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Life Cycle Costing of new generation of molds for microinjection molding process

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Abstract

The growing need for flexibility and sustainability in industrial production has made it necessary to evaluate new strategies for the design and manufacture of molds for injection molding, especially for low-volume production. This study proposes a Life Cycle Costing (LCC) model to compare two micro-injection mold configurations: a conventional one (CIM) and a topologically optimised one (TOIM). The model considers three main stages of the life cycle: production, use and end of life, integrating economic, technical and energy parameters. The results show that, for limited batches (e.g., 200 pieces), the conventional mold is more advantageous in terms of cost per piece €15.85, compared to €17.43 (-9%). However, as production increases, the gap between the two solutions narrows significantly, making TOIM competitive due to its greater structural efficiency and lower weight. Furthermore, the parametric model developed allows the analysis to be adapted to different production scenarios and mold configurations. Although CIM remains more economical in most cases, TOIM represents a strategic solution for sustainable and technologically advanced production. The work provides a useful decision-making tool for selecting the most suitable solution based on economic and environmental objectives.

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Keywords: Life Cycle Costing; LCC; Microinjection Molding; Topological Optimization; Sustainable Manufacturing

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1. Introduction

Over recent decades, the European industry has faced growing competition from regions with lower labor costs [1]. Specifically, the rise of mass customization has compelled companies that traditionally produce molds to adapt to small-volume production. Conventional plastic injection molds can typically justify their high initial investment only when amortized over large production volumes throughout their lifecycle. For smaller production volumes, achieving a competitive cost through amortization of the mold cost becomes challenging, if not unfeasible [2].

As a result, the cost-effective production of large parts in small volumes increasingly relies on unconventional processes such as Resin Transfer Molding (RTM), which often involves the use of fiber-reinforced resins and open molds or alternative sheet metal processes [3,4]. However, these processes come with limitations, as they do not accommodate the use of thermoplastic materials in the design phase. This compromises key advantages such as component lightness, dimensional accuracy and superior surface finishing. At the same time, in order to address the progressive reduction in the life cycle of components and, consequently, the increasingly shorter time to market, which necessitates increasingly customized and innovative products, it is necessary to develop innovative technologies that enable the production of injection-molded components but at the same time guarantee competitiveness even with small batch sizes.

Nowadays, rapid tooling and additive manufacturing (AM) technologies play a pivotal role in reducing mold production times [5]. These times are significantly influenced by the quantity and type of materials used in mold manufacturing. For this reason, optimizing the mass of molds during the design phase is essential, as it reduces not only the production cycle time but also the operational cycle time [6–9]. This optimization results in lower production costs, making molds competitive even for low production volumes.

However, weight and cost savings do not always guarantee the same durability as molds produced using conventional methods [10]. By analyzing scientific literature, the need to compare not only manufacturing technologies but also the environmental performance of molds throughout their lifecycle has been highlighted. As an outcome of this analysis, key aspects to be compared have been identified to achieve a comprehensive understanding of the technologies in terms of both economic and environmental sustainability.

This paper presents a model for comparing the life cycle cost of two types of micro injection molding tools from an economic perspective. Specifically, the model aims to compare two types of molds developed in a previous work [11] by the authors. The proposed model follows trends in product and process design supporting the application of Life Cycle Engineering (LCE) approaches. The novelty of the work consists in comparing, from an economic point of view, conventional moulds used in the microinjection moulding process and topologically optimised moulds. Specifically, the model considers the resources involved in all stages of the mould life cycle using a cradle-to-grave approach. This paper is structured as follows: firstly, an introduction to the state of the art, in the second section a description of the microinjection molding process analysed, in the third section the methodology applied and finally in sections 4 and 5 a discussion of the results and conclusions.

