cost-prioritized scenarios select optimized steel molds; (ii) scenarios prioritizing lightweight design and environmental performance select advanced polymers and additive manufacturing; (iii) balanced scenarios identify PEEK as the optimal solution. The proposed framework enables the concurrent selection of material and technology aligned with design objectives and geometric optimization, providing quali-quantitative support for sustainability-oriented industrial decision-making across the life cycle.

Introduction

Life Cycle Engineering (LCE) is a comprehensive, sustainability-driven methodology used in product development to balance technical performance, costs, and environmental impacts across a product's entire lifespan. LCE encompasses activities over one or more life cycles and requires rigorous analysis to quantify sustainability and set precise targets for reducing environmental impact. By integrating complementary technologies and decision-making frameworks, LCE allows environmental objectives to be achieved by ensuring products remain functional and economically sustainable from raw material extraction to disposal [1]. The implementation of LCA within the Sustainability Development Goal (SDG) framework transforms high-level policies into actionable engineering requirements. This integration ensures that every phase of a product's life, from resource extraction to end-of-life recovery, supports the broader mission of social and environmental equity. With the tightening of international regulations, the ability to quantify and act on life cycle data becomes the primary mechanism for achieving the 2030 goals [2]. Indeed, the sustainable development concept was identified as meeting the needs of the present without compromising the

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ability of future generations to meet their own needs [3]. This approach is crucial since design decisions made early in the design process can have multiple impacts on life-cycle metrics such as time, cost and quality. The motivation for LCE is the environment, economy, regulations and standards. Design for the environment (DFE) is an element of LCE. The primary goals of DFE are to efficiently manage renewable resources, reduce the use of non-renewable resources, and minimize toxic release into the environment [4]. According to LCE principles as life-cycle design, is a decision-making methodology that considers environmental, performance and cost requirements throughout the duration of a facility. According to LCE principles, the life cycle design of a product or service is a decision-making methodology that takes into account environmental, performance and cost requirements throughout the entire life of an asset. Numerous existing methods analyse the cases studies in different dimensions, namely in terms of costs [5], environmental impacts [6], social impacts [7] or/and products technical performance [8]. Considering the aforementioned works, different sustainable models were applied by the authors, some already published [9, 10, 11]. In this work an innovative approach is proposed to provide designers and practitioners to choose the most sustainable way to develop engineering design alternatives for a specific problem.

Design Alternatives from a Life Cycle Engineering Perspective

To evaluate the impact of different design alternatives in the entire life cycle of a product, three pillars are considered, namely economic, environmental and technical or functional performance. Considering these three sustainability pillars, a ternary model can be used. This type of model allows the aggregation and mapping of the best choice according to the boundary conditions and a system of importance weights is given to each sustainability pillar. On the other hand, the map model provides a basis for analysing situations where alternatives are technically or functionally equivalent, or where technical aspects are highly correlated with cost and environmental performance analysis. Indeed, the map model offer better support in choosing between different design alternatives with different technical/functional performances and when the importance attributed to the various parameters involved in the use life is not a relevant issue. According to both proposed models, the selected case study is represented by a microinjection molding process. Specifically, the design of molds used in the microinjection process is a highly complex task, as it must comply with numerous technical constraints, including material selection, mechanical loads, molds lifespan, production rate, surface quality of the final parts, processing time, and characteristics of the injected materials. The investigated case study is detailed by authors in [10, 11]. Figure 1 reports the proposed decision-making support framework of the LCE model considering both models, i.e. map and ternary model.

The flowchart provides an overview of the proposed sustainability approach, starting from the definition of boundary conditions up to the obtained outcomes for the representation of the solution. The proposed model provides all the necessary information that needs to be available during the design phase in a single decision-making tool that integrates the three main pillars of economic and environmental sustainability and technical performance of the output. Considering the economic perspective and environmental sustainability the impacts are obtained through Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) methodologies. These are obtained using the Process Based Approach (PBA) applied to model both costs aliquots and environmental resources consumption with the relative emissions. The detailed methodology regarding PBA can be analyzed in [10,11].