1.1 State of the art

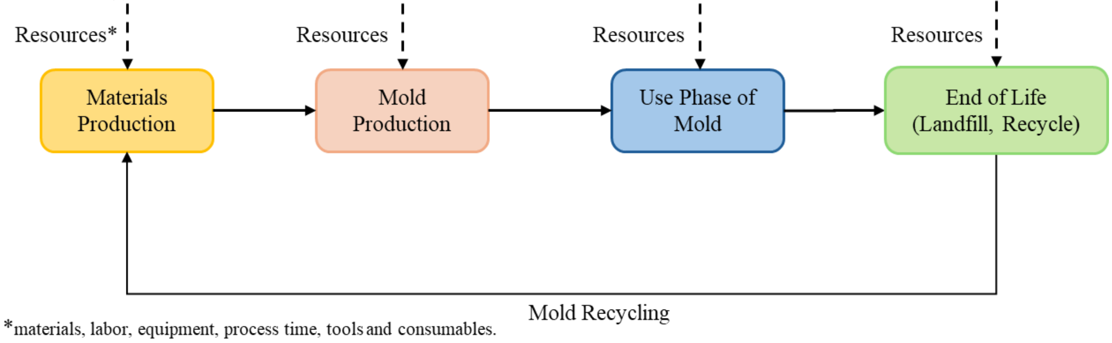
Regarding economic sustainability, the concept of Life Cycle Costing (LCC) originated in the United States in the early 1960s to optimize the costs of large-scale assets [12]. Throughout history, the LCC has been developed for different contexts, including products, machines, infrastructure and projects, focusing on different aspects [13]. Over time, depending on the type of product, asset or project under analysis, the LCC started to be developed on four main types of models: logistics decision support models, total cost models, design exchange models and repair level models. The cost analysis is an important factor in the decision-making process for analysing the economic viability of a technology or a product.

One of the first studies where cost analysis was applied involved defining the correct orientation of a component in the additive process in order to minimise the manufacturing cost [14]. However, it should be pointed out that cost analysis is not limited to the evaluation of production costs, but must include the costs of labor, materials and machinery, as highlighted in the study developed by Hopkinson and Dicknes [15].

The product design sector has supported the development and integration of several aspects in LCC: reliability, quality and product assurance [16], design impact on manufacturing costs [17], utility of a product to consumers [18], eco-design and translation of environmental burdens into costs [19,20].

In this context, life cycle costs encompass all expected expenditures from the initial stages through to the end-of-life phase. The primary goal of LCC analysis is to provide a framework for selecting the most cost-effective approach among different alternatives within a specified timeframe. Numerous studies have demonstrated that applying this methodology leads to products with reduced acquisition, operational and disposal costs [21–23].

An LCC study typically accounts for all costs associated with a product throughout its life cycle from cradle to grave [24]. This provides a comprehensive estimate of the total costs incurred from the design of a product to its decommissioning. The LCC model to be developed will follow established LCC procedures [25]. The main steps involve defining the lifecycle phases and collecting relevant data for modeling the molds. The application of a life cycle approach, therefore, requires the definition and characterization of the mold life cycle phases. Based on the literature and the expertise of the researchers involved [20,26], four critical phases of the lifecycle for injection molds were identified, as reported in fig. 1. Specifically, considering costs and environmental aspects such as emissions, resources and energy consumption.



*materials, labor, equipment, process time, tools and consumables.

Figure 1. Critical LCC phases for microinjection molds.

On the other hand, considering the device sector, as reported in literature, the LCA and LCC analysis of a personal activity monitor device manufactured by roll-to-roll processes identified electronics assembly and injection molding as the production steps with the greatest influence on environmental impacts and costs [27,28]. Another research compared fused filament fabrication (FFF), a 3D printing technology, with injection molding for the mass production of plastic packaging [29]. This study concluded that FFF has five times more environmental impact than injection molding, with the high energy consumption of printing accounting for 80% of the impact. From a financial point of view, FFF is significantly more expensive for mass production, although it may be more advantageous for small production quantities [30,31].