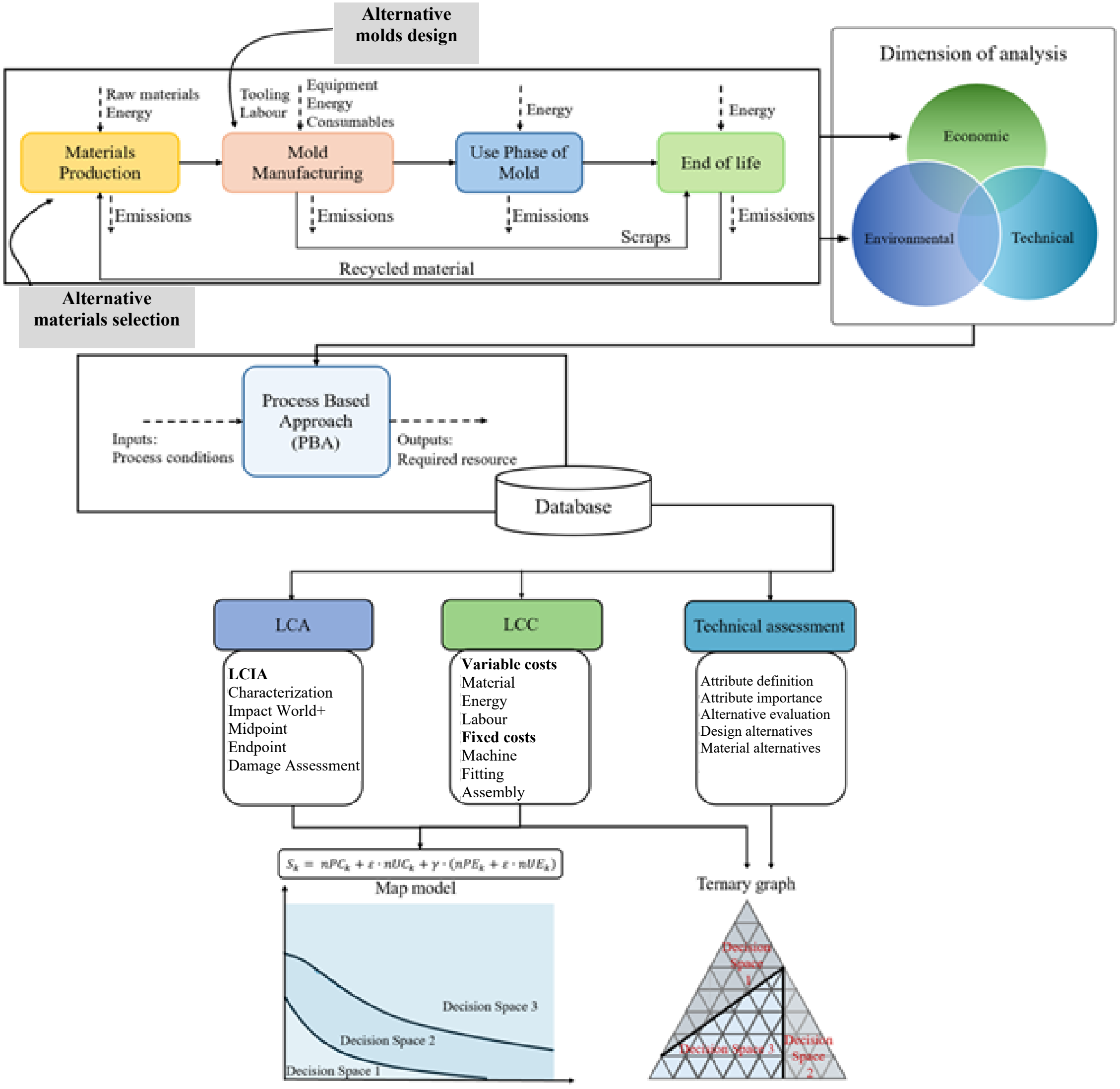

Fig. 1. Flowchart and boundary conditions of the LCE proposed model.

Map model

The proposed map model aims to compare different design alternatives in the microinjection molding process. Firstly, integration of costs related to the environmental impact during the different product life cycle. Secondly, the separation between cost assessment and environmental impact evaluation often induces decision-makers to select design alternatives based on two sustainability criteria thereby creating a trade-off with mechanical performance considerations.

The first step to implement the map model to compare the design material alternatives involves standardising the costs and environmental emission developed in each phase of the life cycle. The normalized values are subsequently aggregated to evaluate production flow (i.e. material and product manufacturing) and use flow (i.e. mold use and EoL phases). Specifically, for each design material alternative the Score ($S_1, \ldots, S_k$) is accounted according to Eq. (1):

$$S_k = (nPE_k + \varepsilon \cdot nUE_k) \cdot \gamma + nPC_k + \varepsilon \cdot nUC_k \quad (1)$$

where, nPE_k and nUE_k represent the normalized production and use environmental emissions for each design alternative, respectively; nPC_k and nCU_k represent the normalized production and use flow costs for each design alternative, respectively. Looking at the terms ε and γ, both terms represent the importance of the environmental costs and emissions of the product's life cycle. For instance, when production costs have an importance of 100%, this means that latter are extremely important for any decision-maker involved in the supply chain. Finally, the decision domain (ε, γ) represents the best choice considering costs and environmental emissions.

Ternary Diagram model

The ternary graph model provides a space of solutions when a Technical performance Assessment (TA) has to be included in the model, in this case the integrated performance assessment can be added to the model via ternary graph firstly introduced by [12]. In the proposed model, each axis represents the pillar that has to be assessed, in this model economic, environmental and technical performance of the investigated mold system are incorporated in a multi-criteria decision tool. Thereby, for each investigated solution $(1, \dots, k)$, the normalized LCC $(nLCC)$, normalized LCA $(nLCA)$ and normalized technical performance assessment (nTA) are accounted by using the Eq. (2):

$$S_k = w_1 \cdot nLCC + w_2 \cdot nLCA + w_3 \cdot nTA \quad (2)$$

where, $w_{1,\dots,3}$ represents the weight of each pillar, i.e. economic, environmental and technical, respectively. By applying Eq. (2) the outcome of the model allows a global assessment of the investigated case study. On the other hand, using this approach the importance of each weight is a critical task because for each specific case study the weight may change and consequently the best application domain.

Life Cycle Engineering model

To evaluate the best choice that meets the correct trade-off between the economic, environmental and technical performance of the investigated molds, two problems were analysed. Firstly, the mold material selection problem, in this case a set of different materials was selected within the design constraints. Looking at the selected materials, the mold design was adapted to guarantee the similar technical performance due to the expertise of the designers. The other part of the investigated case study involves the technology selection problem strictly linked to the material choice; specifically, different injection mold configurations were selected considering different manufacturing processes that perform differently in the manufacturing phase.

Mold components material selection

To demonstrate the applicability of the proposed model to material selection, the present study investigates a case study focused on molds used in the microinjection molding process, which are usually manufactured from steel. The model aims to evaluate the feasibility of using alternative materials with different properties, such as aluminium alloys and high-performance polymers, and to assess their potential to enhance mold performance. A preliminary analysis of the mold's static and dynamic behavior was carried out to identify candidate materials for the next phases of the proposed model. The selected materials and their respective properties, summarized in Table 1, are steel (AISI H13), aluminium alloy (AA 7075-T6), polyether-ether-ketone (PEEK), and high-temperature resin Formlabs (HT V02).

Table 1. Properties of set of selected materials.

	Set of materials			
Properties	**Steel**	**AA**	**Peek**	**HT V02**
Yield Strength (a) [MPa]	1000 – 1200	480 – 520	90 – 110	75 – 90
Young's Modulus (b) [GPa]	205 – 215	70 – 72	3.5 – 4.0	2.7 – 3.2
Density (c) [kg/m^3]	7800	2900	1320	1200
Ductility (d)[kN·m/kg]	30 – 40	50 – 60	20 – 25	10 – 15
Strain Hardening exponent (e) [N·m/kg]	0.10 – 0.15	0.06 – 0.10	0	0
Corrosion Resistance (f) [0/0.5/1]	0.5	1	1	1
Hardness (g) [HV]	480 – 520	160 – 180	25 – 30	20 – 25
Ferromagnetism (h) [0/1]	1	0	0	0
Coefficient of Anisotropy (i) [-]	1.6	0.7	1.2 – 1.5	1.3 – 1.6

In mold design practice, material selection is typically driven by the fulfillment of minimum safety requirements to ensure the successful execution of the process. This approach often overlooks higher-performance materials that may increase manufacturing costs in the production phase although could provide increased performance throughout the entire mold lifecycle. Such improvements may include extended service life, reduced mold weight, and, consequently, optimized efficiency during the use phase. Another relevant aspect of the present case study concerns the temporal scope of the analysis and the different stakeholders involved. Costs and environmental impacts generated during the manufacturing phase are attributed to the mold producer, whereas those arising during the use phase are attributed to the molding operator. Moreover, impacts generated during the use phase may extend beyond company boundaries, as environmental emissions can vary significantly depending on the energy mix of the country in which the mold is operated. Consequently, benefits such as energy savings achieved through mold weight reduction may be valued differently by the mold manufacturer compared to the operator, particularly when considering both environmental impacts and cost implications related to the material selection in the manufacturing phase. The investigated case study highlights the importance of using a model separating the manufacturer from operator in the product's life cycle.