2. Microinjection molding process

The proposed decision-making tool is applied to a specific case study in microinjection molding, considering the experimental equipment and process parameters described in a previous work [11]. Different types of steel can be used in the mould manufacturing process, as demonstrated by various studies investigating mechanical properties under varying microstructures [32,33]. The HASCO K20 molds analysed 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.

2.1 Case study design

The analysed case study is aimed at cost analysis and the development of a decision-making tool for analysing molds for the microinjection molding process. Specifically, the molds were made of steel and were topologically optimised as described in [11]. The study aims to compare the sustainability of conventional microinjection molds (CIM) and that of topologically optimised microinjection molds (TOIM) both from an economic point of view through the LCC and from a global point of view through a decision-making support tool. Mechanical analysis and mold environmental impact analysis were discussed and developed in [11]. Specifically, the main dimensions of the initial geometry of the molds are 95 mm x 95 mm x 12 mm for width, length and thickness, respectively. The CIM and TOIM weights used in the study are 1.24 kg and 1.02 kg, respectively, with a weight reduction of 22%.

3. Methodology

A schematic representation of the processes involved in mold production is illustrated in fig. 2. In detail, the parameters used in the LCC analysis are also reported in the proposed model.

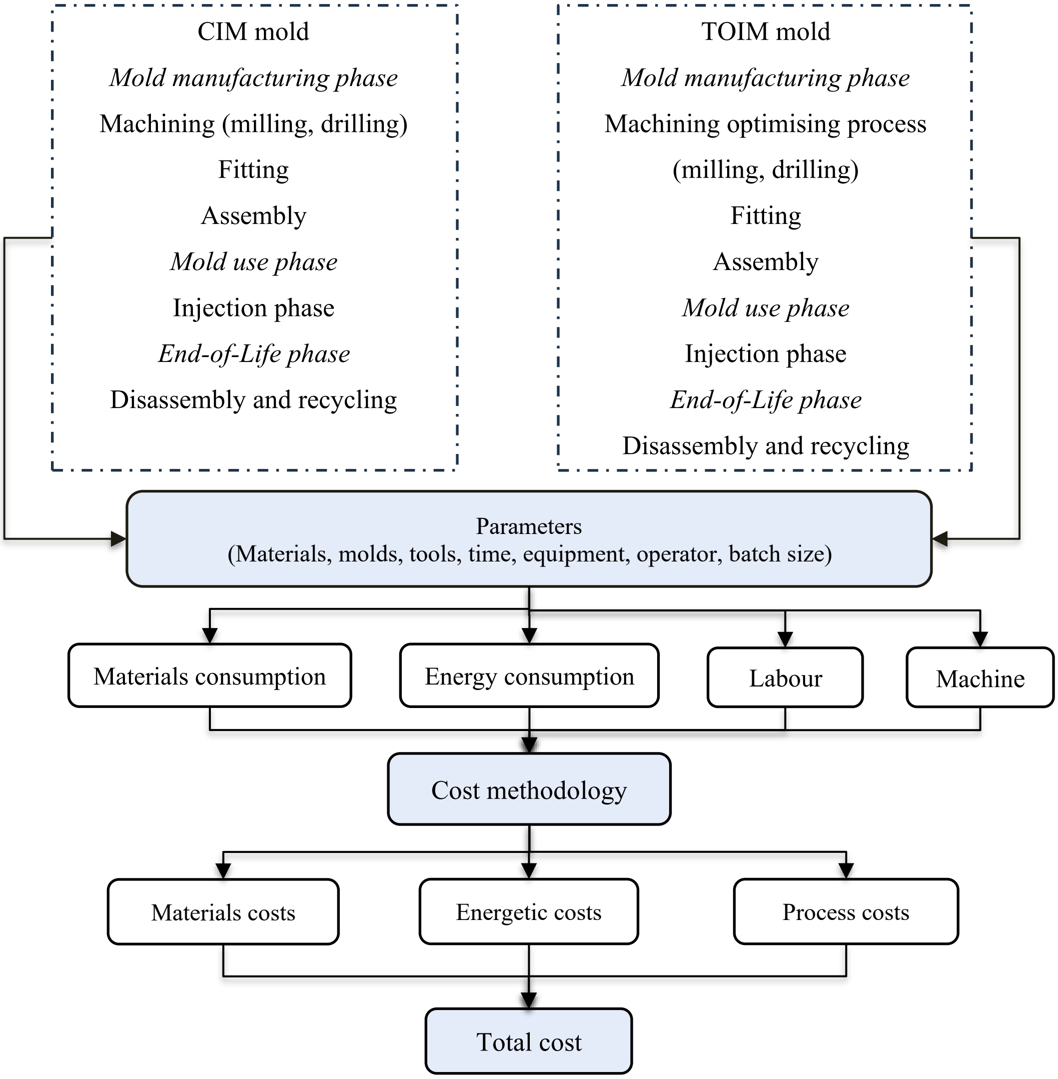


Figure 2. The proposed Life Cycle Cost model.

In order to achieve the impact of the molds used in the microinjection molding process, all relevant production steps to obtain the mold, materials consumed, labor involved, equipment used, process time required, tools and consumables spent should be considered. The identification and calculation of all these data, together with material and tooling costs and labor payroll, allow the estimation of the time and cost of mold manufacturing. The comparison should also include subsequent mold life stages such as injection of plastic parts, setup operations and molds' turnover, mold maintenance, end-of-life phase of the mold and recycling or reuse of components. Indeed, the selection of a mold manufacturing technology has an effect not only on the manufacturing costs but also on the mold use phase costs, the mold lifetime and its reuse/recycling potential.