Boundary Conditions

To perform the proposed analysis considering the overall life cycle and material selection for microinjection molds, boundary conditions have to be defined. Specifically, the analysed phases and both environmental and costs flows have to be detailed, as reported in Figure 2.

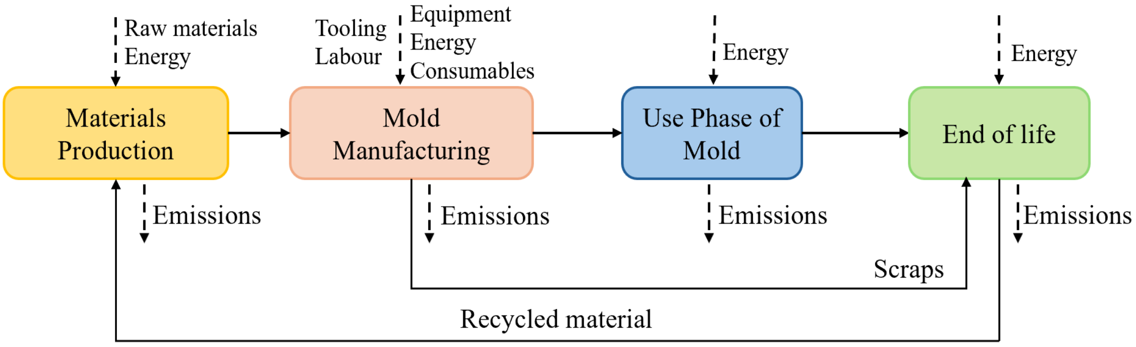

Fig. 2. System boundaries for the analysed molds.

Economic and Environmental Assessment

After defining the system boundaries and considering the mold lifecycle phases, both environmental and cost impacts were evaluated using LCA and LCC methodologies, as previously described. The LCC and LCA results for the selected materials show that raw material-related costs (materials, energy, and processing) have a major influence, while the End-of-Life phase contributes negligibly. The use phase is more significant than the End-of-Life phase. For a production volume of approximately 1000 parts, the LCC results indicate that the total cost-effectiveness corresponds to the sum of all lifecycle phases, as reported in Table 2. By considering the expected production volumes for molds manufactured from PEEK and HT V02 resin and taking into account the microinjection molding process conditions reported in [10, 11], the experimental validation allowed the estimation of an average safe service life of approximately 1000 and 500 injection cycles, respectively, as reported in [12]. This assumption was adopted within the LCC framework.

Table 2. LCC assessment of molds for the analysed materials considering a production volume of about 1000 pieces (€/pc).

Molds lifecycle phases	Analysed Materials			
	Steel	AA	Peek	Formlabs
Materials production	7.21	8.51	7.25	11.97
Mold manufacturing	4.90	5.62	5.47	7.84
Mold use phase	0.39	0.24	0.30	0.40
EoL of mold	0.11	0.06	0.13	0.16
Overall LCC	12.61	14.43	13.15	20.32

The Ecoinvent v3.10 data provided by SimaPro 9.6.0.1 software and information extracted by experimental setup and literature were combined as well as data modelled and calculated for the investigated processes and materials, e.g., detailed values of energy and masses. The energy consumption considered in the LCA analysis was modelled based on the electricity market in Italy.

To assess the impact of mold used in the microinjection molding process IMPACT World+ methods v1.04 was used, available in the SimaPro 9.0.6.1 software. The outcomes were reported in Table 3.

Table 3. LCA assessment of molds for the analysed materials (kgCO$_2$eq/pc).

Molds lifecycle phases	Analysed Materials			
	Steel	AA	Peek	HT V02
Materials production	4.13	10.27	4.49	4.82
Mold manufacturing	18.60	15.01	6.25	4.06
Mold use phase	0.81	0.28	0.15	0.13
EoL of mold	-11.47	-4.41	-2.13	-2.12
Overall LCA	12.07	21.15	8.76	6.89

The environmental impact due to microinjection process is almost related to the material production and manufacturing processes, strictly linked to energy consumption during the manufacturing step, i.e. machining, roughing and finishing, tempering, quenching for metal and post processing for the polymeric material. Considering the use phase, the environmental impact is due to an injection of one piece, this value is calculated according to [10]. Looking at EoL phase, the material recycling energy is accounted for considering a percentage recycling rate of 98% and 90% for steel chip and mold scraps [10]. Whereas the aluminium recycling rate for chip and scraps are estimated by literature [13]. Polymeric materials EoL recycling impact, i.e. PEEK and Formlabs resin were assumed mechanically recycled and incinerated with heat recovery according to [14, 15], respectively. Considering PEEK, the recycling rate was extracted by literature [16].

Discussion of Results

This section examined the results of the assessments calculated in the previous phases. The decision space is divided according to the importance levels due to production and use flows. In detail, the decision space is realised considering Eq. (1). The most suitable materials from both environmental and economic perspective are graphically presented in Figure 3. In detail, the (ε, γ) decision domain represents respectively the level of importance given to both costs and environmental impacts considering the use (utilisation and EoL phases) flows. In the model, the production flows were assumed to be significant for any stakeholder involved in the supply chain.

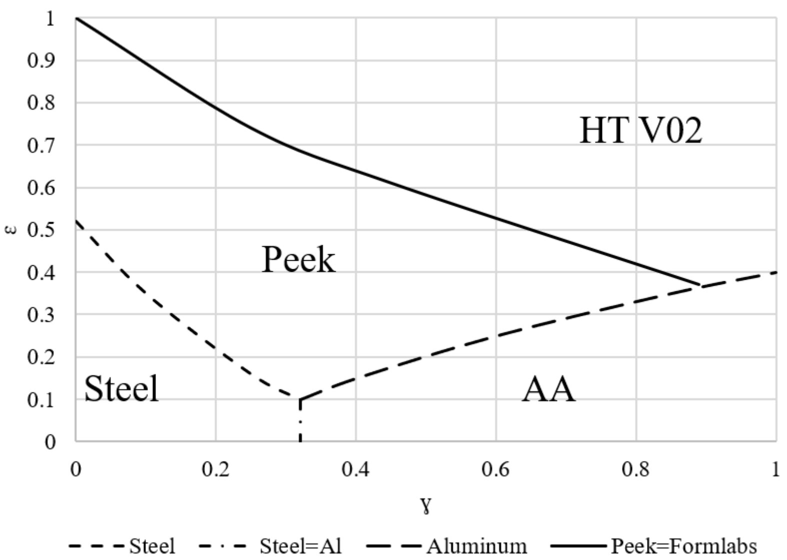

Fig. 3. Map model applied to material selection for molds manufacturing.

Technology Selection

The second part of the analysis focuses on mold material and manufacturing technology selection based on technical properties. Considering the weight of each requirement that the molds have to be satisfy, the proper manufacturing process has to be selected. To select the properly material for mold's manufacturing the weight of each requirement directly associated with the material properties was defined in Table 4.

Table 4. Weight used for the material properties characterization.

Mold requirements	Weight	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
Resistance	0.25	10.00	5.00							
Lightweight	0.15	4.00	4.00	7.00						
Corrosion resistance	0.05						15.00			
Stiffness	0.20		10.00	5.00						
Formability	0.15				5.00	5.00			8.00	5.00
Easy to handle	0.10		2.00	5.00				8.00		
Easy to recycle	0.10			7.00					8.00	
Tot.	1.00	3.10	4.05	3.25	0.75	0.75	0.75	0.80	2.00	0.75
Weighting [%]		19.14	25.00	20.06	4.63	4.63	4.63	4.94	12.35	4.63

To calculate the score for (TA), the weights associated with each material property listed in Table 4 were used. Specifically, the score (S_k) for each material analysed was calculated by normalizing the material characteristics listed in Table 1 and weighing them using the weight calculated in Table 4. Therefore, the score (S_k) for each material was obtained by summing each weighted material characteristic for each mold requirement. The overall score for the selected material that respects the mold requirements results in 0.76, 0.43, 0.29, 0.30 for Steel, AA, PEEK and HT V02 resin, respectively. Based on the obtained results, and therefore of the material that proves to be the most suitable, it is possible to select the type of technology that optimizes the overall sustainability assessment. The proposed decision-support tool allows the definition of an optimal decision space consistent with the strategic priorities of the different stakeholders. For instance, if the objective is cost minimization without considering environmental impact, and mold robustness must be guaranteed, the selected material is likely to be steel. Consequently, since no topological optimization process is applied, the selected manufacturing technology is expected to be conventional machining. Conversely, if mold lightness is a key requirement, the material chosen is likely to be AA, and if the mold requirement specifies conformal cooling channels, the manufacturing technology would be additive manufacturing.