Several inputs were considered during the performed LCC analysis. Specifically, at this phase the LCC analysis was applied at steel molds case study to compare CIM and TOIM from an economic point of view. In order to assess the economic viability of the entire life cycle of the steel molds used for the micro-injection molding process, key parameters were considered. Specifically, to apply the cost model across various processes, several inputs are required. These inputs are grouped based on their specific types, including materials, parts, machining tools, time, equipment, operator and part batch. This classification ensures a structured approach to evaluating costs and resource use for each process phase. The algorithm, described in the methodology section, starts by analysing the process parameters to carry out a detailed life cycle inventory. It evaluates the mass and energy flows to determine resource and energy consumption. Simultaneously, it considers facility-related factors to assess labor and machinery use. Finally, data are cross-referenced with cost databases to calculate the total cost of the whole mold's life cycle. Most relevant cost input values used in the proposed model considering a working days per year of 228 and an effective working hours per day of 7. Regarding the other costs considered in the model, the income for a worker involved in CNC machining, drilling and component handling was included at €1500 per month; the purchase cost of a CNC milling machine at €150000; and the cost of the machine used for the microinjection molding process at €82000. In this study, the materials and consumables used in the investigated machining processes were also considered. Specifically, the cost of mold steel and cutting fluid was considered at €3.96/kg and €9.00/lt, respectively. In addition, the cost of the tools used in the machining process and all related accessories on the injection system was considered at €354.30 and €450.00, respectively. Specifically, the mold aliquot represents the different tools used during the machining operations of mold manufacturing, whereas the standard component aliquot includes mold plates, injectors, ejectors, guides, centering pins and standardized cooling systems. The LCC model was developed using a parametric approach that captures key technical relations by interconnecting costs with different input type. In detail, this approach could guarantee the analysis of different scenarios for different mold configurations. In this work, the model was applied to the two selected molds, i.e., CIM and TOIM, for different production scenarios. According to the model aforementioned, the life cycle costing of the mold life cycle was divided into three relevant phases, i.e. mold production, mold use and mold end of life. The cost structure of the two types of molds was presented in the following Table 1.

Table 1. Mold production phase cost for the CIM and TOIM molds and cost distribution by cost category.