Global assessment

In this section, an integrated and comprehensive assessment can be made based on the results obtained for economic, environmental and technical performance. As described in the previous sections, the outcome values for each dimension were normalized and converted into dimensionless quantities, thereby allowing the consistent allocation of weights to each assessed factor and to each dimension. Specifically, the sum of the weights of the three dimensions must be equal to 100%. In detail, when representing different combinations of weights, it is difficult to assign weights in a single way. Indeed, the choice of weights generally reflects the company's strategy, which can design to assign different levels of importance according to the expected life cycle of the product. To overcome this issue, the best choice for representing the decision space is a ternary graph, where for each axis a dimension of analysis is represented. Specifically, the ternary model not only identifies the best material for a given set of weights but also indicates the range of weight combinations that should be used to obtain a specific output. For instance, if the objective of the company is to minimize only the economic dimension (1) with an importance of 90% and a TA relatively low around 20%, the sustainable tool set as the best choice steel material, as shown in Figure 4. On the other hand, if the company's scenario is more balanced with an importance of more 50% for the TA, 30% for the LCC and 10% for the LCA the outcomes of the model shown the point (2) in the graph with the AA as selected material; otherwise, if the scenario is more than 50% for the LCA, around 40% for the economic perspective and 10% for the TA, the point in the graph is (3) and the best material remain AA.

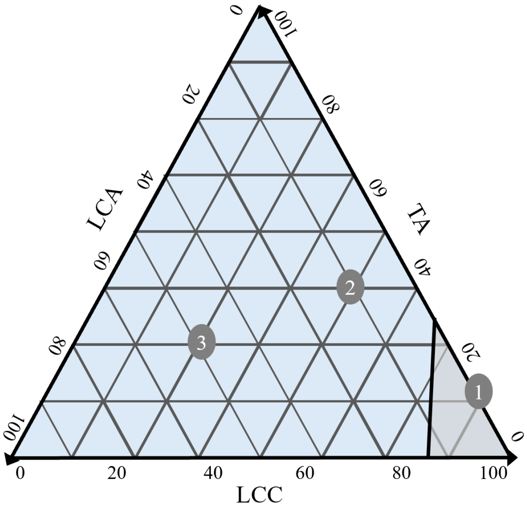

Fig. 4. Ternary graph applied to material selection according to different analysed scenarios.

Analysis of the ternary diagram and scenarios enables the selection of the most suitable material. If the objective is cost minimization with no consideration of environmental impact, while ensuring a minimum technical performance of the mold, scenario (1) is obtained. Conversely, if a more balanced scenario is considered, in which the cost constraint is relaxed and both environmental impact and service life of the mold are regarded as important from a technical perspective, then scenario (3) applies, with AA as the selected material.

Sensitivity analysis

Additional parameters, including reliability and design complexity with mass reduction, were evaluated to broaden the decision space. Based on previous studies [10,11], the environmental and economic impacts of optimized molds were estimated by comparing the material required for optimized and conventional components. Reduced material use provides cost benefits, while optimization introduces extra energy consumption costs that depend on the manufacturing technology used. Conversely, the optimization process results in additional energy consumption costs varying with the selected manufacturing technology. The global assessment, considering the sensitivity analysis performed, led to some changes with respect to the scenario shown in Figure 5. Indeed, with the reduction in the amount of material used, the environmental performance of AA decreased and, consequently, the model predicted the use of two other materials that promote mold lightening and a resulting reduction in environmental impact over the entire life cycle. Therefore, analysing the results, if a weight greater than 85% is assigned to costs, the optimized steel mold represents the best option (1). In contrast, the mold manufactured in AA appears in a region where greater importance is attributed to the environmental dimension and technical performance is weighted between 30–45%. This outcome can be ascribed to the better performance–weight ratio of AA compared with steel. Conversely, when the production scenario is shifted with a focus on lightness at the expense of technical performance, the model converges toward a resin solution (4), which enables improved environmental performance, mainly due to a less energy-intensive use phase. On the other hand, when a more balanced scenario is considered, in which the three dimensions analysed are assigned approximately the same importance (interval between 40–60%), the optimized mold made of PEEK (3) represents the most suitable solution. Finally, the model not only provides a decision-support tool capable of identifying the best material choice but also determines the most appropriate manufacturing technology. Indeed, the environmental and cost assessment accounts for both topological optimization and the associated production route. Consequently, for solutions (1) and (2) and for the corresponding percentage of material removed, conventional machining is the most advantageous process, whereas for solutions (3–4) additive manufacturing offers environmental benefits. In contrast, this outcome is not universally valid, as highlighted in other studies [13, 17], where the two technologies are examined in greater depth: the choice of technology varies according to the percentage of material that must be removed. Indeed, if the optimization process is pushed further at the expense of component service life, the most advantageous technology may no longer be the conventional one.

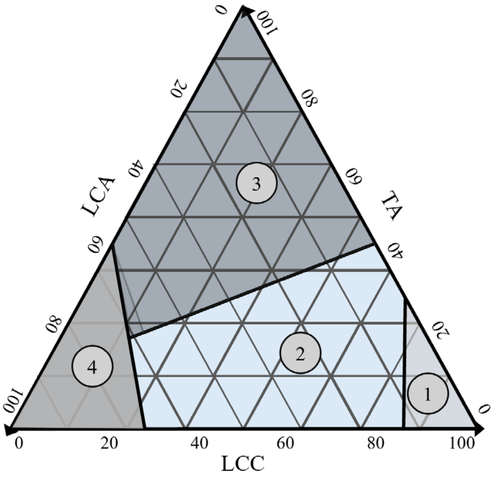

Fig. 5. Ternary graph applied to the selection of mold alternatives.

Conclusions

The work proposes an integrated evaluation framework based on LCE to support material and technology selection for mold design and manufacturing, with a focus on economic, environmental, and performance sustainability. The approach combines LCC and LCA with decision-support and multi-criteria models, allowing the evaluation of alternative scenarios and identification of trade-offs among the considered dimensions. The results show that the reduction of mold mass, achieved through topological optimization, leads to significant environmental and economic benefits, at the expense of a potential impact on the service life of the mold. The sensitivity analysis further revealed that optimal choices strongly depend on the relative importance assigned to cost, environmental impact, and technical performance criteria. When extreme scenarios are considered, such as cost minimization, optimized steel molds prove to be the preferred solution, whereas scenarios oriented toward lightness and environmental efficiency tend towards advanced polymeric materials and the use of additive manufacturing technologies. Conversely, when a more balanced scenario is adopted, high-performance materials such as PEEK emerge as competitive alternatives, capable of combining adequate mechanical properties with reduced impacts over the mold life cycle. The proposed model therefore does not merely identify the most suitable material but also allows to determine the production technology most consistent with the design objectives and with the desired level of geometric optimization, showing how conventional subtractive machining and additive manufacturing assume different roles as requirements change. The model represents an adaptable decision-support tool, capable of integrating the needs of different stakeholders and guiding manufacturing companies toward solutions that are more sustainable from technical, economic, and environmental perspectives. Future work aims to minimize weighting subjectivity through Analytic Hierarchy Process (AHP) and extend the framework to a Life Cycle Sustainability Assessment (LCSA) incorporating social sustainability aspects [18, 19]. Finally, future research activities may extend the model by including additional production scenarios, different production volumes with different types of runners, and further sustainability metrics for materials, as well as experimental validation on real industrial case studies, with the aim of further consolidating the effectiveness of the proposed framework and promoting its large-scale application.

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References

[1] M. Radha Raman, T. Visnu, S. Rajesha, A Study of Tensile Strength of MIG and TIG Welded Dissimilar Joints of Mild Steel and Stainless Steel, International Journal of Advanced Manufacturing and Systems Engineering, vol. 3, 2014, pp. 23–32. https://doi.org/10.14810/ijamse.2014.3203

[2] M. Z. Hauschild, R. K. Rosenbaum, S. I. Olsen (Eds.), Life Cycle Assessment: Theory and Practice, Springer International Publishing AG, Cham, Switzerland, 2018. ISBN: 978-3-319-56475-3.