Items		**Cost distribution**	
		Partial (%)	**Total (%)**
Raw materials	Steel	6.60%	
Milling	Labor and machine cost	26.80%	
	Energy	3.00%	
	Tools and coolant	3.70%	33.50%
Drilling	Labor and machine cost	3.00%	
	Energy	0.10%	
	Tools and coolant	0.50%	3.60%
Fitting	Labor	9.40%	9.40%
Assembling	Labor	0.10%	0.10%
Standard molds		46.80%	46.80%
Type of molds		CIM	TOIM
Total cost		828.68 €	1090.49 €
		Cost category	
Process cost		39.30%	
Materials cost		57.60%	
Energetic cost		3.10%	

In detail, the fitting and assembling aliquots in Table 1 represent the operator's time for fitting and assembling the molds and related auxiliary components to the equipment. Each cost category contributes similarly to the overall mold production cost. Materials represent the largest share, approximately 58% for the two types of molds followed by process costs, which account for about 40%. Finally, the energetic costs make up the smallest portion.

4. Discussion of results

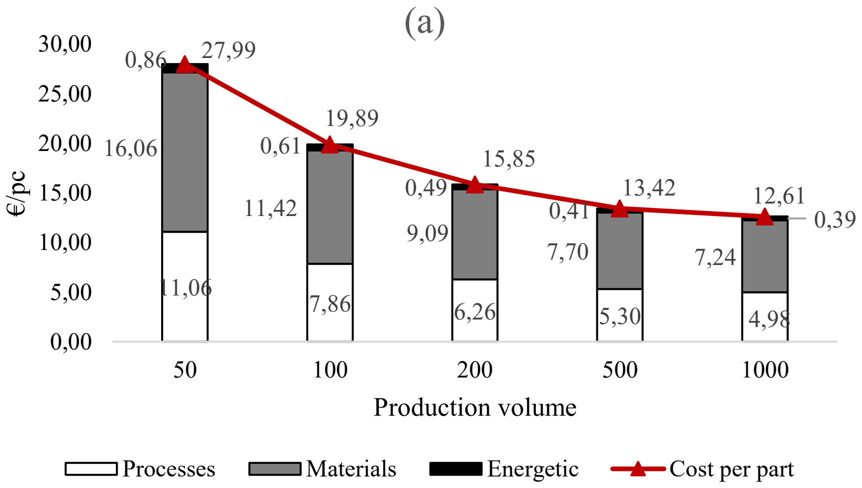
The comparative analysis between the molds was presented in three steps. Firstly, the production phase was analysed to assess the contribution of individual processes and the significance of each cost category in the total mold cost. Subsequently, considering the lifespans of the two molds, the overall cost was assessed for a production volume of 200 parts.

Table 2. Life cycle cost for each investigated molds type and cost distribution for each cost category.

Life Cycle Phases	**Items**	**Cost distribution**			
				Mold type	
		%		CIM	TOIM
Mold production	Process	36.16%	92.00%	299.62	394.28
	Materials	52.99%		439.13	577.87
	Energy	2.85%		23.63	31.10
Use of the mold	Process	2.79%	7.10%	23.12	30.43
	Materials	4.09%		33.89	44.60
	Energy	0.22%		1.82	2.40
End of life	Process	0.35%	0.90%	2.93	3.86
Total cost (€)				828.68	1090.49
Cost per part (€/pc)				15.85	17.43

Specifically, in Table 2, the whole life cycle costs of the molds and their distribution by cost category for the injection of 200 plastic parts are presented. The mold manufacturing phase represents the largest portion of the total cost, around 90%. This is expected in a low production volume scenario, as the high initial manufacturing cost is spread over a small number of parts. As a result, the lower manufacturing cost of the CIM mold significantly impacts the overall life cycle cost, leading to a lower cost per part compared to the TOIM mold. Specifically, the cost per part for a batch size of 200 injected parts is 15.85 € and 17.43 € for CIM and TOIM molds, respectively, with a cost reduction of about 9%.