[3] A. Laurent, C. Molin, M. Owsianiak, P. Fantke, W. Dewulf, C. Herrmann, S. Kara, M. Z. Hauschild, “The role of life cycle engineering (LCE) in meeting the sustainable development goals – report from a consultation of LCE experts”, Journal of Cleaner Production, vol. 230, 2019, pp. 378–382. https://doi.org/10.1016/j.jclepro.2019.05.129

[4] “Sustainable development – EUR-Lex glossary”, European Union, available at https://eur-lex.europa.eu/EN/legal-content/glossary/sustainable-development.html (accessed 2025).

[5] K. Branker, J. Jeswiet, I. Y. Kim, “Greenhouse gases emitted in manufacturing a product — A new economic model”, CIRP Annals – Manufacturing Technology, vol. 60, no. 1, 2011, pp. 53–56. https://doi.org/10.1016/j.cirp.2011.03.002

[6] M. Z. Hauschild, J. Jeswiet, L. Alting, “From Life Cycle Assessment to Sustainable Production: Status and Perspectives”, CIRP Annals – Manufacturing Technology, vol. 54, no. 2, 2005, pp. 1–21. https://doi.org/10.1016/S0007-8506(07)60017-1

[7] M. Hauschild, L. C. Dreyer, A. Jørgensen, “Assessing social impacts in a life cycle perspective—Lessons learned”, CIRP Annals – Manufacturing Technology, vol. 57, 2008, pp. 21–24. https://doi.org/10.1016/j.cirp.2008.03.002

[8] J. R. Chou, “An ARIZ-based life cycle engineering model for eco-design”, Journal of Cleaner Production, vol. 39, 2013. https://doi.org/10.1016/j.jclepro.2013.11.037

[9] F. Borda, G. Ambrogio, L. Filice, F. Gagliardi, Integrated Costs and Environmental Impacts Optimization for Production of a Multi-Material Component, Procedia CIRP, vol. 122, 2024, pp. 587–592. https://doi.org/10.1016/j.procir.2024.02.017

[10] G. Serratore, F. Borda, V. Basile, L. Filice, Life cycle assessment-guided design for sustainable microinjection molds, 2025, pp. 1807–1816. https://doi.org/10.21741/9781644903599-194

[11] F. Borda, V. Basile, F. Gagliardi, L. Filice, "Life Cycle Costing of new generation of molds for microinjection molding process", International Conference on Industry of the Future and Smart Manufacturing 2025.

[12] G. Zaniboni, R. Pelaccia, L. Orazi, R. Surace, G. Rotella, V. Basile, Resin molds to improve thermal energy consumption in injection molding process, 2025, pp. 393–400. https://doi.org/10.21741/9781644903735-46

[13] F. Borda, A.D. La Rosa, L. Filice, F. Gagliardi, Environmental comparison of opposing manufacturing strategies at changing of energy sources, EoL approaches and shape peculiarity for an automotive component, 2024, pp. 1–21. https://doi.org/10.1080/2374068X.2024.2432724

[14] M.F. Ashby, Materials Selection in Mechanical Design, 5th ed., Butterworth-Heinemann, 2016. ISBN: 978-1-85617-608-8.

[15] Formaldehyde Resin as a Solid Fuel and Activated Carbon. (2024). Hungarian Journal of Industry and Chemistry, 52(1), 71-77. https://doi.org/10.33927/hjic-2024-09

[16] A.R. McLauchlin, O. R. Ghita, L. Savage, Studies on the reprocessability of poly-ether-ether-ketone (PEEK), Journal of Materials Processing Technology, vol. 214, no. 1, 2014, pp. 75–80. https://doi.org/10.1016/j.jmatprotec.2013.07.010

[17] Borda, F., La Rosa, A.D., Filice, L. et al. Environmental impact of process constrained topology optimization design on automotive component' life. Int J Mater Form 16, 48 (2023). https://doi.org/10.1007/s12289-023-01771-2

[18] Saaty, T.L. Decision making with the analytic hierarchy process. Int J Serv Sci 1, 83–98 (2008). https://doi.org/10.1504/IJSSCI.2008.017590

[19] Guinée, J.B., Heijungs, R., Huppes, G. et al. Life cycle assessment: past, present, and future. Environ Sci Technol 45, 90–96 (2011). https://doi.org/10.1021/es101396a