To provide a comprehensive analysis of the whole life cycle cost, the graph in fig. 3 illustrates how production volume affects the total life cycle cost of both investigated mold type. Whereas the significance of process and materials costs decreases with the increase in production volume for both mold types, the rate of decrease is slower with the TOIM configuration mold due to its longer optimisation process.



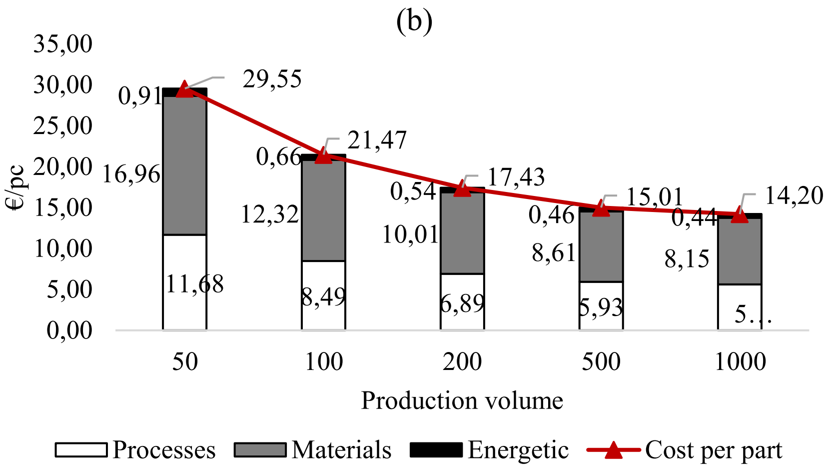


Figure 3. Total unit costs and influence of the batch size in the whole life cycle cost of the molds:(a) CIM mold and (b) TOIM mold.

In order to obtain a complete view of the cost development on the basis of the production batch, the graph in Fig. 4 reports the development of the cost per part for both investigated configurations.

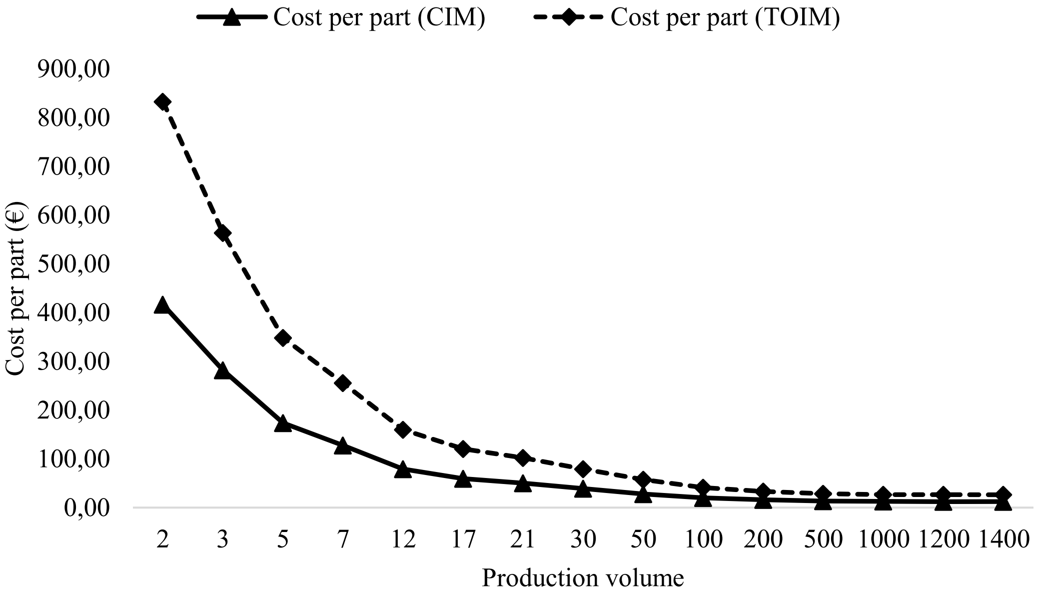


Figure 4. Variation of the cost per part with the production volume in euros.

Looking at the graph in fig. 4, for very low production volumes (e.g., 2-50 parts), the cost per part for TOIM is significantly higher than for CIM, due to higher process and energy costs, mainly due to the longer cycle time and higher production complexity of the topology optimized mold. CIM has a net economic advantage in the early production ranges, maintaining significantly lower costs per part than TOIM up to about 100 parts. In detail, both curves show a non-linear decrease in cost per part with increasing production volume, but that of TOIM falls more slowly, due to limitations in process efficiencies. Starting at around 500 injected parts, the total unit cost converges, with marginal differences between the two molds. However, even at higher volumes (up to 1400 units), CIM continues to offer a slight cost-per-part advantage, albeit less marked. CIM is more cost-effective over the entire production range analysed, although the difference with TOIM decreases significantly as the batch size increases. However, the choice between TOIM and CIM may also depend on other factors, such as sustainability, design flexibility, material use, or advanced functional requirements (e.g., more localised cooling, reduced weight).

5. Conclusion & future perspectives

The study demonstrated the effectiveness of the LCC model in the comparative analysis between traditional and optimised molds for the micro-injection process. The results show that, for small production batches, conventional molds are more cost-effective, mainly due to lower production costs and lower initial investment requirements. However, the adoption of topologically optimised molds, although more expensive in the initial phase, paves the way for more sustainable and potentially more efficient solutions in the long term. Weight reduction, efficient use of materials and design flexibility are characteristics that, if exploited in an industrial context geared towards sustainability and innovation, can justify the initial investment even for medium-sized production batches. The manufacturing phase has the greatest impact on total costs, accounting for approximately 90% of the overall costs for both types of molds. In this phase, CIM shows an immediate economic advantage: its total cost (€828.68) is lower (-24%) than that of TOIM (€1,090.49), resulting in a reduction in the cost per piece, €15.85 and €17.43 (i.e., -9%) for a batch of 200 units for CIM and TOIM, respectively. This advantage stems mainly from the lower production complexity and reduced cycle times during the manufacturing phase of the conventional mold, which requires fewer energy, time and operational resources. The use phase contributes marginally to the total cost (approximately 7-8%) but introduces significant quality and performance aspects. Although TOIM involves a higher initial investment, its optimised design can lead to more efficient use of materials, greater lightness (22% reduction in weight) and potentially better thermal and structural performance during the molding phase. However, these benefits do not translate into a direct economic advantage in the batches analysed. At the end of life, the economic impact is negligible (less than 1%), but it represents a promising area for the introduction of circular economy strategies. Thanks to its advanced design, the TOIM mold can offer greater opportunities for modular reuse and selective recycling of components. The analysis of the influence of production volume showed that for low volumes (2-100 pieces), the CIM maintains a net competitive advantage. However, as production increases, the difference between the two molds gradually narrows: above 500 pieces, the costs per unit converge, with marginal differences. This suggests that, for medium-high production runs, TOIM could become competitive, especially when considering benefits that are not strictly economic, such as environmental sustainability or end-product quality.

Finally, combining LCC study with other environmental parameters allows for more sustainable decision-making, balancing initial environmental costs with long-term benefits. The results of this study indeed emphasise the value of topological optimisation from an economic perspective on a scaled-up production batch to promote sustainability in microinjection molding. The LCC methodology was applied to the support plates, nevertheless it can be extended to all components of the injection mould to further extend its benefits. Future research could explore the scalability of these results to other manufacturing processes and materials by integrating a sensitivity analysis to provide more robustness to the data. In addition, the mold turnover rate during production planning needs to be integrated into future developments to provide a clear and comprehensive view of the sustainability of the microinjection molding process. Further developments should include the integration of environmental and mechanical performance analysis in the LCC model to obtain a complete view of sustainability, the extension of the study to alternative materials, such as light alloys or advanced technical polymers, the simulation of dynamic scenarios in which the production mix and the required mold turnover, the return on investment analysis for the optimised mold in production contexts with a greater focus on environmental sustainability.

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